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Hull forms and straight forward CFD free running trials of high-speed shuttle vessels

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Abstract: SV-SJTU high-speed shuttle vessels are developed by Shanghai Jiao Tong University for fine seakeeping and high speed purposes. A series of SV-SJTUs have been developed, and are introduced in this paper. Straight forward CFD free running trials were conducted and the results are also presented. Hull resistance and motions are predicted by solving URANS equations and adopting the overset mesh method. The results of the straight forward CFD free running trials prove that SV-SJTUs have little resistance and fine hull motion in calm water, and their wave making and splashing differ with different hull forms. This paper presents the designs of a variety of high performance ships, thereby providing quantitative and qualitative references for researchers.

Key words: high-speed shuttle vessel; hull form development; high-performance ships; straight forward CFD free running trials; numerical simulations

CLC number: U661.3, U662.2

0 Introduction

The development of high-performance ships mainly focuses on continuous improvement of speed and seakeeping. Since 1940s, there have been a variety of classic high-performance hull forms, whose representatives include foilcrafts, hovercrafts, deep-V ships, planing hulls, multihulls, wave-piercing catamarans, channel type planing hulls, small-waterplane-area twin-hull ship, etc. They can be generally divided into twin-hull or dynamical lifting, power augmented hull forms and hybrid hull forms. The emergence of these hull forms promotes the development of ships and plays an important role in the history of ship development. Many scientific research institutions, including Shanghai Jiao Tong University, are working to develop more high-performance ships to meet the demands in various fields.

High-speed shuttle vessel of SJTU (SV-SJTU) is a hull form with high speed and fine seakeeping developed by Shanghai Jiao Tong University, which belongs to small- and medium-sized speedboats. So far, high-speed monohull shuttle vessel of SJTU (SV-SJTU-M), high-speed catamaran shuttle vessel of SJTU (SV-SJTU-C) and high-speed trimaran shuttle vessel of SJTU (SV-SJTU-T) have been developed. SV-SJTU belongs to hybrid hull form and combines the characteristics of a variety of hull forms in design. For example, SV-SJTU-M combines the characteristics of wave-piercing form, deep-V hull form and planing (semi-planing) hull form. SV-SJTU-C combines the characteristics of catamaran planing hull, wave-piercing catamaran and wave-piercing monohull. SV-SJTU-T combines

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the characteristics of wave-piercing form, deep-V hull form, planing (semi-planing) hull form, and trimaran. Different hull forms have different hydrostatic and hydrodynamic characteristics. Shuttle vessel pursues high speed, fine seakeeping and fine motion attitude, and also takes into account the stealth characteristics. SV-SJTU has the characteristics of family design of hull form, inherited hull form scheme and stereotyped design.

As a part of the study of SV-SJTUs, this paper attempts to introduce the latest research progress and design characteristics of different SV-SJTUs. Based on the numerical tank experiment, the straight forward CFD free running trials of the SV-SJTUs in calm water is analyzed to reveal the hull hydrodynamic characteristics of different shuttle vessels in calm water. This paper will present and compare the hull form design and hydrodynamic characteristics of various high-performance ships so as to provide the researchers with quantitative and qualitative references.

1 Introduction to SV-SJTUs

SV-SJTU is a small- and medium-sized high speed boat, and the main design ideas are: under the premise of obtaining a good longitudinal attitude, the appropriate design is selected to make the hull lifted steadily so as to reduce the calm water resistance of the hull; the appropriate design should be adopted to ensure a good wave-piercing attitude of the hull in order to achieve smooth motion and high speed in the waves. On the basis of SV-SJTU-M, SV-SJTU integrates the features of new hull form, which derives the SV-SJTU-C and the SV-SJTU-T. Compared with SV-SJTU-M, both the SV-SJTU-C and the SV-SJTU-T have inherited the existing hull form characteristics and integrated new design elements. Table 1 shows the hull principal particulars of SV-SJTU.

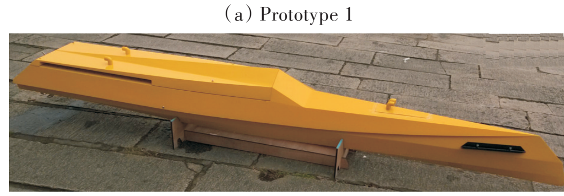
1.1 SV-SJTU-M

SV-SJTU-M was first developed, and the conceptual design[1] and characteristic research of hull form[2] were both carried out. Fig. 1 shows two prototypes of early SV-SJTU-M. On the basis of the prototype design, a new generation of SV-SJTU-M has been further developed. In the prototype scheme, the multi-chine design is adopted for the main hull, and the new generation of SV-SJTU-M includes the hard chine scheme and soft chine scheme. Fig. 2 shows the hull profile and 3D renderings for a SV-SJTU-M.

Table 1 Hull principal particulars of SV-SJTU

Item	Hull principal particular				
	SV-SJTU-M		SV-SJTU -C	SV-SJTU-T	
	Hard chine	Soft chine		Hard chine	Soft chine
Total length/m	16.41	16.41	16.42	24.62	24.62
Total width/m	2.82	2.82	5.58	10.50	10.50
Draught/m	0.70	0.70	0.70	0.70	0.70
Volume of total displacement/m^3	11.29	10.67	11.65	19.00	18.44
Initial stability radius/m	1.55	1.57	6.99	10.77	9.81
Waterline length/m	16.25	16.25	16.27	24.38	24.38
Main hull length/m	–	–	–	24.62	24.62
Main hull width/m	–	–	–	2.82	2.82
Displacement volume of main hull/m^3	–	–	–	16.75	17.31
Demihull spacing/m	–	–	–	5.00	5.00
Displacement volume per demihull/m^3	–	–	–	1.69	1.69
Demihull length/m	–	–	16.42	8.00	8.00
Demihull width/m	–	–	–	0.40	0.40
Channel width/m	–	–	3.00	–	–

