Optimization Design of Duct Geometry Based on Particle Swarm Optimization Algorithm

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Abstract. An optimization method for Darrieus turbine’s duct geometry is presented in this paper. In this method, the geometry parameters of the duct are used as optimal variables, and the energy output quality parameters of turbine are used as objective function. Then the particle swarm optimization (PSO) algorithm is introduced as search strategy to carry out the optimization of duct internal wall geometry. During the optimization procedure, the Kriging response model that meets accuracy requirement is used to replace the CFD simulation method, which offers significant time saving. According to the comparison of the energy output characteristics after the duct optimization, it can be found that the optimization of the duct internal wall geometry effectively improves the stability of the power coefficient. Meanwhile, the better energy-gathering effect also increases the power of the turbine. All these results indicate that the optimization method of duct geometry is feasible and effective.

Introduction

In the past few decades, due to the impact of the fossil energy depletion crisis, the conversion of clean energy has attracted more attention. Darrieus turbine is always used for converting the kinetic energy in rivers or marine currents. So it gains more application[1]. But its main drawbacks are low energy conversion coefficient and strong fluctuations in the energy output procedure. In order to expand the application, it is necessary to improve the quality of hydroelectric power of Darrieus turbines. Malipeddi[2] analyzed the influence of the duct shape on the energy output and power fluctuation properties of Darrieus turbine; Maitre[3] and Pellone[4-5] from the French Laboratory of Geophysics and Industrial Fluids carried out detailed experimental and numerical simulation on the internal flow characteristics of Darrieus turbines, then proposed a method to improve the energy performance by combining airfoils into a duct. In China, Zhang[6] and Cheng[7] studied the feasibility of increasing the diversion duct to improve the stability of energy output. The influence of the end plate on the performance of the turbine is analyzed by Kang[8]. The effect of different blade structure types on the performance of Darrieus turbines was pointed out by Zou[9]. It can be found that most scholars only focus on analyzing the impact of the duct on the performance of Darrieus turbine. How to effectively optimize the design of the duct geometry still lack research. Therefore, an optimization method of the duct geometry is introduced in this paper. In this optimization method, the Kriging response model is used to replace the CFD numerical method to obtaining the performance of the turbine and the particle swarm optimization algorithm is used to search for the best solution. Then the duct geometry can be optimized effectively.

Turbine Model and Parameterization of Duct Geometry

Turbine Model

The Darrieus turbine model in this paper is derived from the turbine tested by Professor Maitre of the Laboratory of Geophysical and Industrial Flows (LEGI) [4]. The structure of turbine has been described in reference [4]. Only the two-dimensional diagram of the hydroturbine and its test tunnel
are shown in Figure 1. In this paper, the design and optimization of the duct was carried out for one-way flow conditions. Half of the initial design geometry of the duct is shown in Figure 2. Its geometry is symmetrical along a plane passing through the rotating axial of the runner and parallel to the inflow direction. Its section shape remains constant along the height direction of turbine.

Parameterization of Duct Geometry

The geometry of the inner wall of duct has an important influence on the performance of Darrieus turbine. The inner wall shrinks first and then spread. The shrinkage curve is curve AB and the spread curve is arc BC. These two curves are smoothly connected at the point B, where is the throat of the duct. The tangent direction at point B is horizontal. The initial design parameters of the inner wall of duct are shown in the Table 1.

| Parameters | Inlet width $L_{in}$/mm | Duct length $L_1$/mm | Distance from throat to inlet $L_2$/mm | Throat width $L_D$/mm | Outlet width $L_{out}$/mm |
|------------|-------------------------|----------------------|--------------------------------------|-----------------------|------------------------|
| Value      | 315                     | 437.5                | 175                                  | 205                   | 315                    |

The function of shrinkage curve is accelerating the fluid and making it reach the throat runner stably and evenly. Therefore, the shrinkage curve plays a decisive role in the duct geometry. So the curve AB is selected as the optimization object in the optimal design of the duct geometry, and arc BC is remains constant.

