The study of multi-parameter optimization design of ducted propeller

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Abstract. Using the prediction method of surface element method and particle swarm optimization algorithm to study the multi-parameter optimization design of ducted propeller. Hicks-Henne function and Bezier function are used to fit the parameter curve of the ducted propeller. Taking the open water efficiency of the ducted propeller as the optimization target, the numerical simulation was performed. By analyzing the result, the multi-parameter coupling optimization design of the ducted propeller can be achieved. After optimization, the open water efficiency and thrust coefficient at the design points have been improved. Among the two fitting methods, the Bezier function gives a better result, which is consistent with the actual engineering. Within the range of the common speed coefficient of each ducted propeller, the efficiency and thrust are improved and meet the requirements. The feasibility and effectiveness of the multi-parameter coupling design of the ducted propeller are verified.

1. Introduction

With the development of propeller theory, people have discovered and paid attention to the advantages and characteristics of ducted propellers, and have theoretically researched on them. During the design of ducted propellers, structural parameters such as pitch, trim, roll, arch, chord length, and blade section affect the hydrodynamic, noise, and vibration performance of the propeller. As the optimization theory is introduced into the design of propellers, scholars have started a series of studies on the optimization design of ducted propellers.

Yang [1] changed the blade type value and the duct type value of the ducted propeller, thereby analyzing the ducted propeller, and obtained the ducted propeller with improved performance. Shi adopted a combination optimization strategy and used mapping data to optimize the design of ducted propellers[2]. According to the pitch, Ni optimized the design of the ducted propeller and analyzed the effect of the pitch and the number of blades on the performance of the ducted propeller [3]. Ma used Isight software to do the propeller-based multi-objective optimization of the propeller and found that the parameters of the propeller are mutually constrained and affect the hydrodynamic performance of the propeller [4]. During the single-parameter optimization design of the propeller, keeping other parameters constant, changing one single parameter will cause the propeller to be uncoordinated. The
parameters are not well coupled, distorting the propeller shape. Therefore, the multi-parameter coupling optimization design of the propeller has theoretical significance and application significance.

Based on the particle swarm algorithm, combined with the Ka series ducted propellers, this study will perform the multi-parameter optimization of ducted propellers to verify the feasibility of multi-parameter optimization of the propellers. First, select pitch, pitch, roll, camber, and chord length as variables, and determine the variable ranges. Secondly, the multi-parameter optimization design of these parameters is performed to obtain a suitable parameter combination and a propeller with better hydrodynamic performance.

2. Computational methods

2.1. Panel method

The panel method is also known as the method of singularity distribution. This method distributes the singular points on the surface of the blade and the duct for calculation. Combined with the corresponding boundary conditions and Kuta conditions, etc., this method can accurately display the details of the pressure distribution on the object surface [5].

In an inviscid, incompressible, non-swirl incoming flow with velocity \( V_0 \), it can be obtained from the Green formula that the perturbation potential \( \phi(P) \) of any point \( P(x, y, z) \) on the boundary surface \( S \) of the flow field can be expressed as:

\[
2\pi\phi(P) = \iint_S \left[ \phi(Q) \frac{\partial}{\partial n_Q} \left( \frac{1}{R(P,Q)} \right) - \frac{\partial\phi(Q)}{\partial n_Q} \frac{1}{R(P,Q)} \right] dS
\]

\( R(P, Q) \) is the distance between a point \( P \) in the flow field and a point \( Q(x_0, y_0, z_0) \) on the boundary; \( \frac{\partial}{\partial n_Q} \) is the normal number of the boundary surface \( S \) at the point \( Q \) [6].