(a) Prototype 1

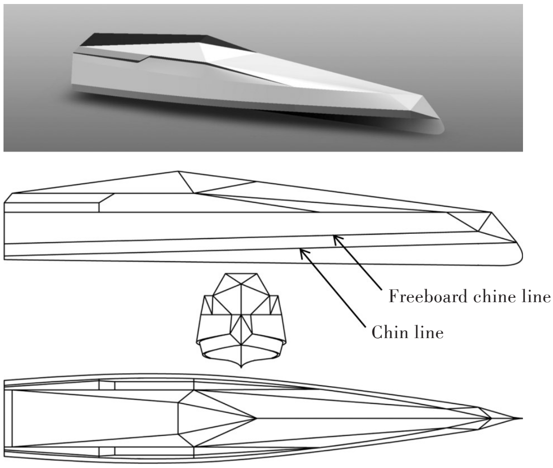


(b) Prototype 2

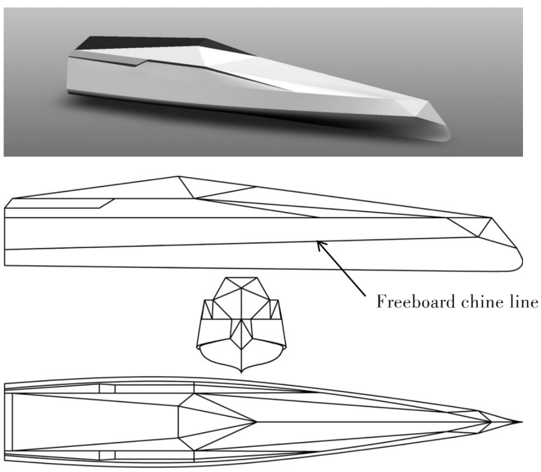
Fig.1 Prototypes of SV-SJTU

New generation of SV-SJTU-M combines the characteristics of wave-piercing form, deep-V hull form and planing (semi-planing) hull form.

The hard chine scheme of SV-SJTU-M adopts the slim wave-piercing bow design in order to reduce the disturbance of the waves to the hull, the wave slamming, the hull acceleration and the resistance in the waves. Freeboard and tumblehome bow have stealth performance. The bow and the superstructure are integrated to reduce the slamming of the waves. The underwater part of the main hull adopts the deep-V design. When the shuttle with relatively sharp bow has high speed, the bow often inserts the waves, thereby leading to speed loss, which is usually overcome by increasing the height of bow freeboard and increasing bow flare. However, wave-piercing bow is relatively thin and such design cannot be used. When hard-chine boat meets waves,



（a）Hard-chine shuttle vessel



（b）Soft-chine shuttle vessel

Fig.2 SV-SJTU-M high speed monohull shuttle vessel

the bow will be quickly lifted to improve the phenomenon of hull being buried in waves and neutralize the adverse effects brought by the thin wave-piercing bow. In order to take into account the requirements of both hydrodynamic force and seakeeping, the dead rise angle of the hull bottom is changed along the length of the hull so that the planing surface can be distorted and the front of the hull can achieve a larger dead rise, thereby reducing the slamming of the waves. If the dead rise angle of the hull bottom is smaller, larger virtual length and dynamic lift can be obtained, which is suitable for the shuttle vessel with high speed and low displacement and simultaneously facilitates the arrangement of water jet propellers. Bow bilge keel adopts the sinking design and the draft is linearly deepened from the stern to the bow, which forms a smooth hull and ensures enough wetted length of the hull. The stern is designed with a transom stern and the hull shrinks in the middle to the stern so as to reduce the residual resistance of the hull. The new generation of SV-SJTU combines the research results of the early semi-planing wave-piercing catamaran and anti-submergence freeboard[3], which uses the anti-submergence freeboard to control the hull wetness and increase the hull buoyancy and dynamic stability. Meanwhile, the volume loss caused by the tumblehome of freeboard can be made up through the freeboard chine design. Based on the above measures, the shuttle vessel can achieve a smooth lift with a small stern trim angle, which reduces the wetted surface area and the hull resistance and improves the speed in calm water. In addition, the exposure of the hull bottom to air and waves can be avoided, which ensures that the hull stays in a good longitudinal attitude to cut the waves and thereby enhances its seakeeping.

The soft chine scheme of SV-SJTU-M is derived from the hard chine scheme. The bottom bilge of hard chine hull form is chamfered to take into account the hull resistance in the medium-low speed section. The bottom surface with the convex hull design (the section curve protrudes to the outboard) can increase the hull strength, as shown in Fig. 2(b).

1.2 SV-SJTU-C

SV-SJTU-C is an innovative hybrid hull form that inherits the design features of the new generation of SV-SJTU-M and integrates the hull form features of high-speed catamaran planing hull and high-speed wave-piercing catamaran, as shown in Fig. 3.

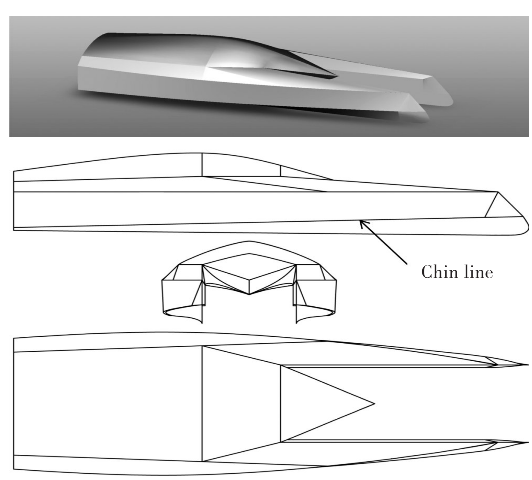


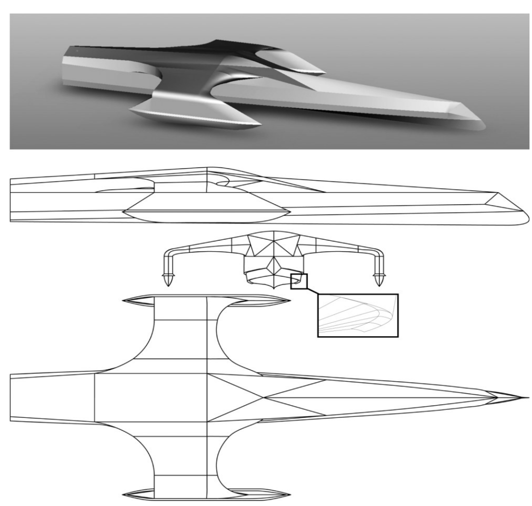
Fig.3 SV-SJTU-C high speed catamaran shuttle vessel

