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A comprehensive review on hull forms and relevant researches of wave piercing vessels

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Abstract: Wave piercing vessels have special hull shapes and behave softly in waves. In recent years, more attention has been paid on wave piercing vessels, and the wave piercing design is becoming popular among practical applications. More innovations related to wave piercing vessels have appeared and more researches on wave piercing vessels are available. Therefore, a comprehensive review on hull forms and relevant researches of wave piercing vessels is presented, which is a good reference for researches related with wave piercing vessels. Moreover, some promising research directions related to wave piercing vessels areas are provided.

Key words: wave piercing vessels; hull forms; hull performance; high performance ships

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0 Introduction

Wave piercing vessel is a general term for ships with wave piercing characteristics. As a kind of high performance ship, the main characteristics of wave piercing vessel are as follows: by reasonable wave piercing design, slamming loads suffered by the hull in waves are reduced and eliminated, and acceleration and motion amplitude of hull in waves are decreased, so that the hull has small resistance and fine seakeeping performance in waves. Due to the economic and military requirements of various countries, wave piercing vessels obtain more and more developments and applications in recent years. Wave piercing vessels are applied in military field, yacht design field and transportation field. Scholars in China and abroad also have studied the subject related to wave piercing vessels to explore the characteristics of wave piercing vessels' hull forms, so as to improve and perfect wave piercing vessels and further realize the innovation of hull forms of wave piercing vessels. At present, a variety of hull forms of wave piercing vessels have been developed. Different hull forms of wave piercing vessels have its own unique advantages. This paper will give an overview and summary on the current situation of hull forms of wave piercing vessels, the hull performance and the hull performance prediction methods.

1 Current situation of hull forms of wave piercing vessels

Wave piercing vessels can be divided into wave piercing monohull (WPM) and wave piercing multihull by the number of hull (demihull). Wave piercing multihull mainly includes wave piercing catamaran (WPC) and wave piercing trimaran (WPT). Hull forms of wave piercing vessels are mainly produced

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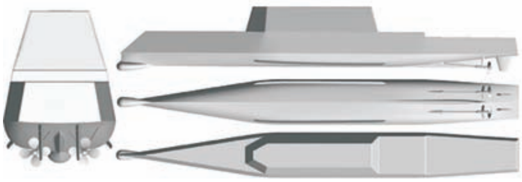
by two ways: the first is modified from traditional hull; the second is utilization of innovative hull design.

1.1 WPM

WPM appeared as early as in the ironclad era. Due to that the hull is easily wetted at high speed or in adverse sea conditions, and as the development of cannon technology, ironclad ships, which adopt tumblehome design, are temporarily out of the stage of history. In recent years, to achieve high speed and fine seaworthiness in adverse ocean environment, WPM with slender hull and bow appears again. In addition, classic WPM has stealth performance due to tumblehome design. With the increase in demand for high-performance ships capable of performing their tasks in adverse ocean environment and the increasing emphasis on stealth technology, WPM receives more and more attention and development, and some innovative WPMs appear successively.

As the most advanced destroyer at present, American DDG-1000 utilizes a classic tumblehome wave piercing design so as to realize the stealth purpose. The ship is also currently one of the most well known wave piercing vessels. Office of Naval Research (ONR) has disclosed ONR-TH (Fig. 1[1]), a kind of WPM which is very similar to DDG-1000, for researchers to explore this type of ship. Most of the published studies related to WPM are based on ONR-TH.

(a) DDG-1000



(b) ONR-TH

Fig.1 WPM developed by US Navy

Very Slender Vessel (VSV) is a slender, high-speed WPM (Fig. 2) co-developed by Defense Advanced Research Projects Agency (DARPA) and Office of the Secretary of Defense (OSD). The design objectives of VSV are as follows: reduce their own target characteristics; directly pass through waves rather than slide on the wave top like traditional deep V planing boat; reduce wave impact load; and achieve high speed and fine seaworthiness in waves. According to the description of the relevant patent[2], VSV mainly has following characteristics and advantages: good performance of hull in bad weather is obtained by utilizing convex bottom shell and broadside auxiliary units; high load is obtained by very small performance loss; lower radar signal characteristics; fuel consumption is reduced by 20% compared with that of traditional planing boat. The design has been put into practical application. Speed of one VSV equipped by British Royal Navy Special Boat Service is more than 60 kn. The design of VSV design has also been applied to a yacht design, Maryslim.

