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Wave-making resistance reduction characteristics based on spherical bow configuration

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Abstract: Nowadays, the mechanism of a bulbous bow on resistance reduction is still ambiguous. By carrying out a study of wave-making resistance based on spherical bow configuration, we can reveal the truth of the problem and find out the effect of reducing resistance and suppressing waves of a bulbous bow on a surface combat ship. As such, the study is fundamentally meaningful. As to ship type DTMB 5415, CFD software STAR-CCM was utilized to analyze the effect and mechanism of the bulbous bow's main configuration parameters on wave-making resistance. To this end, several groups of extended bulbous bows with extended reach and various radius parameters were first set up. Next, analyses were carried out of the variation of resistance and the mechanism of the bulbous bow on resistance reduction, which associate with the known experimental data and CFD calculated data. The final results show that, in certain circumstances, the Froude number, longitudinal position and radius of the bulbous bow have vital and obvious influences on wave-making resistance.

Key words: wave-making resistance; bulbous bow configuration; DTMB 5415 ship type; Computational Fluid Dynamics (CFD)

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0 Introduction

The optimization of bulbous bow configuration is one of the important items in the optimization of hydrodynamic performance of ship. Well designed bulbous bow has better resistance reduction effect, and can well improve the economy of ship operation. In the field of surface combat ship design, due to that the ships often need to install sonar dome, and because of the actual spatial arrangement, the bulbous bow with resistance reduction ability could not be installed, bulbous bows with resistance reduction effect are common in commercial ships. Sonar dome is generally arranged on the basis of technical performance of sonar installation only, so it does not have the function of resistance reduction[1-2]. It is still a frontier research subject in recent years to add resistance reducing bulbous bow to high speed surface-combat ships. Since the 1960s, research on the resistance reduction of bulbous bow were mainly in three aspects: variational method study on optimization of bulbous bow configuration with minimum wave-making resistance as the goal[3-5]; bulbous bow optimization by combining wave-making resistance theory with mathematical programming, genetic algorithm and other mathematical optimization algorithms[6]; resistance reduction design of bulbous bow configuration by combining with the tests based on waveform measurement and its analytical calculation of different configurations of bulbous bow ship type[7]. The mechanism of bulbous bow configuration's effect on resistance has in fact not been clearly demonstrated, and there is little in-depth and detailed research in this respect. Moreover, there is even no published literature of the research on mechanism of resistance reduction of surface ship bulbous bow using the new technology of CFD numerical simulation of modern ships. Although the research of bulbous bow resistance reduction does not belong to a new field of study, there are a lot of basic theoretical and practi-

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cal problems needing to be solved urgently, so as to adapt to the characteristics of the times of energy saving and emission reduction of surface ships.

In this paper, the numerical simulation method of CFD was used to carry out in-depth study of the effect and mechanism of the bulbous bow configuration parameters on the resistance performance of surface ship. In the course of the study, fully considering several key parameters affecting the resistance performance of bulbous bow, on the basis of previous research results, DTMB 5415 was used as the parent ship, and several groups of representative variants were set. By comparing the resistance reduction effect of different bulbous bow configurations, the effect of different parameters of spherical bulbous bow on the resistance reduction effect was analyzed.

1 Analysis of the spherical bulbous bow configuration and CFD calculation of the resistance of bulbous bow ship type

1.1 Analysis of the spherical bulbous bow configuration

In order to simplify the modeling of bulbous bow configuration and CFD calculation, and to facilitate the analysis of resistance characteristics, the research object of this paper, i.e. the bulbous bow, was defined as a simple geometry, that is, the sphere. The main geometric parameters and factors that have great influence on the resistance characteristics are as follows:

1) The longitudinal position of the bulbous bow. It refers to the horizontal distance between the head end of the spherical bulbous bow and the front end of the waterline of the non-spherical bulbous bow, and 2%-5% was taken as the designed waterline length during modelling.

2) The vertical position.It refers to the vertical distance from the central axis of bulbous bow to the waterline surface. In several groups of the variants in this paper, the vertical height of the spherical bulbous bow was selected according to the principle that the lower edge of the bulbous bow was tangent to the extended line of hull bottom.

3) Bulbous bow radius. It refers to the radius of sphere or spherical crown which forms the bulbous bow. When the bulbous bow and main hull are separated from each other, it is the sphere radius, as shown in Fig. 1; when bulbous bow through-connects the main hull, it is the radius of the hemisphere at the ends or of the spherical crown, as shown in Fig. 2.