Mathematical Models for Optimization Design

The shrinkage curve AB is expressed by bicubic curve which is shown in Figure 3.
\[ L = aL_m + (1-a)L_m, \quad a = \begin{cases} \frac{1 - \left( \frac{x}{l} \right)^3}{x_m} \left( \frac{x}{l} \right) \leq x_m \\ \frac{1}{(1-x_m)^3} \left[ 1 - \left( \frac{x}{l} \right) \right] > x_m \end{cases} \]

(1)

Table 2. Initial value and variation range of design variable.

| Design variable | Initial value | Variable range |
|-----------------|--------------|----------------|
| \( L_l / \text{mm} \) | 205          | 195 ~ 220       |
| \( x_m \)      | 0.5          | 0.3 ~ 0.8       |

The time-average power coefficient in a rotation period and the standard deviation \( \sigma \) of \( C_p \) in a rotation period were selected as objective functions. The standard deviation \( \sigma \) represents the stability of the energy output of the turbine. And the \( \overline{C_p} \) represents the energy conversion efficiency of the turbine. Their equations are shown as follows:

\[ C_p = \frac{M \omega}{0.5 \rho A_s V_\infty^2}, \quad \overline{C_p} = \frac{1}{T} \int_{0}^{T} C_p \, dt, \quad \sigma = \frac{\sum_{i=1}^{n}(C_{p,i} - \overline{C_p})^2}{n-1} \]

where \( M \) is the torque of the runner, \( \omega \) is the angular velocity of the runner, \( \rho \) is the density of the water, \( A_s \) is the sweep area of the turbine runner, \( V_\infty \) is the upstream far-field velocity, \( T \) is the time of a rotation cycle of the turbine, \( C_p \) is the power coefficient of turbine, \( C_{p,i} \) is the value of \( C_p \) at the \( i \)th sampling time, \( n \) is the total number of sample points taken in the calculation of \( \sigma \).

The optimization of the shrinkage curve AB was carried out only for the condition which tip speed ratio is 2.5. The mathematical description of the optimization problem is shown as follows:

\[
\begin{aligned}
\text{max} \: & \overline{C_p}(X), \quad \text{min} \: \sigma(X) \\
X = & (L_m, x_m)
\end{aligned}
\]

**Turbine Performance Simulation**

Simulations were carried out to obtain the performance of the turbine. The two-dimensional computational domain is shown as Figure 1. The entire domain was divided into two parts, which were stationary and rotating domain. Both of them were discretized by structured mesh as shown in Figure 4. The SST k-\( \omega \) turbulence model was applied in calculating the performance of turbine. And the upstream far-field velocity (\( V_\infty = 2.3 \text{ m/s} \)) was set at the inlet. The static pressure was set at the outlet. The wall was set to a non-slip wall. The transient numerical simulation was used to calculate the performance parameters of the turbine. The time step is equal to the time that the runner rotated 1° in transient calculation. In order to analyze the reliability of the two-dimensional numerical simulation, the transient numerical simulation of the initial duct-free Darrieus turbine was carried out under tip speed ratio is 2.5 condition. Figure 5 shows the comparison of the power coefficient between the experimental data and the simulation data in a rotation cycle.

![Figure 4. Local mesh of the domain with duct.](image)

![Figure 5. Comparison of simulation and experimental data of initial turbine.](image)

It can be seen from Figure 5 that the maximum value of \( C_p \) in the simulation is higher than that in experimental. Because the resistance torque of the arms which used for connecting the runner blade...
and the shaft were not considered in the simulation. However, the experimental data and numerical simulation data still have obvious similarity. So the numerical simulation method in this paper is reliable.