The hull form takes the hard chine scheme of SV-SJTU-M as the parent ship. The main hull is separated from the center longitudinal section to form a catamaran design, and the middle is connected with a cross structure. The hull form design is similar to the high-speed channel type planing catamaran to some extent but significant differences also exist. Compared with the racing planing catamaran, the cross structure in the front is removed from the SV-SJTU-C, and the superstructure is modified to be streamline. The midship at the bottom of the cross structure is designed to reduce the hull motion and slamming in the waves. Unlike the traditional high-speed channel type planing hull that uses the channel to provide dynamic lift, the SV-SJTU-C has widened and deepened channels to reduce and avoid slamming of the waves to the cross structure. The bow adopts the wave-piercing design to reduce the disturbance of waves to the hull. The superstructure is streamlined in order to allow the green water to flow smoothly through the hull. Compared with SV-SJTU-M, the design of chine line on SV-SJTU-C is modified and the outside freeboard does not adopt anti-submergence design. However, in order to control the hull wetness and green water in the channel, the internal freeboard adopts anti-submergence design. Compared with SV-SJTU-M, the deck area of the SV-SJTU-C is increased and the initial stability is improved apparently (Table 1). Meanwhile, due to the increase of heeling restoring moment brought by the farther distance of the demihull to the longitudinal section in center plane, the dynamical stability of SV-SJTU-C will surely be increased, while the initial wetted surface area will also be increased.

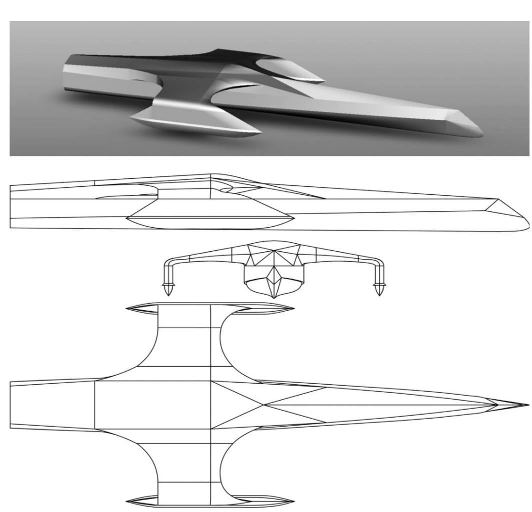
1.3 SV-SJTU-T

After studying trimarans, the researchers believe that the main hull of trimarans should be slender, and when the length-width ratio is between 12 and 18, the wave-making resistance during high-speed navigation can be effectively reduced and the excessive wetted surface area will not result in the increase of frictional resistance. However, the slender main hull will lose a certain degree of initial stability, so the bilateral demihulls need to be added. The displacement of the demihulls does not exceed 10% of the main hull, whose main role is to make up the initial stability loss, increase the roll damping and improve the seakeeping. But, these conclusions mostly focus on large trimaran. Even for SV-SJTU-T, the corresponding Froude number should be less than that of high speed boat. Therefore, it remains to be verified that whether the above conclusions are applicable to SV-SJTU, and the conclusions here are only taken as design reference.

SV-SJTU-T is derived from SV-SJTU-M. The SV-SJTU-M is taken as the parent ship to design the main hull, and demihulls are installed on both sides of the hull to improve the stability. The main hull is obtained by stretching 1.5 times of the SV-SJTU-M along the length direction. Local modification is made in order to take the advantages of the slender hull and further improve the navigation attitude, wave-piercing ability and seakeeping. The length-width ratio at the waterline of the main hull is about 9.4. Considering the restrictions of volume and overall layout of SV-SJTU, slender hull with larger length-width ratio is not appropriate. Corresponding to hard chine and soft chine schemes of the SV-SJTU-M, main hull also adopts the same schemes. Compared with the hard-chine SV-SJTU-M, the bottom cross-sectional shape of the main hull with hard chine is modified to a certain extent. As shown in Fig. 4, the outside chine of the body line is changed from the parallel design to the arc design in order to reduce the hull splashing, and the chine area is further extended.



(a) Hard-chine shuttle vessel



(b) Soft-chine shuttle vessel

Fig.4 SV-SJTU-T high speed trimaran shuttle vessel

Demihull of SV-SJTU-T adopts the symmetric surface-piercing design to reduce the resistance and provide rolling and swaying damping force. The anti-submergence freeboard design is adopted to limit the wetness and green water of the hull with high speed.

Usually, there are two ways to arrange the horizontal positions of the demihulls and the main hull. The first one adopts a large number of optimization calculations to find a scheme that demihull and the main hull can form favorable wave-making interaction, which is often the academic study that the scholars are interested in. The second one separates the demihull from the main hull so as to avoid the interference between them. Reference [4] thought that the prepositional demihull in high Froude number region can reduce the hull resistance. The authors found that at high speed, if the demihull was much too close to the main hull, severe water shutoff would occur and the hull resistance would increase accordingly. This study believes that the fluent flow field around the hull caused by prepositional demihull beyond wave-making range of the main hull is one of the main reasons of the reduced resistance. The demihull of SV-SJTU-T is away from the main hull, which makes the demihull stay outside of the fierce area of the hull wave making and splashing. This measure not only avoids the interference between the main hull and the demihul as well as the water shutoff at high speed, but also further improves the stability and rolling of the hull.

Reference [5] pointed out that when the longitudinal position of the lateral hull of trimaran is in the postmedian area of the main hull, the seakeeping performance is better at most speeds. According to the relevant conclusions in Reference [5] and the research experience of the authors, the bilateral demihulls are arranged in the middle of the hull. The centers of buoyancy of both demihulls and main hull are in the same position in the length direction, and design of postpositional demihull is not adopted in trimaran. The layout of the hull also refers to that of high-speed fighters.

Hence, from the point of view of resistance, the measures of keeping the demihulls away from the main hull and wave making of the main hull are adopted in trimaran. From the point of view of seakeeping, the demihulls are put in the postmedian area of the hull, and coordinate alignment of buoyant centers of demihulls and main hull is carried out in the length direction.