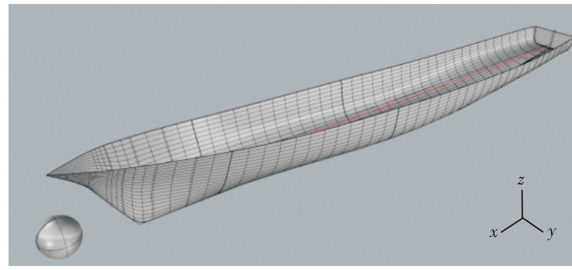

Fig.1 The No. 01 variant scheme of calculation model DTMB 5415

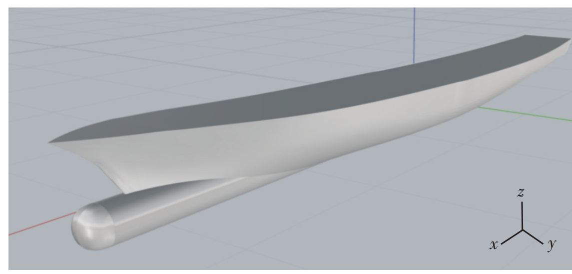

Fig.2 The No. 11 variant scheme of calculation model DTMB 5415

4) Connection type of the bulbous bow with the main hull. In order to investigate the mechanism of resistance reduction of bulbous bow, in the modelling and resistance calculation of bulbous bow by using CFD software STAR-CCM, the 01 variant scheme of bulbous bow was specially designed. Bulbous bow of the scheme did not have actual connection with the hull, as shown in Fig. 1; while the 11 variant scheme of bulbous bow had fair cylindrical through connection with the hull, as shown in Fig. 2. In the subsequent process of model test, separate bulbous bow shown in Fig. 1 will use the thin rod-shaped component extending from the bow to fix its position, which requires it convenient for the rod to adjust the bulbous bow position, and thin rod's strength sufficient to ensure no deformation in the test process.

Due to the installation of resistance reducing bulbous bow, DTMB 5415 prototype sonar dome cannot be normally installed and used like the prototypes. Therefore, a variant bow of ship type DTMB 5415 was proposed, that is to remove the sonar dome to form the basic ship type DTMB 5415G, as shown in Fig. 3.

In the process of adding bulbous bow and its variant, the displacement will change slightly, but the variation was very small, below 0.5%, so it can be neglected in the analysis comparison of resistance characteristics; besides, immersed area will increase to

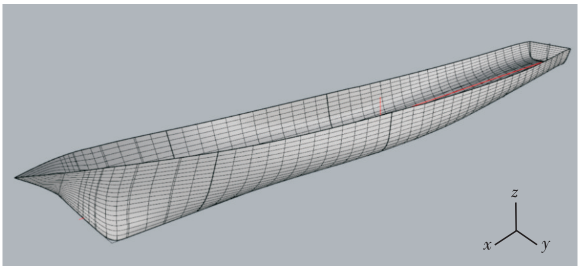

Fig.3 The scheme of calculation model DTMB 5415G

some extent, and the variation was less than 1%. In order to eliminate the effect of immersed area change, this change was included in all kinds of resistance calculation such as friction resistance.

As mentioned above, the bulbous bow is of a spherical shape, and the calculation of its radius may refer to Refs. [7–8]. According to the formula of linear wave–making resistance theory, when the longitudinal position and immersed depth are given, the formulas for calculating the optimal theoretical radius of bulbous bow are shown in Formulas (1)–(4):

$$\frac{M}{\alpha_0}=\frac{\int_0^{\pi/2} A_{\mathrm{FS}(\theta)} A_{\mathrm{DB}(\theta)} \cos^3\theta \cos\left(K_0 \Delta x \sec(\theta)\right)\mathrm{d}\theta}{\int_0^{\pi/2}\left[A_{\mathrm{DB}(\theta)}\right]^2 \cos^3\theta \mathrm{d}\theta} \tag{1}$$

$$K_0=\frac{1}{Fn^2 \cdot L} \tag{2}$$

where

$$A_{\mathrm{FS}}=\frac{2K_0 L^2\left(1-\mathrm{e}^{-K_0 T \sec^2\theta}\right)\sec^2\theta}{\pi\left(K_0 L \sec^2\theta\right)^2-\pi^2} \tag{3}$$

$$A_{\mathrm{DB}}=\frac{8K_0^{\ 2}\sec^4\theta \mathrm{e}^{-K_0 f \sec^2\theta}}{U} \tag{4}$$

The radius R of the spherical bulbous bow is

$$R=\sqrt[3]{\frac{2M}{U}} \tag{5}$$

In the above formulas: θ is angle of wave attack; T is the draft of ship; U is uniform inflow velocity; M is dipole intensity; α_0 is inflow angle of main hull water–plane; L is the length of ship; Δx is the longitudinal elongation of bulbous bow; f is immersed depth of bulbous bow.

