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Marine Propeller Optimization Design

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ABSTRACT

The propeller is a crucial component of the ship propulsion system, and its design is related to the safety and economy of the ship. Since the actual propeller is operated in an uneven flow field behind the ship, the uneven flow field has an essential influence on the cavities, noise, vibration and hydrodynamic performance of the propeller. The purpose of the wake-adapted propeller design and parameter optimization design is to design the propeller reasonably under the condition of accurately predicting the flow field of the ship. This paper takes the HSP propeller as an example, and the stern flow field is hypothetical, combined with the accompanying flow harmonic analysis method, the lifting line program, the lifting surface program, the unsteady surface element program and the optimization design software iSIGHT. Then the wake-adapted propeller design and parameter optimization design system is established. Moreover, in this paper, the HSP paddle is redesigned to verify the effectiveness of the system.

Keywords

Propeller, Wake-adapted, Propeller Theoretical Design, Performance, Parameter Optimization Design

1 INTRODUCTION

With modern detection equipment and weapons (missile, torpedo, mine) developing to high precision and long distance, the possibility of submarine exposure and attack increases dramatically, and survivability, as well as combat effectiveness, is seriously threatened. Submarine low-noise navigation not only keeps the action hidden and avoid being detected but also increases its detection distance. This would make the submarine maintain the initiative of the war.

A submarine usually navigates with high speed and has large scale, so its length Reynolds number is much larger than its critical Reynolds number when sailing underwater, and the flow field around the submarine is a turbulent flow field. Also, the submarine has several appendages and complex lines, which makes the submarine wake become complex flow field characterized by turbulent pulsation, viscous effects, and vortex motion, resulting in the severe uneven flow after the boat (Liu et al 2010). Propellers are working in the wake of the boats, so the cavitation and noise performance of propellers are affected severely by the uneven flow after the boat. In 1963, Beveridge and John L designed wake-adapted propellers using Eckhardt-Morgan method based on Lerps theory, and they obtained ideal performance in both open-water and wake-flow conditions (Beveridge & John L 1963). Donald MacPherson proposed that it is possible to design customized propeller for ships with more and more plants achieving digital construction when he analyzes the wake-adapted design of propellers (Donald MacPherson 2010). Ding et al. analyzed the differences between the flow of single-propeller ships and that of twin-propeller ships and researched with the account of the tangential wake (Ding et al 2011).

The purpose of the wake-adapted propeller design and parameter optimization design is to design the propeller parameters reasonably so that the propeller would have good hydrodynamic performances as well as cavitation performance. This paper introduced the process of wake-adapted propeller design and parameter optimization design firstly. Then the parameterized model is introduced. Finally, the paper verifies the feasibility of the optimization design process according to the redesign of the HSP propeller.

2 THE PROCESS OF WAKE-ADAPTED PROPELLER DESIGN AND PARAMETER OPTIMIZATION DESIGN

This paper combines the theoretical design and optimization design to form a relatively complete propeller design process. The process consists of the resonance analysis method of the accompanying flow field and the selection method of the number of blades, pitch distribution, and skew distribution. Also, lifting line and lifting surface design programs, hydrodynamic performances forecasting program (using unsteady panel method), an optimization design program and iSIGHT software are all involved in this process.

With the continuous development of ship design and construction technology, the shortcomings of the

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propeller design under open-water conditions are gradually exposed, and wake-adapted propeller design methods become the mainstream idea. To achieve the purpose of customized propeller design and parameter optimization, the design process should contain these procedures as follows:

1) Initialization theory wake-adapted design of the propeller: According to ship type characteristics and design requirements, determine the input parameters of the lifting line program, including propeller rotation speed, diameter, thrust, horsepower received by the propeller and wake fraction et al. Among them, the wake fraction can be estimated based on the characteristics of the ship and the experienced formula. Then, carry out the propeller design process that does not consider the influence of skew and rake distribution.

2) According to the principle of selection of rake and skew, combined with initialization pitch angle, resonance analysis the wake and choose reasonable rake and skew distribution.

3) Wake-adapted propeller design: Carry out lifting line and lifting surface design process with the influence of rake and skew. Then, take advantage of hydrodynamic performances forecasting program to predict the performance of the propeller and estimate whether the propeller satisfied the instruction, otherwise, redesign the wake-adapted propeller.

