Blade Profile Design and Optimization of Ocean Energy Low-speed Water Turbine

Fuchuan Lan¹, Jiani Liu¹, Fuxi Zhang¹,²,*, Shiming Wang¹,² and Rong Chi¹
¹College of Engineering Science and Technology, Shanghai Ocean University, Shanghai, China
²Shanghai Engineering Research Center of Marine Renewable Energy, Shanghai, China

*Corresponding author email: fx-zhang@shou.edu.cn

Abstract. Based on multi-objective genetic algorithm, naca4415 airfoil (NACA airfoil is a series of airfoils developed by the National Aeronautical Advisory Committee of the United States) is used as the original airfoil to optimize the blade airfoil of low water speed tidal current turbine, The lift drag ratio of the generator airfoil is improved (lift drag parameter is one of the key factors to determine the low-speed water kinetic energy conversion efficiency of the airfoil), the power generation efficiency of the turbine airfoil is improved, and the airfoil is spliced on the basis of the optimized airfoil. The results show that the lift drag ratio performance of the optimized airfoil at the designed angle of attack is improved compared with that of the unoptimized airfoil, and the lifting range increases with the increase of the angle of attack. The pressure coefficient of the optimized airfoil decreases and the flow velocity increases. The pressure coefficient of the assembled S-shaped airfoil and the S-shaped airfoil have good bi-directional energy harvesting performance at the optimal attack angle of 12° to 15°.

Keywords: Blade foil; Multi-objective genetic algorithm optimization; CFD simulation.

1. Introduction
As an important type of ocean renewable energy, tidal energy is an ideal source of offshore self-power supply. Its development and utilization have great research value and strategic significance for our country's marine security and offshore energy supply.¹ The low flow rate and reciprocating characteristics of the current make it difficult for the traditional impeller to capture mechanical energy effectively. The main reason is that the blade profile and angle of attack of the traditional impeller are designed for high-speed directional laminar flow characteristics. For the ocean current that effectively drives the impeller to rotate and even achieve the expected efficiency, the design of the blade foil under low-speed flow conditions plays a key role. The appropriate angle of attack determines the energy conversion characteristics of the tidal current turbine. At present, in order to study how to improve the efficiency of water turbines, domestic and foreign scholars have carried out a lot of research. Battena et al. have studied the momentum method and used this method to design the blades². Grasso et al. used the gradient method to optimize the hydrodynamic performance of the airfoil at an angle of attack of 7°³. Goundar et al. studied the problems of high lift, high lift-to-drag ratio, and cavitation of hydroturbine airfoils⁴. Wu et al. introduced Schmitz theory into the blade design to optimize the efficiency of the turbine⁵. Guojun Zhu and others introduced the RBF neural network to conduct an in-depth study on the multiple working conditions of the turbine⁶. Therefore,
designing a high-performance tidal energy turbine airfoil that meets the working conditions is of great significance for improving the efficiency of the turbine and the utilization of tidal energy. Aiming at the optimization problem of tidal current energy turbine, this paper applies multi-objective genetic algorithm to optimize the design, and then conducts the simulation analysis to obtain the hydrodynamic performance of the new impeller, which provides a certain reference basis for the optimization design of tidal energy turbine in the future.

2. Multi-objective Genetic Algorithm for Airfoil Optimization

Algorithm is a global optimization algorithm based on biological genetics and evolutionary mechanisms, which is suitable for adaptive probability optimization technology for complex system optimization [7]. In recent years, genetic algorithm has been widely used in the topological optimization of complex geometries, especially the research of fluid-structure interaction, and its general form is:

\[
\begin{align*}
V_{\text{min}} \quad f(x) &= [f_1(x), f_2(x), f_3(x) \cdots, f_n(x)]^T \\
\text{s.t.} \quad x &\in X \\
\text{s.t.} \quad x &\subseteq R^n
\end{align*}
\]  

In the formula, \( V_{\text{min}} \) represents the vector minimization, that is, each sub-objective function in the vector objective function is minimized as much as possible. The weight coefficient transformation method is the basic algorithm of multi-objective genetic algorithm. For a multi-objective optimization problem, the weight coefficient \( w \) of each sub-objective function \( f_i(x) \) (i = 1, 2, 3, ..., n) (i = 1, 2, 3, ..., n), the weight coefficient determines the importance of the corresponding objective function in the multi-objective optimization algorithm.