Fig.2 VSV

Transonic hull (TH) with a slender triangular hull was developed and applied for a patent[3-4] by Transonic Hull Company (THC), as shown in Fig. 3. TH's freeboard is almost perpendicular to water surface. THC declared that compared with three kinds of traditional ships, no matter in still water or waves, TH' speed can be improved by 17% under the same horsepower; seakeeping test indicates that TH can keep zero pitch angle and avoid slamming loads at full speed and under various wave conditions, and the acceleration of TH is small.

Fig.3 Transonic hull

Van diepen designed a flat wave piercing bow (Fig. 4), and applied for a patent[5]. Different from the slender wave piercing bow adopted by DDG-1000, VSV and TH, this bow is relatively wideflat. This design aims to use tumblehome surface of bow to balance the lift force generated by wave's buoyancy during wave piercing. According to the description of relevant patent, this design can reduce or even eliminate pitch motion and slamming loads, reduce structure weight of hull, improve seaworthiness, and reduce resistance in calm water.

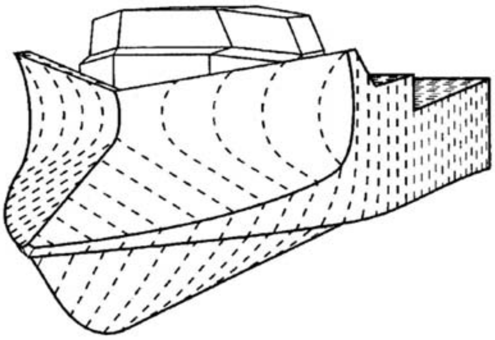


Fig.4 Flat wave piercing bow

X-Bow developed by Ulstein (Fig. 5) is used to improve the hull operation in terrible ocean environment. The design is mainly applied in the field of ocean engineering. Concept of X-Bow was proposed in 2005. By 2016, ship orders using X-Bow have been more than 100. Vos Partner constructed by Guangdong Cosco Shipyard is a medium-sized offshore platform supply vessel with X-Bow.

Fig.5 X-Bow

Wei's team from Shanghai Jiao Tong University designed a high-speed shuttle vessel on the basis of classic tumblehome wave piercing vessel[6-9] and studied the performance, hull form characteristics and optimization of the shuttle vessel at high speed. The high-speed WPM designed by his team has slender bow, transom stern and bow spray strips, and can be operated in the semi-planing mode. Furthermore, spray strips are developed into angle-freebard to better control wetted hull surface.

1.2 WPC

Generalized WPC refers to catamaran that utilizes wave piercing design, and narrowly defined WPC refers to a kind of WPC first proposed by Australia which will be marked by WPC-AU in the following part. This WPC scheme proposed by Australia combines with small waterplane area twin hull (SWATH)'s advantages of low resistance and high seakeeping. Besides, it overcomes the shortcomings of SWATH such as insufficient reserve buoyancy of demihull and relatively small space through deep V hull. This WPC scheme has attracted a lot of attention and praise for its high speed and seakeeping performance. At present, research and application of WPC are mostly based on this scheme. HSV of AMD company built for Australia Navy is shown in Fig. 6. Type 022 missile boat of Chinese Navy utilizes a similar design scheme. China Ship Development and Design Center has carried out in-depth research on similar WPC and has formed series design.

