Influence of airfoil trailing edge on blade design and machining of small wind turbine

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Abstract: In the design of small wind turbine, narrow structure is often produced at the trailing edge of airfoil, which brings great difficulties to production and processing. In this paper, the airfoil sd7080 is modified by removing part of the airfoil trailing edge to meet the processing technology. Through the calculation and analysis of the Q blade software, part of the airfoil trailing edge is removed, and the airfoil and wind-wheel aerodynamic characteristics are changed. Results: Under the same angle of attack, after removing part of the airfoil trailing edge, the lift coefficient $C_L$ and drag coefficient $C_d$ of the airfoil are reduced, $\alpha<8.6^\circ$, the lift-to-drag ratio $C_L/Cd$ decreases, $\alpha>8.6^\circ$, the lift-to-drag ratio $C_L/Cd$ slightly increases; After removing the trailing edge of some airfoils, the wind energy utilization coefficient $C_p$, torque and thrust of the wind turbine are slightly reduced, and the aerodynamic performance meets the use requirements. Finally, this paper introduces the blade modeling method, and processes the blade through 3D printing technology. The research provides reference significance for the initial design and processing of small wind turbine blades.

1. Introduction

Wind energy is generally recognized as one of the most promising renewable energy, and the design of its blades is critical to the acquisition of wind energy. Small wind turbines generate electricity mainly for buildings, which may or may not be connected to the grid, making them ideal for power systems in remote areas. For the design of small wind turbine blade domestic and foreign scholars have done a lot of research. Reference [1] a 2 kW small horizontal axis wind turbine was designed and analyzed with Q blade software, the results show that the airfoil SD7080 is the most suitable airfoil to generate high power at low wind speed. Reference [2-3] introduces the common design methods of wind turbine blades, and describes the three-dimensional modeling method of blade aerodynamic shape. Reference [4] design and analysis of wind turbine blade with Q blade and MATLAB tools, and verify that Q blade software can calculate wind turbine characteristics correctly. Reference [5] the airfoil was modified by thickening the trailing edge of the airfoil to meet the processing requirements of the blade, and the aerodynamic characteristics of the airfoil before and after the modification were analyzed. In reference [6] , the blade element momentum method is used to simulate the wind turbine, and various factors are considered in the design, and the variation trend of power coefficient with blade number and tip speed ratio is studied. A method for aerodynamic shape optimization of horizontal axis wind turbine based on torque matching between rotor and coupled generator is presented in reference [7] . Reference [8] a low Reno number airfoil is designed for a small horizontal
axis wind turbine to achieve better startup and low wind speed characteristics, the aerodynamic characteristics of the improved airfoil (AF300) are verified in an open-circuit wind tunnel.

There are many kinds of processing methods and materials for small wind turbine blades. Yellow shirt is a common material for small blades. The conventional processing method is to cut the blades from solid wood blocks. The longer blades are processed by vacuum pouring and resin transfer molding, but both methods require a die to be machined first. 3D printing is a rapid prototyping technology, which is very convenient for machining complex parts and parts with high-order curved surfaces, using 3D printing technology to process blades can save cost and time. In this paper, on the basis of previous studies, a small wind turbine is manufactured by 3D printing technology. It is found that the trailing edge of the airfoil is too thin to be processed normally, the main reason is that when the conventional 3D printing technology is used to process the parts, the thickness of the parts is greater than 0.2 mm so that the machining accuracy can be guaranteed, the thickness of the blade at the trailing edge of the airfoil is usually less than 0.14 mm. To solve this problem, the method of removing the trailing edge of some airfoils is used to make the designed blades meet the requirements of the machining process, the influence of the trailing edge of airfoil on the aerodynamic characteristics of airfoil and wind wheel is analyzed by using Q blade software.

2. Basic theory of blade design and analysis

The leaf element momentum theory is the most common way to describe the aerodynamics of a wind turbine blade and is found in many textbooks and books[9].

![Figure 1: Leaf element velocity at spanwise R](image)

![Figure 2: Velocity on the ring micro element swept by leaf element](image)

The leaf element theory divides a leaf into several leaf elements along its development. For a wind turbine with B blades, the thrust on the nth leaf element is:

\[
dT = \frac{1}{2} \rho U_1^2 C_L (C_m - C_d) d\phi
\]

In the formula, the effective velocity, \( \rho \) air density, \( CL \) airfoil lift coefficient, \( c \) airfoil chord length and \( Cd \) airfoil drag coefficient of \( UT \) acting on the blade element are calculated. The torque caused by the circumferential force is:

\[
dQ = \frac{1}{2} \rho U_1^2 C_L (C_m - C_d) \Omega d\phi
\]