4) Optimized design of wake-adapted propeller: This step is to improve the performance of some aspects of the propeller further. Take the theoretical design paddle as the parent type, and explore the range of variation of the design variables. Then, optimization program, iSIGHT software and unsteady panel method program are used to optimize the parameters of the propeller.

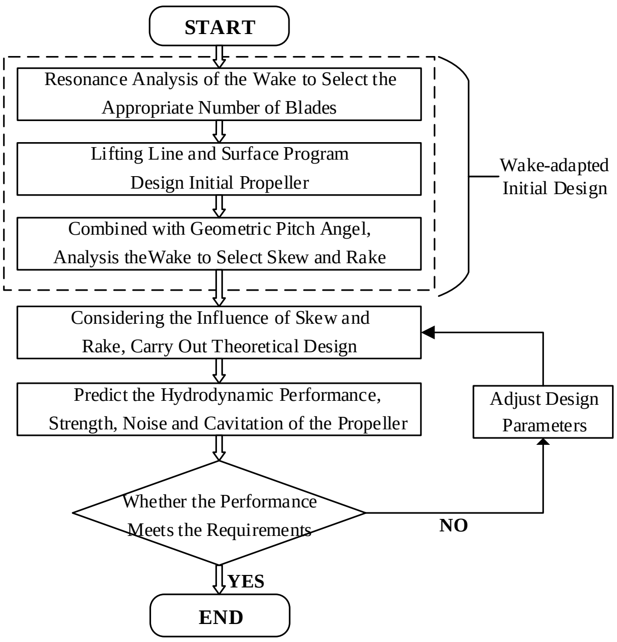


Fig. 1 Propeller wake-adapted theory design process

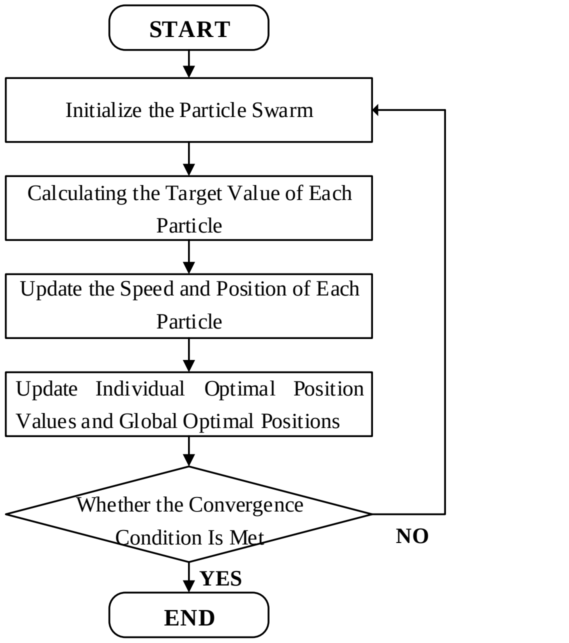


Fig. 2 Propeller wake-adapted optimization design process

3 PARAMETERIZED MODLE OF THE PROPELLER

The B-spline curve is flexible for curve control (LAXMI PARI DA 1993). If the geometric parameters of the paddle are parameterized based on the B-spline curve, smooth geometric parameter distributions in the radial direction can be obtained with fewer control points. The specific expression of the B-spline curve of the radial distribution of the propeller geometry is as follows:

$$p(u) = \sum_{i=0}^{n} d_i N_{i,k}(u) \qquad 0 \le u \le 1 \quad (1)$$

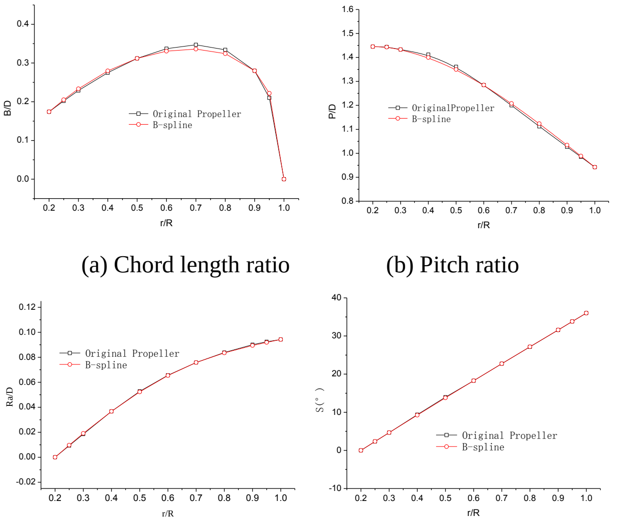
Where $p(u)$ is the geometric parameter distribution; $d_i\,(i=1,\ldots,n)$ are the control vertices of the curve shape; $N_{i,k}(u)$ is the basis function of k-order normalized B-spline.