Fig.6 HSV wave piercing catamaran

Different from the WPC designed by AMD company, WPC designed by the team of Great Britain adopts stepped planing catamaran. On the basis of the stepped planing catamaran, the bow of the WPC is modified into a slender wave piercing bow which has certain leaning angle, and the fore connecting bridge is removed, as shown in Fig. 7. The superstructure is streamlined to reduce slamming. This WPC aims to break the transatlantic speed record. According to British "Daily Mail": under proper conditions, it only take 48 h for this WPC to across the Atlantic; average speed of the ship is as high as 105 km/h, which is expected to break 1992's record of traversing Atlantic of 2 d 10 h 54 min in 2018 summer. But, its actual performance of this WPC remains to be seen.

1.3 WPT

WPT is primarily evolved from WPM and WPC. Pathway 1 takes WPM as parent hull, and demihulls are added on both sides of the parent hull to further improve the stability of hull and improve hull rolling;

Fig.7 Wave piercing catamaran designed by the team Great Britain

pathway 2 takes WPC as parent hull, and the appendage is added between two demihulls to improve longitudinal motion and vertical motion in waves. Besides, there are other types of WPT.

The most famous WPT is "Earthrace" yacht, as shown in Fig. 8. "Earthrace" is made up of a central wave piercing main hull and left and right demihulls, which is designed to break the UIM "Speed Record of Motor Vessel Around the World". Allegedly, "Earthrace" windshields are able to withstand water pressure up to 7 m, and theoretically can withstand 15 m wave height. However, this ship so far has only been submerged up to 4 m in sea trials. The ship sank when collided with Japanese whale catcher, and new "Earthrace" is under construction. Unfortunately, no public research information related to the ship is found.

Fig.8 Earthrace wave piercing trimaran

France and Britain have also put forward some design schemes of destroyer and frigate based on WPT. Ocean Eagle 43 (Fig. 9) designed by France is a high performance trimaran for maritime surveillance and security maintenance. Ocean Eagle 43 and "Earthrace" have similar arrangement, but Ocean Eagle 43's length-width ratio of central main hull is bigger, with symmetric demihulls in the middle part of the ship along the length direction. In addition to increase the stability of hull, the arrangement of demihulls is beneficial to improving the turning ability of a slender hull.

Fig.9 Ocean Eagle 43

Based on AMD WPC, Zhao et al.[10] equipped a semi-submerged body (SSB) underneath the central hull bow, forming wave piercing multihull.

Matveev et al.[11] proposed a special WPT concept which is different from the above concept of wave piercing vessel, as shown in Fig. 10. This concept design utilizes slender struts to connect three sliding demihulls with airfoil shape superstructure, with comprehensive utilization of dynamic lift of water and air.

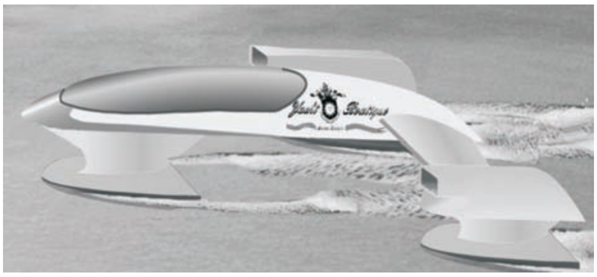


Fig.10 WPT by Matveev et al

2 Summary of hull performance of wave piercing vessel

Hull performance mainly includes the buoyancy, stability, unsinkability, resistance and propulsion, maneuverability and seakeeping of ship. Compared with traditional hull forms, wave piercing vessel more emphasizes on its excellent performance in waves. Therefore, wave piercing vessel's seakeeping attracts more attention. At the same time, unconventional design is mostly adopted in wave piercing vessels, therefore, its safety (stability, unsinkability, etc.) is also of great concern.