According to the given longitudinal position and immersed depth, the curve of the optimal theoretical radius of the bulbous bow changing with the Froude number is shown in Fig. 4.

As can be seen from Formulas (1)–(5), the radius and the Δx of bulbous bow are correlated, but the effect of the Δx on the calculated result of bulbous bow radius R is not large. In order to investigate the effects of bulbous bow's longitudinal position and radius on the resistance reduction performance, the two main parameters were taken as independent input variables in the calculation. Moreover, because the

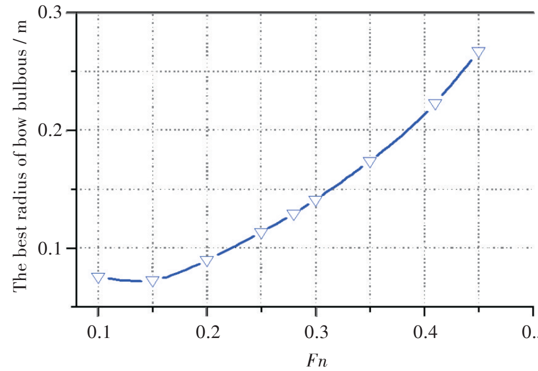

Fig.4 The best radius of bulbous bow of DTMB 5415

influence of the vertical position of the bulbous bow on the resistance with the change of speed is not as sensitive as that of the longitudinal position on the resistance, in order to make the conclusion clearer, the vertical position is taken as a definite value temporarily.

Through the Matlab programming, the theoretical optimal spherical bulbous bow radius was finally obtained as shown in Table 1. In the table, the best radius is approximately between 0.129 4–0.141 0 m, which is determined according to the cruising speed[9]; bulbous bow extended reach (longitudinal position) was determined by combining the previous research results, the construction process and operating characteristics of target ship type [5, 7, 9–10], which is independent input parameter. In the following section, the CFD method was used to calculate and analyze the effect and mechanism of the bulbous bow's resistance reduction, which is based on the bulbous bow parameters shown in Table 1.

Table 1 Configuration parameters of bulbous bow variants

Variant model schemes	Bulbous bow radius R /m	Extended reach of bulbous bow Δx /m	Ratio of extended reach to ship length/%
DTMB 5415G	—	—	—
DTMB 5415 01–05	0.129 4	0.171 6	3.0
DTMB 5415 01–06	0.129 4	0.257 4	4.5
DTMB 5415 11–05	0.129 4	0.171 6	3.0
DTMB 5415 11–06	0.129 4	0.257 4	4.5
DTMB 5415 12–06	0.141 0	0.257 4	4.5

1.2 CFD calculation of resistance and processing of calculated results

Viscous flow CFD numerical simulation software STAR–CCM was used to simulate and calculate the flow field and resistance of the basic ship type DTMB 5415G, and ship types DTMB 5415–01 and DTMB 5415–11 with bulbous bow.

For the basic ship type DTMB 5415G and ship type DTMB 5415-11 with bulbous bow, in accordance with the most commonly used Froude method for the processing of wave-making resistance coefficients of the high-speed surface ships in engineering application[10], the residual resistance can be used as characterization of wave-making resistance, that is, the main component of the residual resistance is considered to be wave-making resistance, and the two are approximately equal:

$$C_{\mathrm{w}} \approx C_{\mathrm{r}} \tag{6}$$

where: C_{w} is the wave-making resistance coefficient; and C_{r} is the residual resistance coefficient. Each resistance coefficient was defined by the expression commonly used in engineering, i.e.,

$$C_{\mathrm{w}} = \frac{R_{\mathrm{w}}}{\frac{1}{2}\rho v^2 S}$$

$$C_{\mathrm{r}} = \frac{R_{\mathrm{r}}}{\frac{1}{2}\rho v^2 S}$$

where R_{w} is the wave-making resistance; R_{r} is residual resistance; v is viscosity coefficient; and ρ is water density. The wetted area S of the basic ship type DTMB 5415G was calculated as light body, and the surface area change caused by the addition of variant bulbous bow was included in the ship type DTMB 5415-11. From the point of view of physical meaning , the main component of C_{r} should be the pressure difference resistance C_{p}, so it is directly determined by the pressure difference resistance with the simultaneous influence of the wave surface and viscosity using the STAR-CCM software.