**Optimization Method and Results**

The optimization of the shrinkage curve of the duct is a multi-object optimization problem. Therefore, the particle swarm optimization algorithm was introduced to solve this problem. In order to reduce the time of the performance simulation of the turbine in the optimization, the Kriging response model was introduced to establish the response between the design variables and the objective function. Then it was used to replace the CFD calculation process in the optimization.

**Kriging Response Model**

To build the Kriging response model, at least $2n+1$ sample points must be selected in the design space, where $n$ represents the number of the design variables. In order to establish the Kriging response model with sufficient accuracy, the optimized Latin hypercube sampling method was used to selected the sample points in design space. Finally, a total number of 18 sample points were selected. And numerical simulation method described in section 4 was applied to obtained the objective functions which these sample points corresponding to. Then the response between the design variables and the objective function was established by Kriging response model. The response are shown in Figure 6.

![Figure 6. Kriging response between the design variables and the objective functions.](image)

The Sobol random sampling method was used to choose test sample points in the design space to calculate the correlation coefficient $R^2$, which is used as a standard to verify the prediction accuracy of the Kriging response model. When the value of $R^2$ is higher than 0.9, the response model has enough accuracy. The values of $R^2$ for the two objective functions in this paper were 0.98 and 0.95, respectively. Therefore, the established Kriging response model has enough accuracy to replace CFD calculation in optimization.

**Optimization Results**

The particle swarm optimization algorithm was selected as the algorithm to optimize the shrinkage curve of the duct. In the optimization, the inertia weight coefficient of the PSO algorithm was set to 0.9, the group size was set to 30, the individual optimal position learning factor was set to 0.9, the group optimal position learning factor was set to 0.9 and the maximum particle velocity was set to 0.2. After optimization, the objective functions of all the samples in the optimization process are shown in Figure 7. A solution that the two objective functions were balanced improved was selected as the final optimized solution. Then the optimized geometry of the duct can be compared with initial in Figure 8.
The performance comparison between the turbine with initial and optimized duct was carried out by the CFD method. The condition of tip speed ratio equal to 2.5 was selected as the simulation condition. The comparison of the design variables and objective functions between initial value and optimized value are shown in the Table 3.

Table 3. Comparison of the design variables and objective functions between initial value and optimized value.

| Design variables | Initial | Optimized | Objective functions | Initial | Optimized | Degree of improve |
|------------------|---------|-----------|---------------------|---------|-----------|-------------------|
| $L_{D}$/mm       | 205     | 195.3     | $C_p$               | 1.5703  | 1.689     | ↑ 7.5%            |
| $x_m$            | 0.5     | 0.69      | $\sigma$            | 0.1758  | 0.1139    | ↓ 35.2%           |

It can be seen that the time-averaged power coefficient $C_p$ and the standard deviation $\sigma$ of $C_p$ have been improved. And the improvement of $\sigma$ is the most obvious, which indicates that the optimized duct improved the energy output stability of Darrieus turbine effectively. The comparison of $C_p$ in a rotation cycle is shown in Figure 9.

In Figure 9, the fluctuation range of the power coefficient are represented by $\Delta C_{pi}$ and $\Delta C_{po}$. The former represents the fluctuation range of the power coefficient before the duct optimization. And the later represents the fluctuation range of the power coefficient after optimization. The value of $\Delta C_{pi}$ is equal to 0.6459 and the $\Delta C_{po}$ is 0.4351 by calculation. It can be found that the fluctuation range of the power coefficient is reduced by 32.6% after the optimization, which indicates that the optimization of the duct geometry is effective.
Conclusion

1) The Kriging model was used to establish the response relationship between the design variables and the objective functions which reflecting the quality of energy output of turbine. It was combined with the multi-objective particle swarm algorithm to set up an automatic optimization method of the inner wall of the duct, which shortens the optimization period and improves the efficiency of the turbine.

2) By comparing the energy output characteristics between the initial and optimized ducted turbine, it can be found that the optimized duct effectively improves the stability of the Darrieus turbine's power coefficient and increases the energy output of the turbine.

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