Considering the boundary condition on each face, the integral equation can be expressed as:

\[
2\pi\phi(P) = \iint_{SB} \phi(Q) \frac{\partial}{\partial n_Q} \left( \frac{1}{R(P,Q)} \right) dS + \iint_{SW} \phi(Q) \frac{\partial}{\partial n_{Q1}} \left( \frac{1}{R(P,Q)} \right) dS + \iint_{SB} (V_0 \cdot n_Q) \left( \frac{1}{R(P,Q)} \right) dS
\]

\( n_Q \) is the unit normal vector on the boundary surface and \( \Delta\phi \) is the jump of velocity potential through the wake surface. Considering the three-dimensional influence, it is necessary to introduce the pressure Kuta condition to solve the flow problem. Pressure Kuta conditions are as follows:

\[
(\Delta p)_{TE} = p^+_{TE} - p^-_{TE}
\]

Combining these conditions, the integral equation can be solved, and the velocity on the blade can be solved either. The pressure distribution can be obtained through the Bernoulli equation.

2.2. Particle swarm optimization

In 1995, particle swarm optimization (PSO) was proposed [7,8]. This model is described as below: each particle consists of its current position \( x_i \) and velocity \( v_i \), the optimal position is represented by \( \vec{P} \), the global optimal position is represented by \( P_{gd}(T) \), and the local optimal position is represented by \( P_{id}(i) \). The position and velocity of each generation of particles are calculated by the following two formulas:

\[
\begin{align*}
V_{id}(t + 1) &= w \cdot V_{id}(t) + c_1 \cdot r_1 \cdot (P_{id}(i) - x_{id}(t)) + c_2 \cdot r_2 \cdot (P_{gd}(t) - x_{id}(t)) \\
x_{id}(t + 1) &= x_{id}(t) + k \cdot V_{id}(t + 1) \\
1 \leq i \leq n, 1 \leq d \leq n
\end{align*}
\]
is the inertia weight, which reflects the choice between the global search and local search of the convergence speed of the particles. \( c_1 \) and \( c_2 \) are non-negative constants and are generally considered as cognitive and social parameters. \( r_1 \) and \( r_2 \) are random numbers between [0,1]. \( k \) is a limiting parameter, which restricts the flying speed of particles.

2.3. Curve fitting method
In this paper, the Hicks-Henne function [9] and the Bezier curve [10] are applied to fit the distribution curve of different parameters of the propeller.

3. Model and optimization
In the multi-parameter optimization design of ducted propellers, the optimization variables include pitch distribution, disk surface ratio, and thickness distribution. The linear function superposition method and Bezier curve method representation are applied. The paddles optimized by the Bezier fitting method are denoted as Bezier, and the paddles optimized by the linear function fitting method are denoted as Hicks-Henne. The open water efficiency of the propeller is the objective function of optimization design. The thrust meets the requirements during the optimization process.

The surface element method theory is used to predict the performance of the propeller. The standard particle swarm optimization method is applied to search the variables. The basic parameters of the particle swarm algorithm, such as the number of population, the number of iterations, the range and method of weight change, have been determined. The open water efficiency of ducted propellers is calculated by the surface element method theory. The meshing of the ducted propeller is shown in Figure 1[11].

4. Results and discussion
The distribution curve of the propeller shape parameters is fitted by the Bezier function and the Hicks-Henne function, respectively. As shown in Figure 3, the optimization using the Bezier method to fit the curve results in a higher propeller open water efficiency than the Hicks-Henne method. The Hicks-Henne method stagnates at the beginning of the iteration and converges to the optimal solution, which verifies the rationality of the Bezier method to fit the curve. In the multi-parameter optimization of the propeller, the curve fitted by the Hicks-Henne method does not match the variation of the propeller-type parameter, thus the optimization process converges very early. The results fitted by the Bezier method are consistent with the changes in the propeller value. Using the Bezier method to fit the curve of multi-parameter optimization is more reliable.
Table 1 Comparison of Two Fitting Methods