2 Study on straight forward free running trials of shuttle vessel

The studies on straight forward free running trials of shuttle vessel are conducted based on numerical tank experiments. In order to accomplish the study, this paper investigates the hydrodynamic characteristics of straight forward free running trials of SV-SJTUs by solving the URANS equation based on CFD. With the accumulation of technology and academic knowledge, the accuracy and reliability of numerical calculation have been greatly improved, which has been more and more widely used and recognized in scientific research and engineering applications[6] and has been an effective means to optimize the design of hull form except the model experiments. When the Froude number is high, the hull may have large longitudinal and vertical coupling motions. Therefore, in order to predict the hull performance more accurately in numerical calculation, it is necessary to consider the influence of sailing change on prediction results. The most effective way to obtain and simulate the hull motion is to use dynamic meshes. For the sake of comparison, all the hull forms are scaled down to the models with approximate dimension and hull weight. The research on the straight forward CFD free running trials of SV-SJTUs is based on the model scale. The simplified principal particulars of the models used for calculation are shown in Table 2.

2.1 Calculation method and verification

Numerical tank is built by using CAD modeling and CFD technology. By using the overset mesh technique and the six-degree-of-freedom model, the hull motions are simulated and predicted. The background mesh uses object trimmed mesh to control the mesh density, which reduces the number of meshes and improves the delamination and orthogonality

Table 2 Principal particulars of models for CFD free running trials

Item	Calculation model				
	SV-SJTU-M(hard chine)	SV-SJTU-M(soft chine)	SV-SJTU-C	SV-SJTU-T(hard chine)	SV-SJTU-T(soft chine)
Total length L_{oa}/m	2.75	2.75	2.75	3.47	3.47
Mass M/kg	53.1	49.6	53.9	53.0	51.4

of the meshes. The mesh with the hull uses polyhedral mesh that obtains good delamination and orthogonality through rational layout. Reasonable layout of the mesh density and improved orthogonality and delamination of the meshes are very crucial to eliminate the saw-teeth phenomenon of free surface and capture the wave making and splashing[7], which are vividly presented in Fig. 7–Fig. 10 of Reference [7]. In the case of CFD-related research, it is usually necessary to perform mesh independence verification and calculations in advance. Scholars carried out a lot of mesh independence research, which mainly focused on the effect of mesh number on numerical calculation results. It can be seen from Reference [8] that when the number of meshes is more than 1.5 million, its impact on the calculation results will be very small. However, the effect of meshes on the calculation results is not only from the number of meshes. For example, under the premise that the number of meshes is sufficient, the distribution of meshes, the division of near-wall meshes and the selection of wall functions also have significant effect on the calculation results. Strict mesh independence research is a huge project. In order to solve the problem of mesh independence analysis, the authors directly filled a sufficient number of meshes with reference to the related research results, i.e., greater than 2 million. The mesh density is reasonably distributed according to the pre-calculation and the influence of $y+$ on the calculation results is studied. Wall function with high $y+$ and the rougher near-wall meshes will have sufficient accuracy. In addition to the authors' verification calculation, the selection of wall function also refers to Reference [9]. The development of computer hardware makes the number of meshes no longer be a bottleneck of limiting the numerical simulation. What's more, a smaller number of meshes cannot well capture the hull splashing. Based on the above reasons, the authors do not carry out special mesh independence calculation verification but fills the sufficient mesh elements at a time to process the meshes conservatively by referring to the existing research results and mesh division experience. In this section, the number of meshes used in the study is about 2 million–2.8 million, which satisfies the requirement of the number of meshes.

The SST k-ω[10] turbulence model combined with the characteristics of k-ω and k-ε turbulence models is used to solve the unsteady RANS equation. The Volume of Fluid (VOF) model is used to capture the free surface.

In order to further verify the accuracy of the calculations and ensure the reliability of the results, this paper validates the numerical simulation method through tank experiment. The study in this section uses the NACA sliding wedge published in Reference [11] and the geometrical model of the planing hull as well as the corresponding experimental setup and data presented in Reference [12]. Limited to the length of the paper, this section mainly shows the verification results of the planing hull based on Reference [12], and briefly introduces the verification results of the sliding wedge based on Reference [11]. The geometric profile of the planing hull in Reference [12] is shown in Fig. 5 and the model geometry is shown in Table 3. Based on the numerical simulation of the planing hull in Reference [12], the free mode is used to release the two degrees of freedom of heave and pitch. The numerical simulation based on NACA sliding wedge adopts a fixed mode. The calculation settings, the calculation domain and the mesh division are shown in Fig. 6.

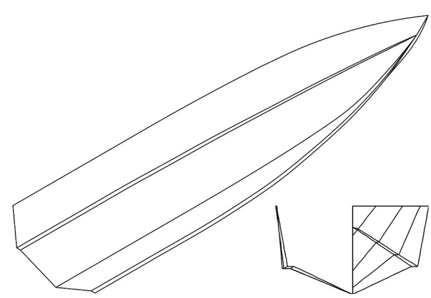


Fig.5 Perspective and profile of a planing hull for verification

Table 3 Principal particulars of the model for verification

Item	Principal particular of the model
Total length L_{oa}/m	2
Total width B_{oa}/m	0.46
Draught T/m	0.09
Mass M/t	0.024

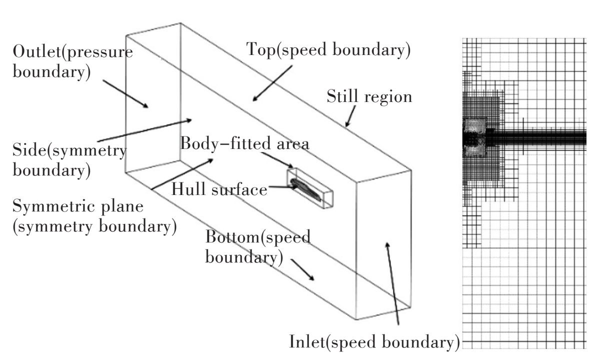


Fig.6 Computational domain settings and meshes

The average relative error of lift measured in the tank experiment of the sliding wedge in Reference

[11] is 3% and the maximal relative error is 8%. The average relative error of the measured resistance is 20% and the maximal relative error is 50%. Based on the verification and calculation of the NACA sliding wedge, the average error of lift is 5.11%, which is slightly larger than the inherent average error of 3% of the experimental value, but the errors are both less than the maximal relative error. However, the resistance calculation error (average value of 6.15%) is much less than the reference value of 20%. In References [13] and [14], the accuracy of CFD calculation is verified based on the NACA sliding wedge and it is concluded that the numerical simulation has sufficient accuracy in the performance prediction of the planing hull. In Reference [13], the maximal error of resistence is 20.28% and the average error is 10.06%. The maximal error of resistance in Reference [14] is 13.26% and the average error is 9.65%. Compared with the calculation results in References [13] and [14], prediction accuracy of resistance by numerical simulation in this paper is slightly higher, while the error of lift prediction is slightly larger.