For the ship type DTMB 5415-01, bulbous bow and the main hull are separated from each other, due to that viscous pressure resistance (i.e. form resistance) caused by trailing vortex from spherical flow separation was larger, the value $C_{\mathrm{r}}(\approx C_{\mathrm{p}})$ calculated directly by STAR-CCM software based on pressure difference resistance will be significantly larger than C_{w}. If the hypothesis was still made according to the Froude number, characterizing C_{w} by C_{r} will obtain unreasonable results (which can be found in the comparative analysis between numerical calculation results of C_{p} and prediction results of C_{w}). Therefore, it was proposed in this paper to deduct the viscous pressure resistance of the sphere in the process of solving wave-making of ship type DTMB 5415-01, i.e.,

$$C_{\mathrm{w}} = C_{\mathrm{r}} - C_{\mathrm{e}}^{'} \tag{7}$$

In the formula, $C_{\mathrm{e}}^{'}$ is the coefficient of viscous pressure resistance (i.e., form resistance) of the sphere. As for the resistance, the experimental results with final conclusions have been achieved in relevant literature[11], which can be easily calculated by the numerical calculation software of viscous fluid dynamics.

In order to verify the correctness of above calculation results, numerical calculation was carried out for the total resistance and residual resistance of the parent ship DTMB 5415 according to the proposed method, and the numerical calculation results were compared to the model's test results[12], as shown in Figs. 5 and 6. Fig. 5 shows the comparison between the numerically calculated value of the total resistance of the DTMB 5415 model and the experimental value of the model test. Fig. 6 shows the comparison of the results of residual resistance.

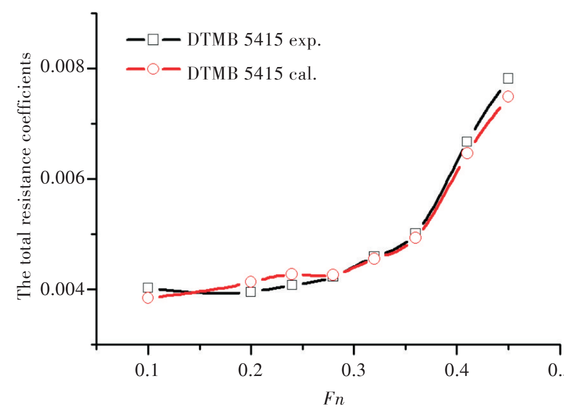

Fig.5 Comparison of the total resistance coefficients between experiment values and calculated values with DTMB 5415

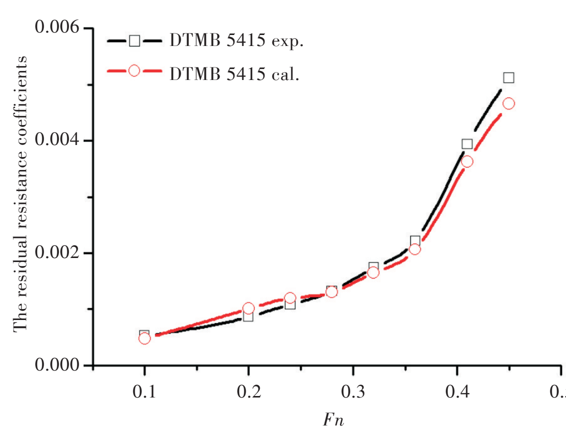

Fig.6 Comparison of the residual resistance coefficients between experiment values and calculated values with DTMB 5415

As can be seen from Figs. 5 and 6, the theoretical calculated values of the total resistance and residual resistance of the model were consistent with the overall trend of the experimental value, with small deviation. The maximum deviation of calculated total resistance value was less than 10%, and the maximum deviation of calculated residual resistance value was less than 8% . The maximum deviations both occurred in the low speed domain, which was beyond the practical low speed range of the object ship type of high-speed displacement ship with transom stern that we study. In the low-speed domain, effective power of the ship and energy consumption of the main engine were smaller, and power reserve was sufficient, indicating the deviation of above magnitude was in the practical allowable range. It can be also seen from the figures that in the common medium and high speed ranges of object ship type, the value and trend of the calculated values were in good agreement with the experimental values. It indicates that the CFD numerical simulation method and software are accurate and effective, which is suitable for the comparative study of the resistance of ship type and the analysis of the resistance reduction mechanism of bulbous bow.