In the optimization design process of the propeller, the geometric parameters of the propeller have different values at a different distance in radial directions. When the geometric parameters are optimized, the geometric parameters of different radial distance need to be regained, which is represented by a curve. The new geometric parameter distribution obtained by changing the control vertices cannot control the transformation range of the geometric parameters well. Therefore, for designers, the geometric parameter distribution on the curve should be considered directly rather than controlling the shape of the polygon. From the initial curve, calculating the control polygon and finding a reasonable curve shape are reasonable (Hu Zhigang et al 2000). Specifically, the geometric parameters along the radial direction of the B-spline curve are known, and $p_1, p_2, \cdots, p_n$ are selected along the curve, then, control vertices $d_1, d_2, \cdots, d_n, d_{n+1}, d_{n+2}$ are calculated inversely. According to these control vertices, the B-spline curve is fitted, and the geometric parameter values at a different radial distance are obtained. The governing equations and boundary conditions are listed as follows (Hu Jian 2006):

$$\frac{(d_i + d_{i+1} + d_{i+2})}{6} = p_i \qquad i = 1,2 \cdots n \tag{2}$$

$$d_1 = d_2, d_{n+1} = d_{n+2} \tag{3}$$

Combining the above B-spline curve theory, this paper compiled related programs to express geometric parameter based on FORTRAN, and take the P4382 paddle as an example to verify the feasibility of the program, using the program to express the distribution of chord length, pitch, skew and rake.



(c) Rake (d) Skew

Fig. 3 Comparison of geometric parameters of the original paddle and parametrically expressed paddle

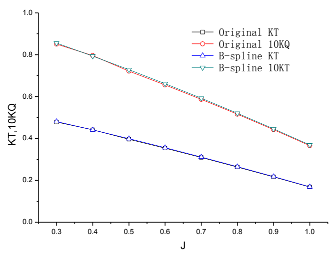


Fig. 4 Comparison of the open-water performance curves of the original paddle and the parameterized expression paddle

Given the advantages of the B-spline curve, four control points are selected in this paper. The specific location of the four control points depends on the distribution of the geometric parameters. As shown in Fig. 3, the chord length, pitch, thickness, camber, rake, and skew of the parameterized paddle are consistent with the original data. The hydrodynamic performance of the paddle after the parameterized expression is calculated and compared to the hydrodynamic performance of the original paddle. As shown in Figure 4, the open water performance curves are basically consistent between these two propellers. It can be seen that the inverse B-spline parameterized expression program of this paper can be used to express the geometric parameter of the propeller.

4 CASE ANALYSIS

3.1 Input of Design Parameters

In order to verify the validity of the theoretical design and optimization design process of the marine propeller in this paper, the redesigned HSP propeller is taken as an example. The experimental values of the geometric parameters, accompanying flow field and hydrodynamic performance of the HSP paddle are described in the literature (Hu Jian 2006). According to the test conditions of the HSP paddle, partial input parameters of lifting line design program are given, as shown in Table 1. Axial wake distribution information is presented in a table in the literature, and Fig.5 originate from the table to make axial wake information visual. Moreover, the average axial data at each radius is obtained, as shown in Table 2, where r/R is the dimensionless radius, and this is also applicable to the following.