The foil design is related to the fluid mechanics and structural strength fields. In the design process, there will also be conflicts in foil design elements, such as hydrodynamic performance and structural requirements. When the design requirement is high ratio of lift-to-drag, the relative thickness of the blade type and the lift-to-drag ratio are mutually restricted [8]. In this paper, a multi-objective genetic algorithm based on the weight coefficient change method is used. In the calculation, the sub-objectives compete with each other, and the weight coefficient change can coordinate the conflicts that will appear. The corresponding mathematical expression is:

\[
u = \sum_{i=1}^{n} \omega_i \cdot f_i(x)
\]  

Taking \( u \) as the evaluation function of the multi-objective problem, multi-objective optimization turns into single-objective optimization. Weighting coefficient in this design is obtained by analytic hierarchy process (AHP).

2.1. Design variables

The design variables are selected with 7 control points (P1, P2, P3, P4, P5, P6, P7) of the leading edge of the NCCA4415 airfoil blade and 3 control points (P8, P9, P10) of the bottom surface. Figure 1 is the airfoil control point diagram.
2.2. Objective Function

The lift-drag ratio is a key issue in the research of airfoil design. According to the leaf element-momentum theory, the larger the lift-drag ratio, the chord length of the blade can be reduced under the same tip speed ratio, thereby reducing the working load of the blade.\[9\] Design the blade airfoil to run under the corresponding Mach number $Ma$, the maximum lift-drag ratio of the design attack angle $\alpha$ is taken as one of the objective functions:

$$f_1(x) = \max\left(\frac{c_l}{c_d}\right)$$  \hspace{1cm} (3)

Here, $c_l$ and $c_d$ are the lift coefficient and drag coefficient under the free rotation condition under the design angle of attack.

2.3. Constraints

In the blade profile design, the pursuit of a high lift coefficient will make the leading edge of the foil sensitive. Studies have shown that as the sensitivity of the leading edge increases, the performance of tidal energy turbines will drop by 30%, according to the priority of the weighting coefficient $\omega$. More important, the weight coefficient $\omega_1$ is greater than $\omega_2$. At the designated angle of attack, the lift-to-drag ratio value must be greater than the original lift-to-drag ratio, ie $c_l/c_d > Y_0$, and the lift coefficient must not be less than the original lift coefficient, ie $c_l \geq X_0$.

Studies have shown that the lift-to-drag ratio of an airfoil is also affected by the relative thickness and relative camber of the airfoil \[11\]. At a small angle of attack, the relative thickness increases along with the decreasing lift-to-drag ratio of the airfoil gradually; at a large angle of attack, the NACA4415 can still maintain a high lift-to-drag ratio. The maximum thickness of the initial airfoil is 15% of the chord length, and the relative thickness is restricted by $13\% \leq t/c \leq 17\%$. \[12\]The camber on the foil increases with increasing the lift resistance. But the lift coefficient increases slowly with respect to the increment gradient of the camber, and the lift-to-drag ratio presents a dome-like trend. According to Cen Mei’s research\[12\], for an airfoil with a maximum relative thickness of 15% and its maximum relative camber at 6%, the maximum lift-to-drag ratio is about 5.4. Therefore, the constraint on the relative camber is set as $5\% \leq f/c \leq 8\%$.