2 Analysis of the resistance reduction effect of bulbous bow

The residual (wave-making) resistance coefficient curves of the related ship type with bulbous bow calculated by the above method are shown in Figs. 7 and 8 (both represent comparison of wave-making resistance between the ship type schemes of separated bulbous bow and through bulbous bow). In Figs. 7 and 8, the difference between the two schemes is that the extended reach of the two variant bulbous bow are different.

According to the comparison of Figs. 7 and 8, wave-making resistance of the variant model 01 with deducted separated spherical bulbous bow's viscous resistance (form resistance) has the same trend of wave-making resistance with the variant model 11, and the difference between the two groups of curves is smaller. As a result, the fair connection of the bulbous bow with the hull is an important factor in the ship's resistance reduction during the design process of the extended bulbous bow. One difference between the separated and the through bulbous bows is that the relative inflow length of the through bulbous bow is greater than that of the separated bulbous bow for the bulbous bows with the same parameters, and the comparison between the 2 groups of curves in Figs. 7 and 8 shows that, resistance reduction mechanism of bulbous bow is that the superposition of bulbous bow wave and the hull wave results in the cancellation of each other, rather than being caused by changes in the relative inflow length.

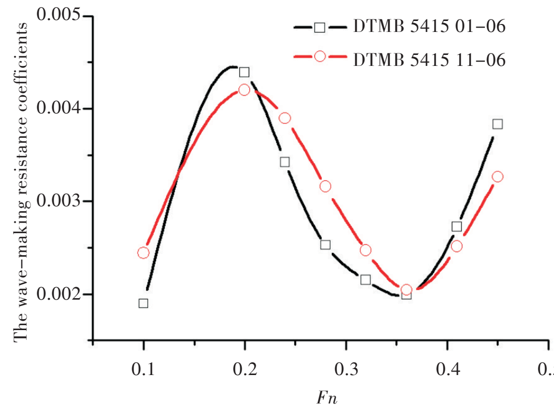

Fig.8 Comparison of wave-making resistance coefficients between variants 01-06 &11-06

In order to compare the influence of different bulbous bow radii and longitudinal extended reaches on the resistance reduction effect, the CFD method was used to calculate the resistance curve as shown in Figs. 9 and 10. From Figs. 9 and 10, we can obtain the preliminary rule of the influence of the bulbous bow radius and longitudinal position on the resistance reduction effect, concluded as follows:

1) For a given longitudinal position of the bulbous bow, there exists a critical velocity value[13], and the bulbous bow ship type will show a significant resistance reduction tendency when the speed exceeds the velocity value.

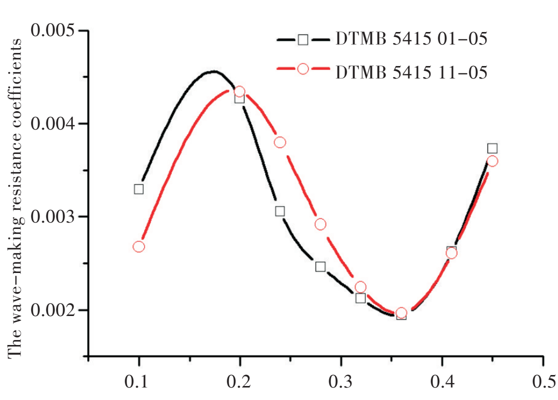

Fig.7 Comparison of wave-making resistance coefficients between variants 01-05 & 11-05

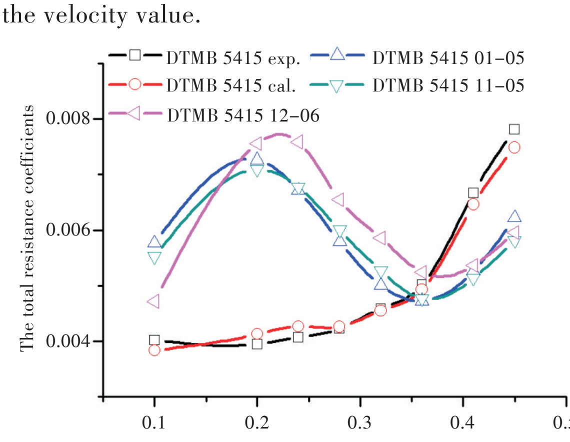

Fig.9 Comparison of the total resistance coefficients between prototype and variants