2.1 Speed and resistance

An optimal design for high-speed wave piercing vessel significantly reduces resistance and increases its speed. Compared with traditional planing boat, fuel consumption of VSV is reduced by 20%. THC declared that compared with three kinds of traditional ships, no matter in still water or waves, TH can improve the speed by 17%[12] under the same horsepower. WPC-AU not only has low smooth water resistance, but also has small wave added resistance at high speed. World's fastest ferry Francisco high-speed WPC is a large dual fuel high-speed roll-on roll-off ship with liquefied natural gas (LNG) as main fuel, with no-load speed more than 58.1 kn. But, Zhao et al.[13] also pointed out that from the point of view of calm water resistance, WPC-AU is not suitable for low-speed sailing.

2.2 Seakeeping

Due to the pertinency of wave piercing vessel design and optimization on sailing in waves, wave piercing vessel generally shows excellent seakeeping. Motion, added resistance, and acceleration in waves have been significantly improved, realizing the moderate motion in waves. THC claimed that compared with three kinds of traditional ships, speed of TH in waves was increased by 17% under the same horsepower, which indicated that TH had smaller wave added resistance. It can be noted from seakeeping test of Reference[14] that compared with traditional BL-175, TH shows an overwhelming advantage in seakeeping. At the speed of 50 kn, wave heights of 1 m and 2 m, compared with BL-175, the reduction of acceleration near the bow of TH is up to 71%. TH can keep zero pitch angle and avoid slamming loads at full speed and under various wave conditions, and the acceleration of TH is small. In the study of flat bow, Van Diepen et al.[15] pointed out that the accelerations (1/10 significant value) at the bow, stern and barycenter of ship utilizing wave piercing design are smaller than those of traditional hull, but the maximum acceleration of bow in wave piercing vessel is larger or smaller than that of traditional ship according to the different bow shapes of wave piercing vessel; the sinkage and pitch amplitude (1/10 significant value) of ship with wave piercing design are smaller than those of traditional hull; compared with traditional hull, heave, pitch and acceleration of tested wave piercing vessels decline significantly. According to different speeds and sea conditions, the maximum damping is as high as 40%. X-Bow's tank test result[16] shows that compared with traditional bulbous bow, ship utilizing X-Bow design has following advantages in waves: no bow slamming loads; smaller acceleration and pitch; does not cause violent bow splash during wave piercing; smaller stall in waves. After the model test of WPT mentioned in Reference [11], Dubrovsky[17] pointed out that compared with traditional planing boat, bow acceleration of this design is smaller at the same speed .

Roll angle affects human's athletic ability, which can be roughly divided into three areas: there is no effect on human activity at 0°-4°; within the scope of 4°-10°, athletic ability decreases obviously; at 10° or more, crews have difficulties in eating, sleeping and walking on board. Freeboard tumblehome design of wave piercing vessel can affect the roll performance of hull. Lin et al.[18], on the basis of comparing ONR tumblehome hull with flared hull, pointed out that near synchronous rolling area, roll angle of tumblehome hull is much larger than that of flared hull; when wavelength is equal to resonance value, roll angle of tumblehome hull is 2 times that of flared hull, as shown in Fig. 11. But, wave piercing vessel's rolling performance in waves can be improved by utilization of innovative hull design. For example, VSV's extrusion design of broadside can improve rolling performance and increase reserve buoyancy. Ikeda et al.[19] pointed out that through researches: due to short natural period, big transverse damping, and small wave exciting moment, the rolling resonance amplitude of a 112 m WPC-AU in the transverse waves is small. Trimaran design is very beneficial for rolling of wave piercing vessel. According to the sea test data disclosed by CMN shipyard, the pitch angle of Ocean Eagle 43 utilizing WPT design in level 5 sea condition and at the speed of 28 kn is within ±2°, and the roll angle is within ±6°, which shows its advantage in terrible ocean environment.