It can be seen from Fig. 7 that the numerical simulation results (CFD) and experimental results (EXP) of the planing hulls published in Reference [12] are in good agreement in terms of the size and changing trend. The average relative error of the calculated resistance is 8.98% and the maximal relative error is 14.57%. The stern trim angle measured by the numerical tank experiment is slightly larger than the experimental value, but the maximal deviation is only 0.45°. If the number of digits after the decimal point of heaving value in Reference [12] is rounded off by the numerical simulation, the calculation value of the hull heaving is almost consistent with the experimental one. As Reference [11] only presents the hull profile and does not present the hull offset table, a certain error exists between the calculation model and the experimental model when considering the error of CAD reverse modeling. In addition, considering the errors from physical model and mesh discretization, it can be considered that the numerical prediction accuracy of resistance and motion through the method used in this paper satisfies the engineering requirements.

At the same time, by considering the verification results based on the two models and comparing the calculation errors of the hydrodynamic prediction of NACA sliding wedge in References [13] and [14], it can be believed that the prediction of hull resistance through the numerical tank in this paper has a high

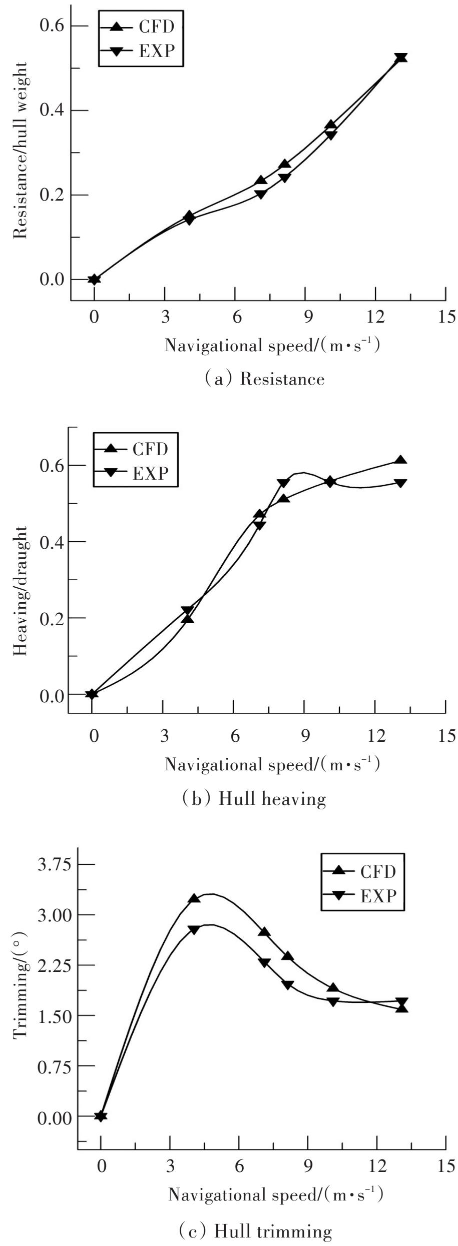


Fig.7 Hull resistance and motions of the planing hull for verification

accuracy. Therefore, the hydrodynamic performance of hull can be predicted and compared under the premise of the same mesh and calculation setting.

2.2 Hull resistance of shuttle vessels

This section shows and compares the calm water resistance of different SV-SJTUs and analyzes the resistance components of different hull forms, as shown in Fig. 8. The experiment data of resistance for M-HULL are published in Reference [15]. Because its model weight and scale are similar to those used in this study, M-HULL is used as a comparative hull form, which is a new high-performance multi-purpose hull form developed by the US M Ship Company and has unique features in high speed and stealth.

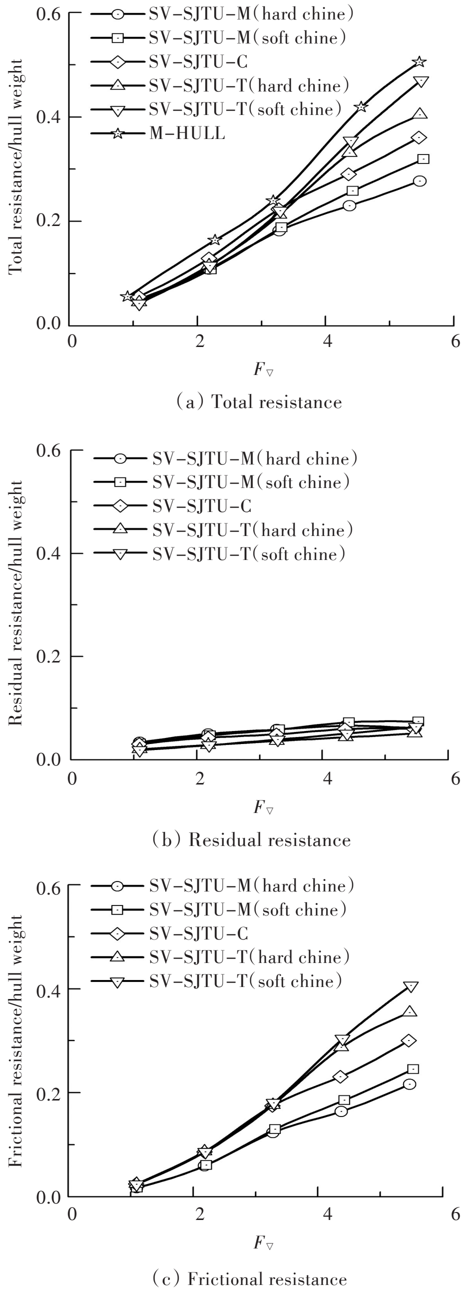


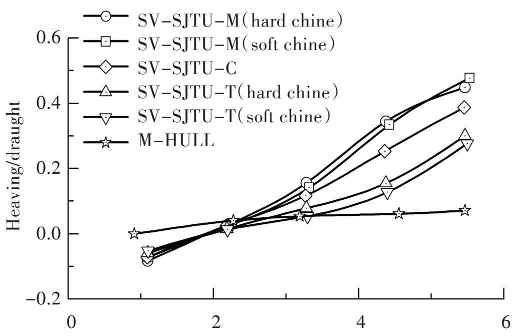
Fig.8 Hull resistance of SV-SJTUs in calm water