Momentum theory, in terms of conservation of momentum and Conservation of angular momentum, calculates the thrust and torque on a ring of tiny elements coincident with the lutein. The total resultant forces acting on the nth lutein are:

\[
dT = 4\pi \rho U_1^2 a(1-a) d\phi
\]

In the formula, the a axis inducer, \( A = 1-U_1/U_0 \), \( U_0 \) wind speed upwind, \( U_1 \) blade wind speed, so the larger the value of \( a \), the wind through the blade, the greater the speed reduction. The torques acting on the ring lutein are:

\[
dQ = 4\pi \rho U_1^2 (1-a) \Omega r^3 d\phi
\]

In the formula, \( B \) rotation inducer, \( \phi \) blade angular velocity
The usual revision to the lutein-momentum theory is the “Ludwig Prandtl Tip Loss Factor”\( f \). The simple form of tip loss factor \( F \) is:

\[
F = 2 \cos^{-1}\left(\frac{e^{-i}}{\pi}\right) / \pi
\]

\[
f = B(R - r) / (2r \sin \phi)
\]

Taking into account the Ludwig Prandtl Tip Loss Factor \( F \), the parallel formulas (1) and 3), (2) and (4) can be derived:

\[
\frac{(1-a^2)\alpha F}{(1-a^2)^2} = \frac{BCC \cos \phi}{8 \pi r \sin^2 \phi}
\]

\[
bF = \frac{BCC}{(1+b)} \frac{8 \pi r \cos \phi}{8 \pi r \cos \phi}
\]

\[
a(1-a^2) = b(b+1)\lambda^2
\]

By using formula (7), the \( C_i \) formula (10) for the chord length of the blade element section airfoil can be obtained, and the dip angle \( \phi \) formula (11) for the blade element section airfoil can be obtained by simultaneous (7) and (8). The results are as follows:

\[
C_i = \frac{(1-a^2)\alpha F}{(1-a^2)^2} \times \frac{8 \pi r \sin^2 \phi}{BC_u \cos \phi}
\]

\[
\tan \phi = \frac{bF}{(1+b)} \times \frac{(1-a^2)^2}{(1-a^2)\alpha F}
\]

When the airfoil, tip speed ratio and radius of blade are determined, the available formulas (10) and (11) can be used to calculate the chord length and inclination angle of each section airfoil.

3. Aerodynamic design

3.1. Wind-wheel diameter and tip speed ratio

Wilson model is usually used in blade design. Wilson model is the basic application of blade element momentum theory, so this paper also uses Wilson model to calculate blade aerodynamic configuration parameters. The wind wheel diameter \( D \) through formula (12) is determined. Wind turbines are assumed to operate at wind speeds of 5 ~ 8 m/s, temperatures of 15 °, air density \( \rho = 1.1162 \), viscosity \( \mu = 1.81 \times 10^{-5} \). In the initial design, the rated wind speed is \( U_0 = 10 \text{m/s} \), the wind energy utilization coefficient is \( CP = 0.48 \), the rated power is \( P_n = 1 \text{kw} \), and the wind turbine efficiency is \( \eta = 0.75 \). The tip speed ratio \( \lambda \) of high speed wind turbine is 6 ~ 8. In this paper, the tip speed ratio \( \lambda \) is 6.3.

\[
D = \sqrt{\frac{8P_n}{C_p \rho U_0^2 \pi \eta}}
\]

In the formula, \( CP \) wind energy utilization factor, \( P_n \) rated power, \( D \) wind wheel diameter, \( \rho \) air density, \( U_0 \) rated wind speed, \( \eta \) wind turbine efficiency.

3.2. Airfoil selection

Small wind turbines usually operate at low wind speeds and low Reynolds numbers. It is important to choose an airfoil with good aerodynamic characteristics at low wind speeds and low Reno numbers. In reference [1], the author calculated the aerodynamic characteristics of 10 airfoils, and the results showed that the airfoil SD7080 had the best wind energy utilization ratio at low wind speed and low Reynolds number. Based on the experience of predecessors, this paper selects the airfoil SD7080 as the airfoil design. Q Blade is an open source wind turbine computing software based on XFOIL tool, which can quickly and conveniently calculate the aerodynamic characteristics of airfoils and wind-wheels. In order to calculate the aerodynamic characteristics of the airfoil, the Reno number must be determined, and the Re can be calculated by the following equation (13)[10]. The chord length of the airfoil at the tip of a small wind turbine blade is generally between 0.03 m and 0.1 m, so in normal
operation, the Reno number is between $1 \times 10^5$~$4 \times 10^5$. The optimum angle of attack $\alpha = 6^\circ$, $\alpha = 6^\circ$ corresponding to $CL = 0.9235$ is obtained by calculating the aerodynamic characteristics of SD7080 airfoil under the condition of Reno number $Re = 1 \times 10^5$ with Q Blade Software.