| Iter | Kt    | kq    | η     | kt    | kq    | η     |
|------|-------|-------|-------|-------|-------|-------|
| 0    | 0.20057 | 0.02713 | 0.58824 | 0.20057 | 0.02713 | 0.58824 |
| 1    | 0.21183 | 0.02822 | 0.59733 | 0.19986 | 0.02695 | 0.5902 |
| 2    | 0.21247 | 0.02824 | 0.59871 | 0.20002 | 0.02682 | 0.59338 |
| 3    | 0.21284 | 0.02825 | 0.59952 | 0.2004 | 0.02684 | 0.5941 |
| 4    | 0.21284 | 0.02825 | 0.59952 | 0.2004 | 0.02684 | 0.5941 |
| 5    | 0.21298 | 0.02826 | 0.59964 | 0.2004 | 0.02684 | 0.5941 |
| 6    | 0.21357 | 0.02829 | 0.60082 | 0.2004 | 0.02684 | 0.5941 |
| 7    | 0.21357 | 0.02829 | 0.60082 | 0.2004 | 0.02684 | 0.5941 |
| 8    | 0.21357 | 0.02829 | 0.60082 | 0.2004 | 0.02684 | 0.5941 |
| 9    | 0.21357 | 0.02829 | 0.60082 | 0.2004 | 0.02684 | 0.5941 |
| 10   | 0.21357 | 0.02829 | 0.60082 | 0.2004 | 0.02684 | 0.5941 |

Table 1 shows the variations of thrust coefficient $K_t$, torque coefficient $K_q$, and open water efficiency $\eta$ during the optimization process using two fitting methods in multi-parameter optimization. In the Bezier method, $K_t$ increased by 6.5%, $K_q$ increased by 4.3%, and $\eta$ increased by 2.1%; In the Hicks-Henne method, $K_t$ increased by 0.1%, $K_q$ increased by 1%, and $\eta$ increased by 1%. Both fitting methods increase the open water efficiency of the propeller and increase the thrust coefficient. Multi-parameter optimization increases efficiency while maintaining the same thrust. The $K_t$, $K_q$, and $\eta$ obtained by the Bezier method are all increased, which is consistent with the actual conditions.

Figures 2 and 3 show the variations of pitch and maximum thickness distribution, respectively. The optimal solution produced by the optimization process varies on the distribution curve of each parameter, which is greatly different from the original model. Because the original propellers have equal pitches in different radial directions, if the equivalent value change method is used, the pitch of the propellers varies widely, resulting in a large distortion of the shape of the propellers. The curve fitting method is adopted, and the pitches in each radial direction are fluctuated based on the original value without causing large distortion. In the Hicks-Henne method, the pitch change at the blade root is abrupt, which is not conducive to the hydrodynamic performance of the propeller, causing the optimization process to converge earlier; the Bezier method fits the pitch gradually and does not produce sudden changes, and finally converges to a position with higher open water efficiency. Figure 3 shows the curve of the variation of the maximum thickness distribution of the ducted propeller. It can be seen that the thickness
obtained by the Bezier method optimization is larger than the original propeller, which meets the strength requirements of the propeller. The thickness obtained after the optimization of the Hicks-Henne method is smaller than that of the original propeller. Although the amplitude is not large, it will affect the strength of the propeller.

### Table 2 Disk-surface ratio

|               | Original | Bezier  | Hicks-Henne |
|---------------|----------|---------|-------------|
| Disk-surface  | 0.55     | 0.467   | 0.5148      |

Table 2 shows the variations of the disk-surface ratio after optimization. It can be seen from the table that no matter which fitting method is used, the disk-surface ratio obtained is reduced, and the result of the Bezier method is smaller.

### 5. Conclusion

Based on the theory of the surface element method and the intelligent particle swarm optimization algorithm, the multi-parameter coupling optimization design of the ka0.5 ducted propeller is designed in this study. The Hicks-Henne function and Bezier function are used to fit the optimization variables. The optimization objective is the open water efficiency of the propeller.

1. Multi-parameter coupling design uses two different methods to control the change of variables. The open water efficiency has increased. Thrust coefficient and torque coefficient stay the same. The Bezier method has higher blade efficiency, and the thrust coefficient and torque coefficient remain the same values, which is consistent with engineering practice.

2. The numerical simulation validates the feasibility and effectiveness of the multi-parameter coupling design proposed in this study. It provides a theoretical basis for the subsequent multi-target and multi-parameter coupling design of ducted propellers and can be used in engineering applications.

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