As shown in Fig. 8, the total resistance of both SV-SJTU-M and SV-SJTU-T that adopt the soft chine design at low speed is relatively small (low-speed is relative to small power boats, and for large ships, the Froude number range in this paper is in the high-speed and ultra-high-speed range). At high speed, the resistance of the SV-SJTU-M is the smallest, while that of the SV-SJTU-T is the largest. When the volumetric Froude number F_∇ = 5.5, the resistance ranks in the following descending order: SV-SJTU-M (Hard chine), SVSJTU-M (Soft chine), SV-SJTU-C, SV-SJTU-T (Hard chine) and SV-SJTU-T (Soft chine). The resistance of the hard chine scheme shows a greater advantage in the high-speed section. When F_∇ = 5.5, the resistance of SV-SJTU-M (Hard chine) is reduced by 7.1% compared with that of SV-SJTU-M (Soft chine) and the resistance of SV-SJTU-T (Hard chine) is reduced by 11.4% compared with that of SV-SJTU-T (Soft chine). Compared with the M-HULL, the SV-SJTUs in the calculated navigational speed range have a smaller hull resistance.

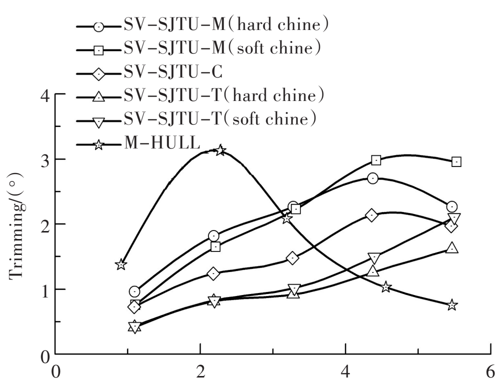
It can be seen from Fig. 8 that the frictional resistance is the main component of the resistance of SV-SJTU. For example, when F_∇ = 5.5, the frictional resistance accounts for 77%-87% of the total resistance. The change of residual resistance with speed is far less dramatic than that of frictional resistance, and the residual resistance does not increase with the speed all the time. Comparing the resistance of 5 kinds of shuttle vessels and their components, we can see that the residual resistance of the SV-SJTU-T with slender design is smaller, while the frictional resistance is greater. Compared with SV-SJTU-M, the increased resistance of SV-SJTU-C and SV-SJTU-T is due to the increased frictional resistance. While the increase of frictional resistance can be attributed to the increased wetted surface area of SV-SJTU-C and SV-SJTU-T when compared with SV-SJTU-M.

2.3 Hull motions of SV-SJTUs

The sailing attitude is the key control parameter in the design of shuttle vessel. The calculation results show that the sailing attitude of different hull froms involved in this paper has achieved the design goal of obtaining a smooth uplift of the hull under the premise of using the design to obtain a good longitudinal attitude (Fig. 9), thereby ensuring that the hull can penetrate the waves successfully with the bow instead of using the bottom to impact the waves. The stern trim of the shuttle vessel series in the full-speed section is very small, with the maximal trim of stern less than 3°. Overall, because the SV-SJTU-T is relatively slender, both hull lift and stern trim angle are less than those of SV-SJTU-M. The changing trend of stern trim angle of SV-SJTUs is different from that of planing hull and M-HULL. As shown in Fig. 9, peak stern trim of the shuttle vessel does not appear at the low-speed section but moves toward the high-speed section. SV-SJTU-T requires a higher navigational speed to reach the peak, and the peak of trim by stern does not appear in the speed range in this paper.



(a) Hull heaving

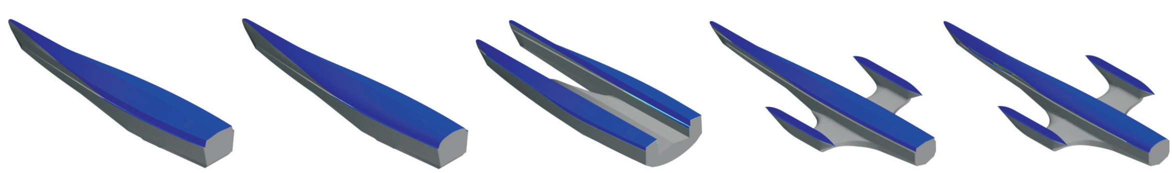


(b) Hull trimming

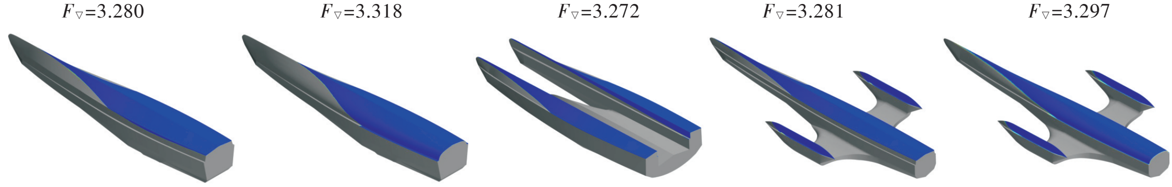
Fig.9 Hull motions of SV-SJTUs in calm water