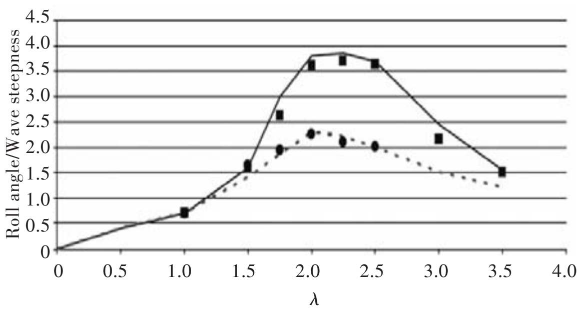
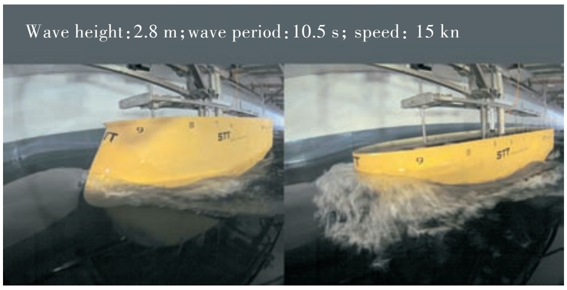
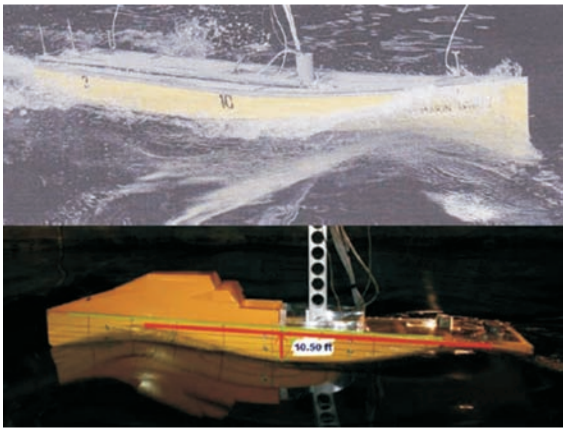


Fig.11 Normalized roll motion angle for different values of λ with $F_n = 0.066$. The solid line shows the numerical results for the tumblehome hull and the dashed line the numerical results for the flared hull

Compared with flared bow, wave piercing bow's disturbance to wave is small, and violent splash is not produced easily near the bow, which can reduce slamming. Fig. 12 shows the disturbance of wave piercing bow and flared bow to wave surface when they encounter waves. Fig. 12(a) shows the bow splash situation of ship with X-Bow design and ship with traditional bulbous bow design under the same wave condition. It can be noted from Fig. 12(a) that ship utilizing X-Bow design does not cause a violent bow splash as flared bulbous bow with does, which is also verified by sea test. Fig. 12(b) presents the comparison of splash situation of TH and ship with axe type bow when they encounter waves. Obviously, wave piercing bow's disturbance to wave is smaller, and almost no splash is produced by bow.



(a) Comparison between X-Bow(left) and bullbous bow (right) under the same sea conditions



(b) Comparison of splash situation in bow between TH (lower) and ship with axe type bow (upper) when they encounter waves

Fig.12 Wave piercing bows have small disturbance to the waves

Slamming load that WPM encounter is from mainly bow, wave piercing bow's weak disturbance on waves significantly reduces slamming loads that hull is faced. However, WPM with low freeboard in waves will face a high probability of superstructure slamming, overlow freeboard makes waves directly overflow bow deck and then impact superstructure. Zhang et al.[20] observed the obvious phenomenon of green water during test. Therefore, smooth superstructure and high hull freeboard are very useful to WPM. Besides, High Performance Ship Group of Ship Mechanics Committee, Chinese Society of Naval Architects and Marine Engineers (CSNAME) pointed out that wet deck slamming is the top priority for WPC research. French et al.[21] determined the critical value of slamming by experiment. For WPC-AU with length of 112 m, speeds of 20 and 38 kn, and modal period of 8.5 s, when the significant wave height is less than 1.5 m, slamming will not happen.