$$Re = \frac{\rho U r C}{\mu}$$  \hspace{1cm} (13)

In the formula, the chord length of C blade tip airfoil
To sum up, the wind turbine blade specific design parameters as shown in Table 1

| Name                              | Parameters | Name                              | Parameters |
|-----------------------------------|------------|-----------------------------------|------------|
| Radius R of wind wheel R          | 1.2m       | Selected angle of attack Alpha    | 6°         |
| Radius of Root Circle $r_h$       | 0.012m     | Lift coefficient CL               | 0.9235     |
| Tip speed ratio $\lambda$         | 6.3        | Airfoil type                      | SD7080     |
| Nominal wind speed $U_0$          | 10m/s      |                                   |            |

### 3.3. Calculation of aerodynamic configuration parameters of blade

(1) divide the blade into 15 parts and calculate the speed ratio of each section. The ratio of the circumference of the radius $R$ of the first cross-section is:

$$\lambda_i = \frac{\lambda \times \frac{R}{r}}{R}$$  \hspace{1cm} (14)

(2) to solve the following conditional extremum problem by fmincon function in MATLAB tool:

$$\max : \frac{dC_p}{d\lambda_i} = \frac{8}{\lambda_i^2} h_i(1-a_i)F_i\lambda_i^3$$  \hspace{1cm} (15)

$$s.t. a_i(1-a_i)F_i = h_i(1+b_i)\lambda_i$$  \hspace{1cm} (16)

Through a series of iterative calculations, the axial inducer $AI$, tangential inducer $bi$ and tip loss coefficient $Fi$ corresponding to the maximum value of the first blade element wind energy utilization coefficient $CP$ were obtained.

(3) the chord length and twist angle of each section airfoil are calculated by using equations (10) and (11) in MATLAB. The results are shown in Table 2:

| Radius $r$ | Chord length $c$ | Angle $\theta$ | Radius $r$ | Chord length $c$ | Angle $\theta$ |
|------------|------------------|----------------|------------|------------------|----------------|
| 0.12       | 0.227            | 32.516         | 0.696      | 0.099            | 4.204          |
| 0.192      | 0.224            | 23.848         | 0.768      | 0.09             | 3.286          |
| 0.264      | 0.201            | 17.874         | 0.84       | 0.083            | 2.517          |
| 0.336      | 0.176            | 13.699         | 0.912      | 0.076            | 1.865          |
| 0.408      | 0.154            | 10.684         | 0.984      | 0.069            | 1.304          |
| 0.48       | 0.136            | 8.43           | 1.056      | 0.062            | 0.817          |
| 0.552      | 0.121            | 6.692          | 1.128      | 0.554            | 0.39           |
| 0.624      | 0.109            | 5.317          | 1.2        | 0.048            | 0.043          |

### 4.1. Comparative analysis of aerodynamic characteristics of airfoils

In this paper, the airfoil is modified by removing the tip of the trailing edge of the airfoil to meet the machining requirements, therefore, the trailing edge of airfoil is modified according to the minimum chord length of blade tip. The thickness of trailing edge of airfoil is changed to 0.2 mm, the result is as follows:
Using the Qblade software, the aerodynamic characteristics of the modified airfoils were simulated under the conditions of Re = 1 × 10^5, attack angle 0° ~ 20°, and the results are as shown in figures 4 and 5:

As can be seen from Fig. 4, the lift coefficient CL and drag coefficient Cd of the modified airfoil are lower than those of the original airfoil. The lift coefficient CL is almost constant in the range of 0° ~ 12°, and the drag coefficient Cd is almost the same as that of the original airfoil in the range of 0° ~ 8°, in the range of 8° ~ 20°, the decreasing range of drag coefficient increases gradually.

As can be seen from Fig. 5, compared with the original airfoil, the lift-drag ratio of the modified airfoil decreases in the range of 0° ~ 8.6°, but increases slightly in the range of 8.6° ~ 20°. Based on the analysis of the aerodynamic characteristics of airfoil, it is found that the airfoil has a good lift-drag ratio in a larger angle of attack when the angle of attack α = 6° is taken as the optimum angle of attack, and the corresponding CL = 0.9235 when the angle of attack α = 6° is taken as the modified airfoil, the optimum angle of attack α = 6.5° and corresponding CL = 0.9229. Therefore, when using the modified airfoil to design the blades, it is necessary to modify the design parameter α in Table 1 and recalculate the aerodynamic configuration parameters. The results are as shown in table 3:

| Radius r | Chord length c | Angle θ | Radius r | Chord length c | Angle θ |
|---------|----------------|---------|---------|----------------|---------|
| 0.12    | 0.227          | 32.016  | 0.696   | 0.099          | 3.704   |
| 0.192   | 0.224          | 23.348  | 0.768   | 0.09           | 2.786   |
| 0.264   | 0.201          | 17.374  | 0.84    | 0.083          | 2.017   |
4.2 Calculation of aerodynamic characteristics of wind turbine