2.4 Hull wetness and wave making of shuttle vessel series

Fig. 10 shows the distribution of hull wetness of SV-SJTUs when $F_\nabla = 3.3$ and $F_\nabla = 5.5$. The blue areas in Fig. 10 represent the wet surfaces of the hull. Due to the inheritance and derivation of the geometric characteristics among the hull forms, the hull wetness among different shuttle vessels shows similarity and difference. It can be seen from Fig. 10 that the shuttle vessels are provided with sufficient wetted length to ensure the seakeeping. The hard chine scheme and the soft chine scheme show a difference in hull wetness. When $F_\nabla = 3.3$, the hull has not been fully lifted yet. At this time, the anti-submergence freeboard plays a role in limiting the hull wetness below the chine line of the anti-submergence freeboard. When $F_\nabla = 5.5$, the hull has been fully lifted. The hard chine design limits the hull wetness below the chine line, while hull wetness of the soft chine hull is still below the chine line of the anti-submergence freeboard. Since the stern trim angles of SV-SJTU-C and SV-SJTU-T are smaller than those of SV-SJTU-M, the submergence ratio of the bilge keel should be larger.



(a) SV-SJTU-M(hard chine) F_∇=3.280 (b) SV-SJTU-M(soft chine) F_∇=3.318 (c) SV-SJTU-C F_∇=3.272 (d) SV-SJTU-T(hard chine) F_∇=3.281 (e) SV-SJTU-T(soft chine) F_∇=3.297



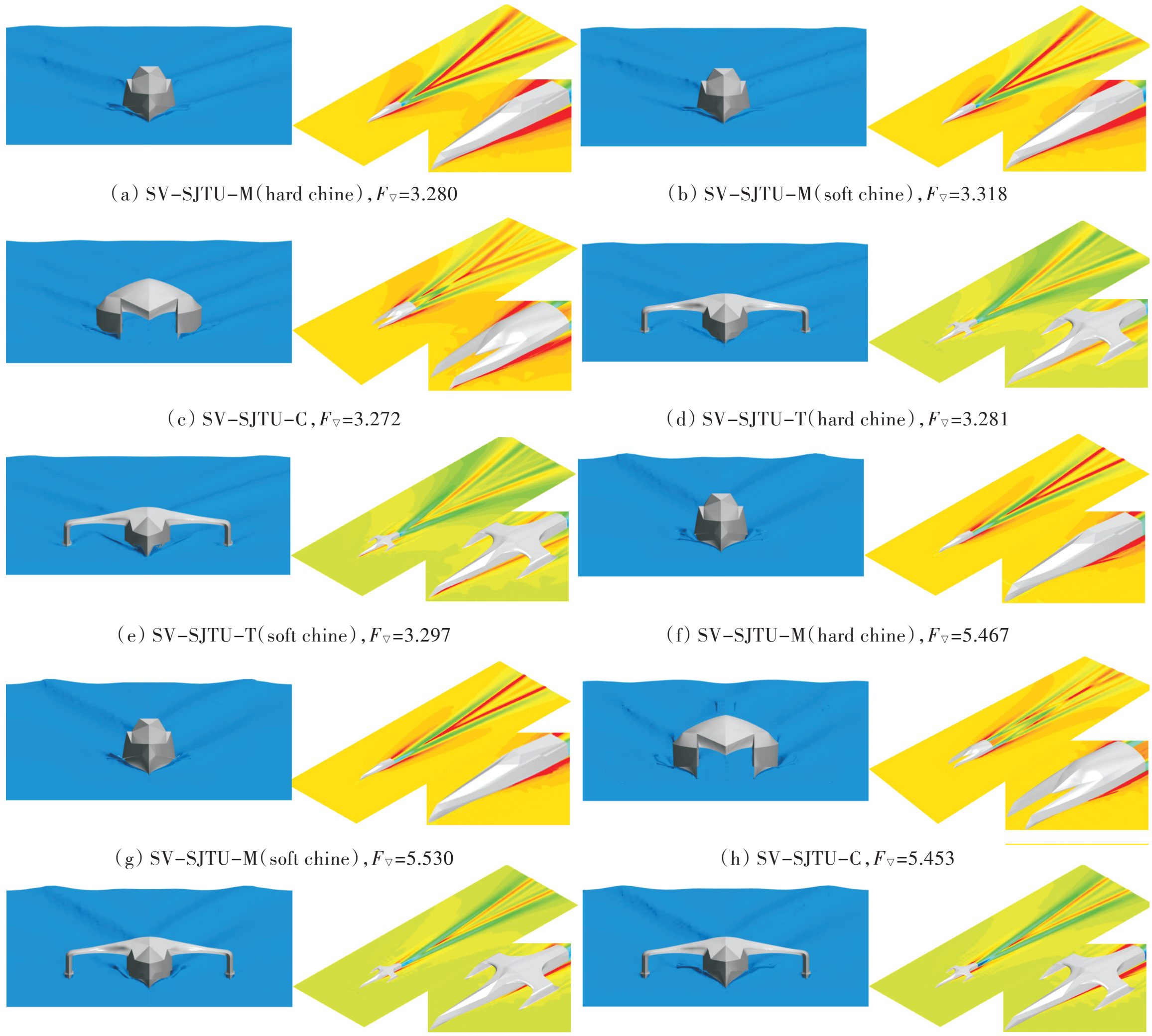
(f) SV-SJTU-M(hard chine) F_∇=5.467 (g) SV-SJTU-M(soft chine) F_∇=5.530 (h) SV-SJTU-C F_∇=5.453 (i) SV-SJTU-T(hard chine) F_∇=5.468 (j) SV-SJTU-T(soft chine) F_∇=5.495

Fig.10 Wet surfaces of SV-SJTUs

Due to the difference of the hull form characteristics among the SV-SJTUs, splashing and wave making are also different, as shown in Fig. 11.

For the soft chine scheme of SV-SJTU-M, splashing is produced by the anti-submergence freeboard when suppressing the green water on the hull. For the hard chine scheme of SV-SJTU-M, when F_∇ = 3.3, the splashing is produced by the chine line and the anti-submergence freeboard when suppressing the green water on the hull, while when $F_\nabla = 5.5$, the splashing is produced by the chine line. When F_∇ = 3.3, the splashing is distributed along the length of the SV-SJTU-M. With the increase of navigational speed, wave making develops towards the postmedian area, and meanwhile the splashing is distributed in the postmedian area.