Wave piercing vessel's superior properties in the short and steep waves are basically recognized, but it does not mean that one wave piercing vessel or specific wave piercing vessel has good seakeeping in all sea conditions. Vakilabadi et al.[22] observed in a model test on heave and pitch of a very slender WPT in regular waves that pitch motion of the model is relatively violent, as shown in Fig.13. The actual operation of traditional WPC shows that the seaworthiness of this kind of WPC depends on its sailing sea area and wavelength range to a large extent, and subjects to slender demihull in the unset sea area, whose heave and pitch motion are greater. It means that high speed of a very slender hull is at the expense of seakeeping. Ocean Eagle 43's main hull and demihull layout scheme may be beneficial to the improvement of this unfavorable situation.

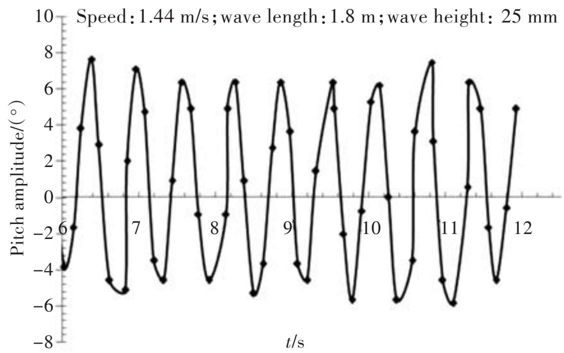


Fig.13 Amplitude of the pitching motion measured during the towing of the wave piercing trimaran model

Some scholars attempt to control and improve the vertical motion and longitudinal motion of traditional WPC-AU in waves so as to expand the application scope of this type of WPC. Practice proves that T-type hydrofoil greatly improves the pitch and heave of ship in waves[23], which can greatly improve the working and living conditions of crews and passengers on board. Controllable T type hydrofoil is installed in WPC firstly. Application of T type hydrofoil on WPC is studied by Chang[24], Liu[25], and Liu[26]. Besides, Ma et al.[27] equipped midbody in WPC, which is proved that this measure can greatly improve the seakeeping of WPC by model test. Zheng et al.[28] improved the longitudinal motion of a 250 t high-speed, light WPC by installing hydrofoil, and model test showed that this measure could reduce the significant amplitude of head sea pitch and heave by 20%-30%.

Motion sickness incidences (MSI) is also one of the important indexes for seakeeping of high-speed ship. Low frequency motion of WPC may cause seasickness, which brings fatigue and discomfort to crews and passengers. Fang et al.[29] studied the vertical motion MSI of a WPC CAT-I with length of 40 m, and pointed out that vertical motion MSI is not obvious at following sea (wave direction angle $\leqslant$ 60 ℃), but it increases with the increase of wave direction angle. Ikeda et al.[19] presented the MSI distribution diagram of a 112 m long WPC-AU.

2.3 Safety

Classical wave piercing vessel is evolved from traditional flared hull tumblehome freeboard and bow. The geometrical volume of hull above freeboard reduces, and the reserve buoyancy of hull changes, which raises concerns about hull safety (e.g., hull stability[30-31], parametric rolling[32-34], capsizing[35]). Most of related researches focus on ONR-TH. Based on published research, for hulls with the same geometrical shape below waterline, safety of tumblehome hull decreases. Bassler et al.[30] pointed out that compared with a flared hull, the tumblehome hull's capsizing risk is more sensitive to slight change of the center of gravity. Mccue et al. [32] pointed out in a study on parametric rolling of ONR-TH that compared with ONR hull with straight wall and flared design, the average initial metacentric height (GM) of ONR hull with tumblehome design in waves is smaller, and its parametric rolling in head sea will be reached at a lower forward speed.

3 Research methods of hull performance of wave piercing vessel

Research methods of hull performance mainly include theoretical method, numerical simulation based on CFD and model test. Different from the traditional ship, due to wave piercing vessel's special shape and navigational status, the effect of freeboard above the waterline and superstructure should be taken into consideration when forecasting hull performance, and non-linear factors such as wetness of freeboard and deck, green water and slamming should be taken into account.

Most of researches related to wave piercing vessels are conducted by means of model tests, which includes towing tank test, and self-propelled ship model test.