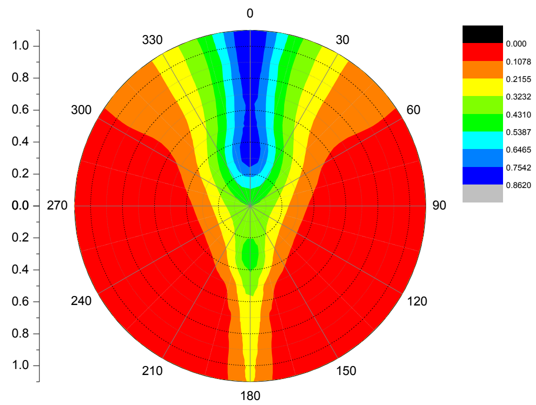


Fig. 5 Axial wake distribution

Table 1 HSP paddle lift line input parameters

Propeller Diameter D(m)	3.6	Boss Ratio r_h/R	0.2
Rotational Speed n(rps)	3.0	Ship Speed V_s(m/s)	9.604
Thrust T(N)	66016.23	Delivered Power P_D(kw)	353.66

Table 2 The circumferential average of the axial flow of the HSP paddle

r/R	0.2	0.3	0.4	0.5	0.6
Axial Flow	0.4568	0.3471	0.2697	0.2192	0.1899
r/R	0.7	0.8	0.9	1	
Axial Flow	0.1761	0.1722	0.1726	0.1717	

3.2 The Selection of Skew and Rake Distribution

Since the wake flow fields of different ships are different, it is necessary to select the appropriate skew distribution according to the specific wake of ships. Before the theoretical design process, the harmonic analysis method is used to analyze the normal wake of the ship, and the skew distribution is rationally selected to avoid the various sections of the propeller rotating to the high flow velocity area simultaneously. And the skew distribution must be considered together with the harmonic components of the accompanying flow field, regardless of the radial accompanying flow, and the normal accompanying flow for each profile is:

$$w_N = w_x \cos\beta_p - w_\theta \sin\beta_p \quad (4)$$

Where w_N = normal accompanying flow; w_x = axial accompanying flow; w_θ = circumferential accompanying flow; and β_p = pitch angle.

Before the theoretical design process, it is necessary to initialize the designed propeller and obtain the pitch angle to carry out the resonance analysis of the normal accompanying flow field. This step is omitted because the geometric pitch angle of the original HSP paddle is known. Through the resonance analysis, the maximum normal phase angle of the 5th order is obtained as shown in Table 3. Table 3 also shows the original skew distribution of the original HSP paddle. The design principle of the skew distribution is that the skew distribution curve should have a relatively large intersection angle with the normal accompanying flow phase distribution curve. According to this principle, the authors initially selected two modes of HSP propellers in the form of balanced and rear skew forms along with the radial distribution.

Table 3 The maximum normal phase and three kinds of the lateral distribution of flow field in HSP impellers

r/R	Maximum normal phase angle (°)	Skew of Original propeller (°)	Balanced Distribution (°)	Rear Skew Distribution (°)
0.1	-37.38	0	0	0
0.2	-36.6	-0.21	-0.32	0.01
0.3	-13.02	-3.93	-7.82	1.18
0.4	2.83	-2.94	-8.61	3.82
0.5	10.94	-0.06	-4.22	7.76
0.6	6.77	4.31	3.8	12.85
0.7	3.94	11.1	13.94	18.94
0.8	3.48	20.06	24.64	25.86
0.9	2.29	30.45	34.38	33.48
0.9	1.43	35.97	38.41	37.49
0.9	0.92	38.78	40.13	39.54
1	0.38	41.62	41.62	41.62

Under the condition of other geometric parameters keeping accordant, the unsteady hydrodynamic performance of different HSP propellers was predicted, including original skew, balanced and rear skew versions. Based on the Fourier analysis method, the unsteady thrust coefficient of the main blade of the HSP paddle in three skew modes can be analyzed, and the amplitude of each step force of the main blade can be obtained. It can be seen from Fig. 6 that the main pulsation amplitude of the HSP propeller corresponding to the balanced and rear skew distribution is smaller than that of the original propeller and the balanced reduction is larger. Besides, the average thrust coefficient of the main blade of the rear skew HSP paddle (the thrust amplitude of the 0th order) is larger than that of the original paddle, while the balanced HSP paddle has reverse performance. However, the magnitude of the reduction is not large. Therefore, in order to ensure the strength characteristics, under the condition of satisfying the thrust of the propeller, the balanced skew distribution form should be selected as much as possible. If the strength of the paddle is guaranteed, in order to improve the thrust coefficient of the propeller the rear skew distribution can be selected.