Without adopting the design of anti-submergence freeboard, the splashing of SV-SJTU-C is produced by the chine line. The splashing characteristics are similar to those of the hard chine scheme of SV-SJTU-M. When $F_\nabla = 3.3$, the splashing is distributed over the length of the hull. With the increase of navi-



(a) SV-SJTU-M(hard chine), F_{∇}=3.280
(b) SV-SJTU-M(soft chine), F_{∇}=3.318
(c) SV-SJTU-C, F_{∇}=3.272
(d) SV-SJTU-T(hard chine), F_{∇}=3.281
(e) SV-SJTU-T(soft chine), F_{∇}=3.297
(f) SV-SJTU-M(hard chine), F_{∇}=5.467
(g) SV-SJTU-M(soft chine), F_{∇}=5.530
(h) SV-SJTU-C, F_{∇}=5.453
(i) SV-SJTU-T(hard chine), F_{∇}=5.468
(j) SV-SJTU-T(soft chine), F_{∇}=5.495

Fig.11 Wave making and splashing of SV-SJTUs

gational speed, wave making develops towards the postmedian area, and meanwhile the splashing is distributed in the postmedian area. It can be obtained by observing the wave making that the free surface in the channel is flat and the flow field in the channel is not affected by the demihulls. Unlike the SV-SJTU-M, the SV-SJTU-C has two wakes at the stern, which merge into one flow at the far end of the stern.

Different from SV-SJTU-M and SV-SJTU-C, the green water and splashing of 2 kinds of SV-SJTU-T are much small when F_{∇} = 3.3, and the anti-submergence freeboard does not play an effective role. With the increase of navigational speed, the splashing appears. Similar to SV-SJTU-M, when F_{∇} = 5.5, for the soft chine scheme of SV-SJTU-T, the splashing is produced by the anti-submergence freeboard when suppressing the green water on the hull. For the hard chine scheme of SV-SJTU-T, the splashing is produced by the chine line. As shown in Fig. 11, demihulls are outside the wave making and splashing area of the main hull and the water shutoff does not occur between the demihulls and the main hull. The demihulls with the surface-piercing design have little disturbance on surrounding flow field and thus the wave making of the demihulls is very small. Because of the small wave making of the demihulls, the stern wave making of SV-SJTU-T is mainly caused by the main hull. Therefore, the characteristics of the rooster tails of SV-SJTU-T are similar to those of the SV-SJTU-M.

3 Conclusions

As a research part of the high-speed SV-SJTUs, this paper introduces the design characteristics of the hull forms and studies the straight forward hydrodynamic characteristics of SV-SJTUs in calm water through the numerical tank experiment. Through the above research, the following conclusions can be drawn.

1) The SV-SJTUs have reached the original design intension, i.e., having high speed with low resistance, under the premise of good navigational atti-

tude.

2) Compared with parent ship, the transverse stability of SV-SJTU-C and SV-SJTU-T derived from SV-SJTU-M has been greatly improved and the rolling has also been further improved.

3) Compared with SV-SJTU-C and SV-SJTU-T, SV-SJTU-M has smaller resistance at high speed. The increased resistance of SV-SJTU-C and SV-SJTU-T is due to the increased frictional resistance, which is due to the increased wetted surface area. The resistance of the hard chine hull is smaller than that of the soft chine hull in the high-speed section, but larger at low speed.

4) The relatively large difference of wave-making characteristics exists between SV-SJTU-M and SV-SJTU-C. Because the wave making of the demihulls with the surface-piercing design is very small, the stern wake of SV-SJTU-T is mainly caused by the main hull. Therefore, the characteristics of the wakes of SV-SJTU-T are similar to those of the SV-SJTU-M.

5) The reason for producing the splashing of hard chine hull and soft chine hull is different. The splashing of hard chine hull is produced by the chine line, while that of soft chine hull is produced by the anti-submergence freeboard. Unlike SV-SJTU-M and SV-SJTU-C, slender SV-SJTU-T will produce fierce splashing at a higher navigational speed.

More technologies (such as hull step, bubble drag reduction, adjustable anti-submergence freeboard) need to be tried on shuttle vessel. Other hydrodynamic performances (such as seakeeping, stability and rolling in the waves, operability coefficient) of the SV-SJTUs still remain to be studied, sorted out and published, which will be completed in the near future.

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PIV技术在某驳船模型强迫横摇水动力测试中的应用

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摘　要:[目的]为研究船舶横摇过程中粘流场细节以提高横摇阻尼数值模拟精度,[方法]开展了粒子图像测速(PIV)技术在静水强迫横摇水动力测试中的应用研究。首先,采用自制的强迫横摇装置在水池中开展某驳船在不同摇幅和振荡周期下船舶横摇水动力与舭部流场的同步测试。观测舭部粘流场在船体振荡过程中的变化规律,研究横摇阻尼系数随摇幅和周期的变化规律。然后,将模型试验测试结果与计算流体动力学(CFD)软件模拟结果进行对比。[结果]结果表明,CFD预报船舶横摇整体阻尼系数精度较好,但预报的局部流场细节与模型试验测试结果间存在一定的差异,[结论]需在模型试验技术和CFD预报技术上开展进一步研究。

关键词: 粒子图像测速; CFD; 横摇运动; 横摇阻尼系数; 流场测量

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新概念高速穿梭艇系列船型及其直航性能

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摘　要:[目的]为了将高速与高耐波性能相结合,上海交通大学开发了高速穿梭艇系列复合船型,目前已发展出单体、双体和三体船型。[方法]介绍高速穿梭艇系列船型的新进展和船型设计特点,并通过数值水池实验对高速穿梭艇系列船型在静水中的直航性能进行研究。数值水池通过求解URANS方程和采用重叠网格技术来预报船体受力和运动。[结果]数值水池实验结果表明,高速穿梭艇系列船型具有优良的快速性和航行姿态,船体兴波和飞溅随船型的不同而有所差异。[结论]展示了多种创新的船舶设计方案,可为研究人员提供定量和定性的参考。

关键词: 高速穿梭艇; 船型开发; 高性能船舶; 直航性能; 数值仿真