2.4. Algorithm Flow

(1) Primary selection of populations. The initial coordinates of the foil are set to the initial population. Suppose the size of the population $N$ is 30, and the maximum number of iterations is $t_{\text{max}}$. In this optimization design, the number of initialization iterations is recorded as $t = 1$, and the maximum number of iterations is $t_{\text{max}} = 200$.\[13\]

(2) Selection of fitness function. The fitness function is set to guide the search of the genetic algorithm. Individuals with greater fitness will be taken as the parent layer and brought into the next layer of operators to achieve the optimal selection of the algorithm. The fitness function can be expressed as:

$$fitness = \frac{1}{1 + SSE}$$  \hspace{1cm} (4)

$$SSE = \sum_{i=1}^{n}(y_i - y'_i)^2$$  \hspace{1cm} (5)

$y_i$ is the corresponding point of the fitted data, $y'_i$ is the corresponding point of the original data, and $SSE$ is getting closer and closer to 0, indicating that the model fits well.\[13\]

(3) Operator calculation. According to the principle of retention of individuals with greater fitness, the fitness values of individuals in the population are calculated and sorted by fitness. A batch of individuals with greater fitness are retained and saved as the parent population, with the population size as $N$. The individuals in the population are randomly matched, the crossover probability of the population individuals is set to 0.8\[13\], and the linear crossover is used to obtain new individuals.

(4) When the steps are repeated, when the final population reaches the given constraints, or the number of iterations $t$ is greater than the maximum number of iterations $t_{\text{max}}$, the optimization algorithm will terminate. The Figure 2 shows the genetic algorithm process.
3. Airfoil Design Results and Simulation Analysis
Taking NACA4415 as the master profile, the new prototype is solved by a multi-objective genetic algorithm. The radius of the leading edge of the optimized blade profile is increased, and the upper and lower profile surfaces are larger than the original airfoil. Compared with the chord length of the original airfoil, the optimized chord becomes shorter. Affected by the change in camber, the tail edge of the optimized profile becomes rounded.

The simulation analysis is carried out to determine the pressure distribution, lift coefficient, drag coefficient, and lift-to-drag ratio at different angles of attack. The SST turbulence model is selected for the simulation\cite{14}, combined with the near-wall function of the K-\omega model.
First, set the parameterization of the impeller. Considering the working environment of the blade foil, the incoming flow temperature is 20 degrees Celsius, the average incoming flow speed is \(U=2.5\text{m/s}\), the incoming Mach number is 0.15, and the Reynolds number based on the foil is about \(6 \times 10^6\); the incoming flow density is \(1.2043\text{kg/m}^3\), the incoming flow viscosity is \(1.814\text{E-5kg/(ms)}\), and the incoming turbulent flow energy is \(4.184\text{E-7m}^2/\text{s}^2\). Then the same flow field is established for the foil before and after the optimization. The figures show the established flow field with the entrance and smooth exit. Figure 4 shows the grid division of the original airfoil, and Figure 5 shows the optimized foil grid, respectively.
Through the parametric scanning operation in the simulation software, the pressure coefficient under different attack angles can be solved. The left side of Figure 4 shows the pressure coefficient of the original airfoil at different angles of attack, and the right side of Figure 6 shows the pressure coefficient of the optimized airfoil at different angles of attack.

The original airfoil NACA4415, when its attack angle, $\alpha = 13^\circ$, the lift coefficient decreases and enters the stall point. Under the designed conditions, the pressure coefficients of the original and optimized airfoils are compared by taking the angles of attack of $1^\circ$, $6^\circ$ and $13^\circ$. Figure 7 is a comparison diagram of pressure coefficient at a design angle of attack of $1^\circ$, Figure 8 is a comparison diagram of pressure coefficient at a design angle of $4^\circ$ and Figure 9 is a comparison diagram of pressure coefficient at a design angle of $13^\circ$.