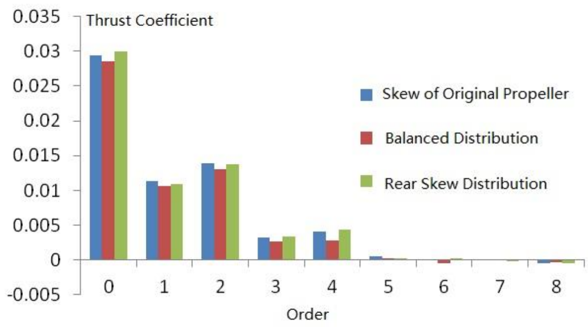


Fig. 6 The amplitude of the thrust coefficient of the main blade of three propellers of a rotation

The main purpose of the rake distribution is to increase the distance between the blade and the hull and reduce the washing effect to the hull, and thus the vibration could be reduced, however, the designers usually design the propeller in isolation and consider the wake of the hull to account for the effect of the speed field on the propeller after the hull. The rake distribution patterns include the blade inner radius front and outer radius rear distribution, the front rake and the rear rake. From the perspective of strength, the rear rake should not be too large to reduce the centrifugal force bending moment; and the front rake is beneficial to the strength of the large skew propeller and can effectively reduce the stress level of the paddle. From the perspective of hydrodynamic performance, the thrust coefficient and torque coefficient of rear rake propeller will increase with the increase of the rake angle, and the front rake can improve the efficiency of the propeller. From the perspective of the cavitation, the rear rake can improve the three-dimensional flow of the tip, thereby delaying the initiation of the tip vortex. Considering the hydrodynamic performance, cavitation, noise, and strength of the propeller, the rake distribution that inner radius front and outer radius rear can be selected.

In this example, the HSP paddle selects the five-blade in the redesigned process. The rake and skew distribution options are shown in Table 4 as the input parameters for the lifting line program.

3.3 Theoretical Design Result

After the selection of the rake and skew, the wake-adapted theory design of the HSP paddle can be carried out. Table 5 shows the geometric parameters of the designed propeller, where B/D is chord length ratio; P/D is pitch ratio; T/D is thickness ratio, and f/B is camber chord length ratio. The pitch of the blade root and blade tip is smaller than that of the original paddle, which is beneficial to reduce the hub vortex and tip vortex of the propeller.

Figure 7 shows a three-dimensional model of the propeller with a smoother geometry. The stress distribution prediction of the designed propeller is based on the program developed by the laboratory using panel method and the cantilever beam method, as shown in Fig. 8. The maximum stress value of the paddle is $2.5*10^7$ Pa (255.1 kgf/cm^2), which is less than the allowable stress of the material of 637kgf/cm2, and the strength meets the requirements.

Table 5 Geometric parameters of the designed propeller

r/R	*B/D*	*P/D*	*T/D*	*f/B*
0.2	0.173	0.708	0.037	-
0.3	0.208	0.925	0.032	0.0175
0.4	0.241	1.036	0.025	0.0253
0.5	0.272	1.069	0.017	0.0291
0.6	0.295	1.014	0.013	0.029
0.7	0.303	0.889	0.011	0.0258
0.8	0.292	0.754	0.009	0.0202
0.9	0.237	0.637	0.007	0.0095
0.95	0.163	0.578	0.007	0.0047
1	0	0.510	0.006	0

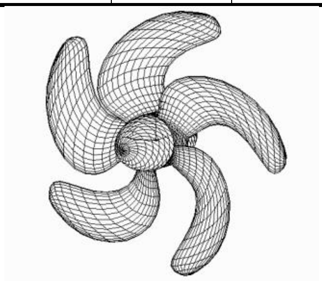
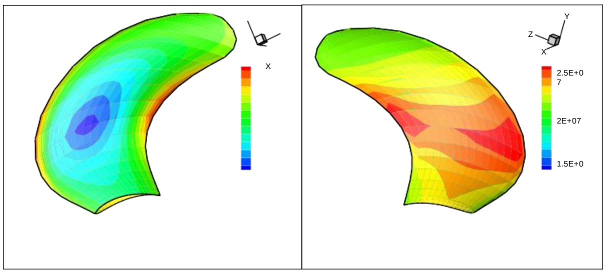


Fig. 7 Designed paddle schematic



(a)Blade face (b) Blade back

Fig. 8 Designed paddle stress profile

In order to better analyze the performance of the redesigned propeller, unsteady panel method is used to predict its performance, and performance comparison is carried out, as shown in Table 6 and Figure 10.