The particularity of wave piercing vessel poses great challenges to traditional theoretical methods, but this does not mean that these research methods fail. Zhang et al.[20] studied the longitudinal motion response of stealth ship with tumblehome low freeboard in regular and irregular head waves by model test and nonlinear time domain methods, and took the impact of hull wet surface variation and green water on longitudinal motion into consideration during time domain calculation. Comparison with experimental results shows that the nonlinear time-domain method which considers the effect of hull wet surface variation and green water on longitudinal motion can accurately predict the longitudinal motion of tumblehome hull in waves.

Development of CFD technology provides a new way for research of wave piercing vessels. Reliable turbulence model, multi-degree of freedom motion model and multi-phase model provide foundation and guarantee for numerical stimulation of wave piercing vessel. Overlapping grid better facilitates the simulation of large amplitude motion of hull. Geometric detail of hull can be fully reserved and the stress, moving posture, green sea and wetness about wave piercing vessels can be captured and described in a great way by numerical simulation based on CFD. With the development of CFD technology, movable propeller and rudder are introduced into the numerical simulation of self-propelled model. When doing paralyzed ship analysis on ONR-TH, Carrica et al.[1] introduced movable rudder and propeller into light body model to simulate the movement of hull in the waves more realistically. Compared with the traditional ship detour flow stimulation, this method is closer to real situation, but the computing resource consumption is huge. The number of grid cell used in Carrica's investigation reaches 2.11×10^7, ordinary personal computer cannot do such a large-scale calculation. Besides, real ship CFD stimulation gradually becomes mature. Real sea conditions and real ship CFD stimulation can provide more direct performance prediction for wave piercing vessel research.

4 Conclusions

Through the above researches, the following major conclusions can be obtained:

1) Wave piercing vessels have been developed rapidly in recent years. Hull forms are more abundant, and hull performance is further explored.

2) Wave piercing vessels generally but not all utilize thin bow to reduce bow buoyancy, slamming and pitch.

3) Compared with some traditional hulls, wave

piercing vessel has certain rapidity advantages.

4) Compared with traditional hull, wave piercing vessels optimized for the motion, stress and acceleration in the waves are improved obviously in the above aspects.

5) The acquiring rapidity of wave piercing vessel utilizing very slender hull design is at the expense of seakeeping, which causes violent pitch and heave motion in some sea conditions. This phenomenon needs to be improved.

6) The safety of tumblehome wave piercing vessel evolved from traditional flared wave piercing vessel is reduced in some severe sea conditions.

Compared with traditional ship which has been studied extensively and deeply, current researches on wave piercing vessel are limited. For wave piercing vessel, the following aspects deserve in-depth study or pioneering research:

1) Hull form innovation and related hull performance exploration of high-speed WPM, high-speed WPC and high-speed WPT;

2) Further improvement of the seakeeping of existing wave piercing vessel;

3) Wave piercing vessel's motion in long-crested waves;

4) Motion and stress of totally enclosed wave piercing vessel in extremely bad conditions (for example, hull passes through waves completely);

5) Special, fast and accurate theoretical method of hull performance forecasting aiming at wave piercing vessel;

6) Optimal design of wave piercing vessel's deck and superstructure slamming as well as reduction of slamming.

Through further research and innovation, wave piercing vessel family will be further developed and expanded, and they will play a more important role in the era of great ocean in the future.

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穿浪船船型及相关研究综述

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摘 要: 穿浪船属高性能船舶。由于其特殊和针对性的船型设计,穿浪船在波浪中普遍具有优良的快速性和耐波性。近年来,穿浪船引起了广泛关注并在实际工程中得到推广。比较系统地介绍单体、双体和三体穿浪船船型的现状,从快速性、耐波性及安全性等方面概述穿浪船船体性能研究的进展,评述穿浪船船体性能的预报方法,提出了若干与穿浪船有关的潜在研究方向。

关键词: 穿浪船; 船型; 船体性能; 高性能船舶