After the above calculation and analysis, this paper designs two kinds of wind-wheels: 1. The wind-wheels designed with normal airfoil are marked as wind-wheels 1; 2. The wind-wheels designed with modified airfoil are marked as wind-wheels 2.

The wind energy utilization coefficient, torque coefficient and thrust coefficient of the wind-wheel under the conditions of $\rho = 1.1162$, $\mu = 1.81$ and $Re = 1 \times 10^5$ are calculated by Q blade software. The results are as follows:

| $\lambda$ | $C_P$ | $C_T$ | $C_D$ |
|----------|-------|-------|-------|
| 0.336    | 13.199| 0.912 | 0.076 |
| 0.408    | 10.184| 0.984 | 0.069 |
| 0.48     | 7.93  | 1.056 | 0.062 |
| 0.552    | 6.192 | 1.128 | 0.554 |
| 0.624    | 4.817 | 1.2   | 0.048 |

![Figure. 6 Variation of wind energy utilization coefficient with tip speed ratio](image)

As can be seen from Fig. 6, the wind energy utilization coefficient $CP$ of wind-wheel 1 and wind-wheel 2 changes in the same trend. The wind energy utilization coefficient is best at the design blade tip speed ratio $\lambda = 6.3$, and drops sharply as $\lambda$ is far away from the design blade tip speed ratio, this trend is consistent with the Wilson design approach. On the whole, the wind energy utilization coefficient $CP$ of wind-wheel 2 is slightly lower than that of wind-wheel 1, and the maximum $CP$ of wind-wheel 1 and wind-wheel 2 are both higher than 0.45. Both of them can meet the application requirements.

5. Blade modeling and machining

The original coordinates $(x, y)$ of the airfoil SD7080 are obtained by Profili software, and the aerodynamic center of the airfoil is taken as the length of C/4 chord, and the origin is $(C/4, 0)$, the actual coordinates of the airfoil $(x_i, y_i)$ are calculated according to the actual chord length $C'$ of each section airfoil.

$$ (x_i, y_i) = [(x, y)-(C/4, 0)]C'/C $$  \hspace{2cm} (17)

The actual space coordinates $(x, y, z)$ of the airfoils with various cross sections can be obtained by rotating the torsion angle $\theta$ of the airfoils $(x_i, y_i)$[11-12],

$$ x = x_i \cos \theta + y_i \sin \theta $$ \hspace{2cm} (18)

$$ y = -x_i \sin \theta + y_i \cos \theta $$ \hspace{2cm} (19)

$$ z = r $$ \hspace{2cm} (20)

The actual coordinates of the converted blade element section airfoil are saved to TXT text format. In the 3D modeling software, the blade element section airfoil curves are established by curve command. finally, the 3D model of the blade is established by lofting command. Save the blade model to STEP format and import it into a 3D printer to process the blade. The result is as follows:
6. Conclusion
This paper introduces the basic theory and steps of blade design for small-scale wind turbine. Considering the processing problem, the airfoil SD7080 is modified by removing part of the trailing edge of airfoil to meet the processing requirements, and the aerodynamic characteristics of airfoil are calculated and analyzed by using Q blade software. According to the aerodynamic characteristics of the modified airfoil, the aerodynamic shape parameters of the blades are recalculated, and the aerodynamic characteristics of the two wind-wheels are calculated and analyzed.

(1) when the trailing edge of the airfoil is removed, the lift coefficient and drag coefficient of the airfoil decrease in the range of 0 °~20 ° at the angle of attack. When the angle of attack $\alpha < 8.6 \,^\circ$, the lift-drag ratio decreases, and when the angle of attack $\alpha > 8.6 \,^\circ$, the lift-drag ratio increases slightly.

(2) Compared with the impeller designed by normal airfoil, the utilization coefficient of wind energy CP of the impeller designed by modified airfoil is slightly lower, but it can meet the application requirements.

(3) after removing part of the trailing edge of the airfoil, the designed blade can be successfully manufactured by 3D printing technology.

In conclusion, in order to save cost and time, the airfoil can be modified by removing the trailing edge of some airfoils in the early stage of wind turbine blade design and aerodynamic characteristics verification.

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