Table 6 Comparison of hydrodynamic performance between original HSP propeller and designed propeller

	KT	KQ
Original Propeller	0.172	0.02687
Designed Propeller	0.168	0.0261
Error	2.33%	2.87%

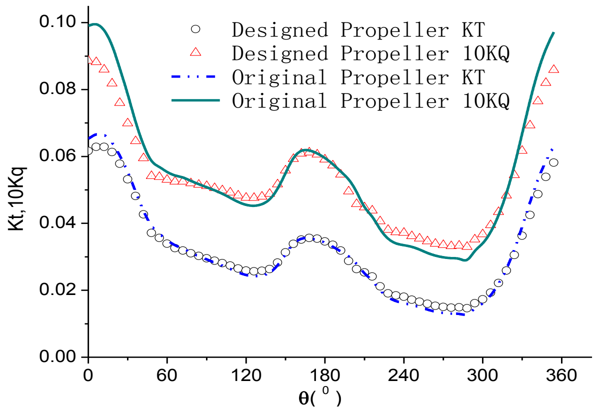


Fig. 9 The thrust coefficient and torque coefficient of the original HSP propeller and the design master blade

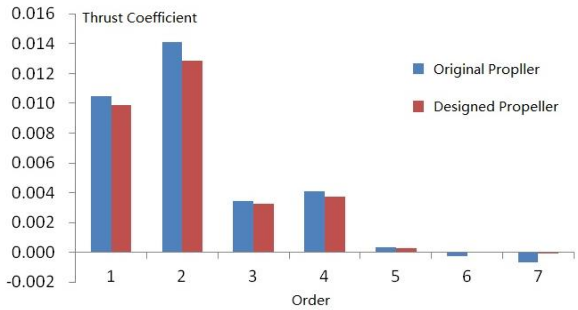


Fig. 10 The amplitude of the thrust coefficient of the main blade of two propellers of a rotation

It can be seen from Table 6 that the designed propeller provides 2.3% lower thrust and this is aimed to give the same thrust and better noise performance in unsteady flow filed. As can be seen from Figure 9, the thrust coefficients and torque factors of the main blade of these two propellers are relatively consistent during one revolution. At the same time, as can be seen from Figure 10, the thrust amplitude of the designed paddle is slightly smaller than the original paddle, and this is beneficial to reducing vibration and noise according to design experience. Noise performance comparison should be carried out to verify the design results, and this will be improved in later study.

3.4Optimization Design Result

In this example, the wake-adapted theoretical designed HSP propeller is considered as the parent type, and the feasibility of the optimized design method is established. Under the designed speed coefficient, the chord, pitch, skew, rake, and camber are optimized by iSIGHT software to reduce the maximum thrust coefficient and the maximum unsteady thrust amplitude of the main blade. Moreover the maximum stress of the propeller is limited to 637kgf/cm2. Specifically, the propeller stress calculation is calculated by the cantilever beam method in order to save time in the optimizing process, and the number of populations is set to 30, and the number of iterations is 12 times when searching for the target paddle.

The unsteady thrust amplitude of the largest main blade of the optimized paddle is designed as the abscissa and the average thrust coefficient is set as ordinate, which constitutes the Pareto Graph as shown in Figure 11. The point which respects parent type is separated in the Pareto Graph. It can be seen that after the optimization design, the performance of the propeller is further improved. Although the 2ed thrust amplitude of the theoretical propeller is larger than that of optimized propellers, the average thrust coefficient is much smaller, and the main reason is that the theoretical propeller designing depends on experience in some extent, so it is not the optimum solution in real condition. Each coordinate point in the Pareto Graph represents an optimization scheme that allows the ship designer to select the appropriate solution paddle for a different ship.