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When the angle of attack is small, the pressure coefficient at the front end of the foil is significantly reduced. The pressure coefficient at the mid-to-front end of the foil has a large drop, and the pressure coefficient of the upper airfoil in the middle and rear section decrease considerably. The pressure coefficient of lower surface of the foil increases. Compared with the original airfoil, the optimized foil at a low angle of attack is more uniformly compressed. Nevertheless, the difference in pressure coefficients between the upper and lower surfaces is small, and the lift-to-drag ratio is not significantly improved. When the designated angle of attack becomes larger, compared with the original airfoil, the pressure coefficient of the middle section of the upper foil decreases and the pressure coefficient of the lower foil slightly increases. Within the range of the designated angle of attack, the pressure coefficient difference between the upper and lower parts of the optimized foil is conducive to the improvement of the lift-to-drag ratio. After optimization, the maximum peak value of the foil pressure coefficient has decreased to 1.2, and the minimum pressure peak value has a slight decreasing. Because the cavitation coefficient of the foil is affected by the minimum pressure coefficient, it remains basically the same after optimization. In the subsequent design, the cavitation coefficient of the foil can be considered in the optimized objective function.

| Angle of attack | Original airfoil | Optimized airfoil | Relative change rate of lift-to-drag ratio |
|-----------------|------------------|------------------|------------------------------------------|
|                 | Lift coefficient | Lift coefficient | Lift coefficient | Lift coefficient | Lift coefficient |
| 1               | 0.554            | 0.571            | 75.890         | 0.571            | 79.305           | 1.045           |
| 4               | 0.894            | 0.954            | 110.37         | 0.954            | 122.31           | 1.108           |
| 13              | 1.543            | 1.604            | 57.150         | 1.604            | 69.740           | 1.220           |

It can be seen from Table 1 that compared with the original airfoil, the optimized airfoil has a higher lift coefficient and a lower drag coefficient. At three angles of attack, the relative change rates of the lift-drag ratio before and after the optimized airfoil are 1.045, 1.108, and 1.220, respectively. The relative change rates of lift coefficient are 1.031, 1.067, 1.039, respectively. The relative change rate of the optimized lift-to-drag ratio increases as the angle of attack increases. The optimized wing
satisfies the objective function and its constraints, has a better lift-to-drag ratio and a larger lift coefficient.

4. S Airfoil Simulation
According to Zhiqian Yang’s research, the S airfoil has the good two-way energy acquisition [17]. In order to improve the energy-capacity of the tidal current turbine, the optimized foil is spliced and smoothed to become an S airfoil. Figure 10 shows the S airfoil after the optimized airfoil splicing.

![Figure 10. The S foil.](image)

The pressure coefficient and flow field velocity of the S airfoil at different angles of attack are demonstrated through the simulation.

![Figure 11. Foil pressure coefficient and flow field velocity when $\alpha = 1^\circ$.](image)

![Figure 12. Foil pressure coefficient and flow field velocity when $\alpha = 4^\circ$.](image)

![Figure 13. Foil pressure coefficient and flow field velocity when $\alpha = 8^\circ$.](image)
The pressure coefficient curve at different angles of attack illustrate that the angle of attack increases along with the increments of the pressure coefficient of the S wing surface. When the angle of attack reaches to $13^\circ$, the pressure coefficient curve tends to be stable. The extreme pressure appears in the front section of the foil and gradually decreases in the direction of center chord. The pressure coefficient of the lower foil decreases more obviously, occurring at the foil tail, opposite to the increasing angle of attack. It can be seen from the velocity field diagram that the velocity of the flow field fluctuates along with growing the angle of attack, with the top speed at $13^\circ$. Therefore, according to the simulation of the S foil, the angles of attack are desired at $13^\circ$ to $15^\circ$.

5. Conclusion

Based on the current status of tidal current energy research, this paper utilizes the multi-objective genetic algorithm to optimize the blade of low-speed tidal energy turbines. Through simulation analysis, the following conclusions are obtained:

(1) The feasibility of the multi-objective genetic algorithm based on the weight coefficient change method for the optimization design of the blade foil was verified, and the master model - NACA4415 was successfully optimized and improved with better lift coefficient, flow field characteristics, and hydrodynamic performance.
According to the analysis of the spliced S foil, the designated angle of attack is preferably between 13° to 15° for more evenly distributed pressure coefficient.

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