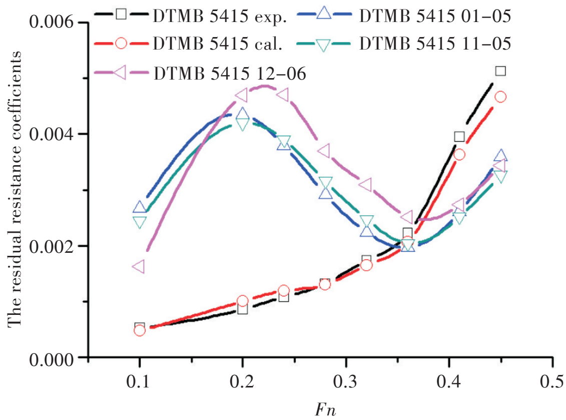

Fig.10 Comparison of the residual resistance coefficients between prototype and variants

2) The resistance reduction effect of the bulbous bow is not applicable to the full speed range.

3) The radius change also has a great influence on the resistance reduction effect. The general trend is that, in the range of parameters selected in this paper, the decrease of radius is beneficial to the resistance reduction effect, and at this time, both the range and interval of resistance reduction increase significantly. Therefore, it is necessary to firstly determine the radius of the bulbous bow with good resistance reduction effect before adjusting the longitudinal position of the bulbous bow to achieve significant resistance reduction.

3 Conclusions

In this paper, the simulation and numerical calculation were carried out by using the CFD before and after installing the resistance reducing bulbous bow on the ship type DTMB 5415, and the calculated resistance values and experimental data were analyzed. Firstly, the feasibility and effectiveness of the CFD calculation were verified by comparing the experimental data of the prototype with the calculated data. Secondly, in the process of research, the main mechanism of the bulbous bow resistance reduction was obtained by the way of separated bulbous bow, which is the superposition and cancellation of bulbous bow wave-making and the hull wave-making. Finally, by comparing the prototype and variant models, the influence of bulbous bow configuration parameters on wave-making resistance performance was obtained, and then the influence of bulbous bow parameters on the resistance reduction effect was deduced. The calculation results show that under the condition of different Froude numbers, these variant models can achieve a better resistance reduction effect in the middle and high speed range of ship (Fn = 0.36–0.45, corresponding to the actual ship speed 26.1–32.6 kn). The wave-making resistance can be reduced by up to 35% at Fn = 0.45. Correspondingly, the total resistance can be reduced by up to 25%.

Moreover, we also try to use CFD methods based on the specific configuration of bulbous bow to investigate into the wave-making resistance reduction characteristics, which has excellent and broad application prospect in the research on the hydrodynamic performance of high-speed surface ships. In order to verify the relevant conclusions more directly, corresponding tests can be carried out in the future.

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基于圆球型球鼻艏构型的兴波阻力减阻特性分析

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摘　要: 球鼻艏减阻的机理至今尚未完全清晰,开展基于圆球型球鼻艏构型对兴波阻力影响机理的研究,对揭示球鼻艏的减阻机理,充分发挥球鼻艏对水面舰船的消波减阻效果具有基础性的重要意义。针对DTMB 5415船型,利用CFD计算软件STAR-CCM,分析前伸出球鼻艏主要构型参数对兴波阻力的影响及其机制。设置几组前伸出球鼻艏,其主要构型参数的前伸量与半径各异,结合采用已知试验数据和CFD计算数据分析阻力的变化规律,以及球鼻艏减阻的机理。结果表明,在特定的傅汝德数条件下,球鼻艏纵向位置和半径对兴波阻力的影响较为显著。

关键词: 兴波阻力; 球鼻艏构型; DTMB 5415船型; CFD

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三维水翼梢涡流场数值研究

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摘　要: 针对三维水翼梢涡流场和梢涡空泡初生的问题,分别建立k-ω,DES和LES模型,对水翼的梢涡流场进行计算研究。为减少误差,在网格的处理上对梢涡流域进行局部加密,对未发生空化时梢涡内的轴向速度和切向速度进行计算,发现LES模型的计算结果与实验值吻合较好。在此基础上,讨论尾涡的卷曲对梢涡压力场的影响,提出了使用气泡静力平衡方程计算初始梢涡空泡数的方法。

关键词: 梢涡; 气泡静力平衡方程; 空泡初生; 水翼