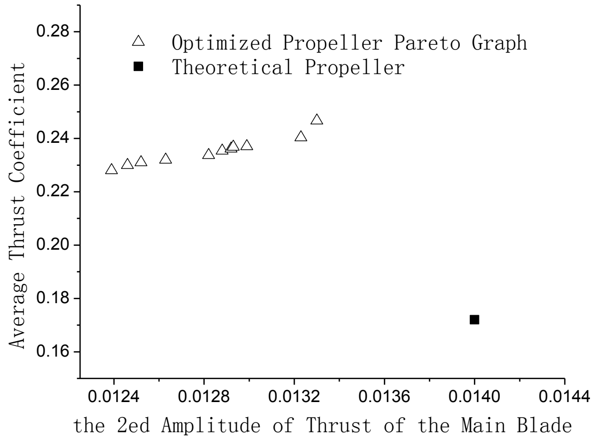
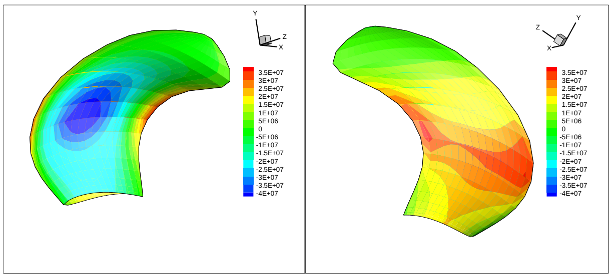


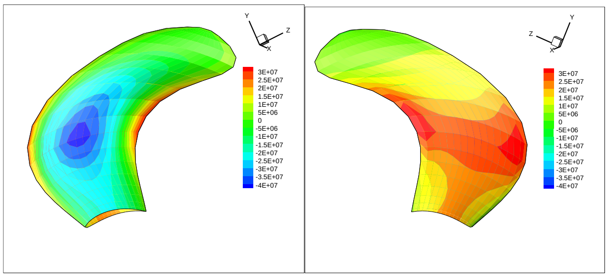
Fig. 11 Propeller Proper Flow Optimization Design Propeller Pareto Frontier

Select two suitable optimization scheme from the Pareto Graph to analysis, starting now referred to as the propeller 1 and propeller 2. Figures 12 and 13 show the stress prediction results for the two options. The maximum stress of the propeller 1 is 3.5*10^7Pa (357.1 kgf/cm2), and the maximum stress of the propeller 2 is 3*10^7 Pa (306.1 kgf). /cm2). It can be seen that the maximum stress of the two schemes does not exceed 637kgf/cm2, and the strength meets the requirements.



(a)Blade face (b) Blade back

Fig. 12 The blade stress distribution of propeller 1



(a)Blade face (b) Blade back

Fig. 13 The blade stress distribution of propeller 2

Table 7 shows the unsteady thrust amplitude and average thrust coefficient of the maximum main blade of the two optimized paddles, theoretical designed paddle and original paddle. As is shown from Table 7 and FIG.14, the unsteady thrust amplitude of the main maximum blade of propeller 1 and propeller 2 are both lower than that of original HSP propeller while the average thrust coefficients are higher. Therefore, the rapidity and vibration performance of the propeller 1 and the propeller 2 are better than those of the original HSP in the wake of the ship.

Table 7 Comparison of Hydrodynamic Performance

	The amplitude of thrust of the main blade	Average thrust coefficient
Original Propeller	0.01408	0.172
Theoretical Propeller	0.1287	0.168
Propeller 1	0.01292	0.2362
Propeller 2	0.01239	0.229

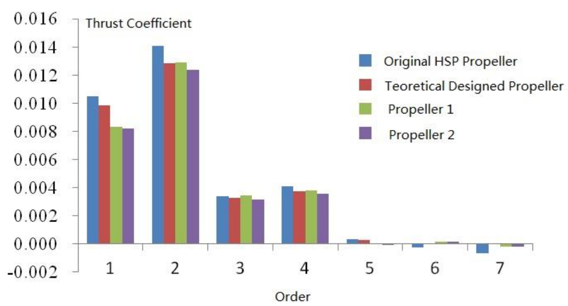
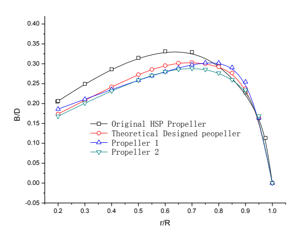
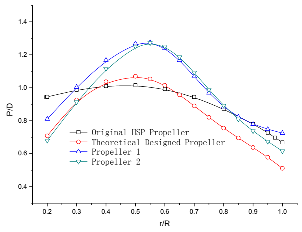


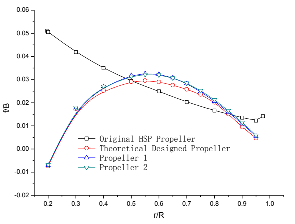
Fig. 14 Unsteady thrust coefficient of primary blades of primary and design propellers



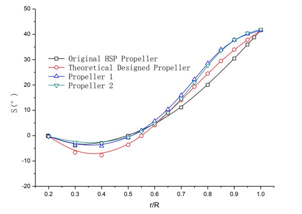
(a) Chord length ratio



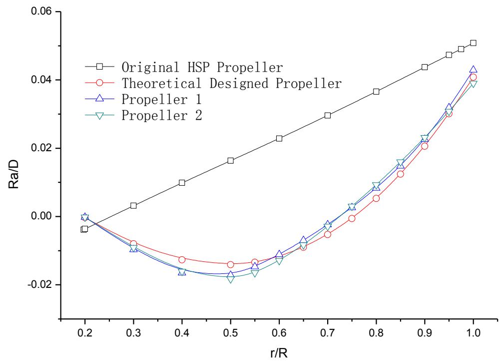
(b) Pitch ratio



(c)Camber ratio



(d) Skew



(e) Rake

Fig. 15 Comparison of geometric parameters of the original paddle and design paddle

Figure 15 shows the chord length, pitch, camber, skew, and rake distribution of the original paddle, theoretical designed paddle and two optimized paddles. Compared with the original paddle, the distribution curves of these geometric parameters of the optimized paddles are both smoother than the original paddle, and the distribution trend is also different from that of the original paddle. The chord lengths at the inner radius of the theoretically designed propeller and two optimized propellers are reduced compared with the original paddle, and thereby the open water efficiency is improved. The pitch of blade root and blade tip of these three propellers is smaller than the original paddle, while the pitch of the middle of the blade is larger than the original paddle, which is beneficial to reduce the hub vortex and tip vortex of the propeller. The pitch distribution along the radial direction of the two optimized propellers is quite different from that of the theoretical designed one. It is concluded that the pitch distribution has a great influence on the unsteady thrust amplitude and the average thrust coefficient of the propeller. The camber determines the distribution form of the load along the chord direction on the blade section. The increase of the camber can avoid the negative pressure peak near the leading edge and delay the occurrence of cavitation. However, the strength of the whole blade is unfavorable in such condition. The camber at the blade root of these three propellers is much smaller than that of the original HSP paddle, which is advantageous for the strength and the hub vortex at the blade root; the camber distribution in the middle of the blades of two optimized propellers is larger than that of the theoretically designed propeller which is useful for improving the thrust of the propeller. The trend of the skew distribution of all these four propellers are similar, but these three propellers have larger skew at the blade tip than that of the original HSP paddle. This is advantageous for reducing the unsteady thrust amplitude of the largest main blade. For rake, the rake of the blade root of the optimized paddles is reduced, and the rake near the blade tip is increased. Actually, the rake distribution of these three propellers is quite different from the original paddle, and this form of distribution is advantageous for the strength of the propeller.

5 CONCLUSIONS

In this paper, the resonance analysis method of the flow field, the selection method of the number of blades, skew and rake distribution, lifting line and lifting surface programs, hydrodynamic performance predicting program and iSIGHT software are combined to form a relative complete propeller optimization design process, and some conclusions are listed as follows:

1) B-spline curve is used in the propeller parameterized expression process, and the geometric parameter distribution of the smooth propeller can be obtained with fewer reasonably selected control points, and the chord length, pitch, thickness, camber, skew and rake distributions are consistent with the original paddle and can be applied to the parameter optimization design process of the propeller.

2) The theoretically designed propeller should have such effect that the hydrodynamic performance is consistent with the original propeller, and the strength meets the requirements, and the vibration and noise performance is better than the original propeller. Moreover, the propeller described in this paper has realized such effect, verifying the effectiveness of the method.

3) The optimized propeller should have better thrust and vibration performance than the theoretically designed propeller. Also, the result has proved that the optimization process is feasible.

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