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Functional design of wind turbine airfoils based on roughness sensitivity characteristics①

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Abstract

To improve aerodynamic performance of wind turbine airfoils, the shape profile characteristic of the airfoil is investigated. Application of conformal transformation, one functional and integrated expression of wind turbine airfoils is presented. Using the boundary layer theory, the aerodynamic model with roughness of wind turbine airfoils is introduced by studying flow separation around the airfoil. Based on the shape expression and aerodynamic performance of airfoils, the function design of wind turbine airfoils is carried out that the maximum lift-drag ratio and low roughness sensitivity are designed objects. Three wind turbines airfoils with different thickness are gained which are used at tip part of blades. As an example, the aerodynamic performance of one designed airfoil with relative thickness of 15% is simulated in different conditions of clean surface, rough surface, laminar flow and turbulent flow. The comparison of aerodynamic performance between the designed airfoil and one popular NACA airfoil is completed which can verify the better performance of the designed airfoil and reliability of the designed method.

Key words: wind turbine airfoils, integrated expression, lift-drag ratio, roughness sensitivity, function design

0 Introduction

As an important component part of wind turbine blade, airfoils are mostly from aviation airfoils and special wind turbine airfoils. The aviation airfoils mainly include NACA230 series, NACA44 series, NACA63-2 series and FX series[1,2]. And the special wind turbine airfoils are developed on the basis of the aviation airfoils, such as NREL S series from Renewable Energy Laboratory in the United States, Riø series from Denmark, FFA-W series from Sweden, DU series from the Netherlands and so on[3,4].

The existing expression method of airfoil profile is described by many discrete points that is difficult to ensure the smoothness of airfoil surface and good aerodynamic performance of airfoils. And the currently designed methods of airfoils are always chosen by changing the local coordinates of original airfoil to get new airfoils with better performance[5,6]. In this paper, the profile feature and expression method of airfoils are discussed firstly. Then to improve the design efficiency of new wind turbine airfoils, a new functional design method is presented that the design objects are maximum lift-drag ratio and low roughness sensitivity.

1 Integrated expression of airfoil profiles

Based on Joukowsky transformation on airfoils, it is known that any airfoil profile can be expressed with a conformal mapping and an analytical function of a finite series of Fourier expansions. Following this idea, the shape expression of an airfoil will be constructed similarly using a conformal mapping and a Taylor series[7].

In general, any airfoil profile can be mapped to a near circle by the relation

$$\zeta = f(z) = z + a^2/z \quad (1)$$

where $a = c/4$, c is the chord length, ζ is the complex variable in the airfoil plane, and z is the one in the near circle plane[8].

The coordinates of z in the near circle plane can also be expressed as

$$z = a\exp(\varphi(\theta) + i\theta) \quad (2)$$

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where the real part of the exponential argument $\varphi(\theta)$ is expressed in a series of sine and cosine functions as

$$\begin{aligned}\varphi(\theta) &= a_1(1-\cos\theta) + b_1\sin\theta + a_2(1-\cos\theta)^2 \\ &+ b_2\sin^2\theta + \cdots + a_k(1-\cos\theta)^k \\ &+ b_k\sin^k\theta + \ldots \\ & \qquad k = 1,2,3,\cdots,n \end{aligned} \quad (3)$$

where $a_1, b_1, a_2, b_2, \cdots, a_k, b_k$ are the unknown coefficients determining the airfoil shape. From Eq. (3), it is noticed that $\varphi(0) = 0$. This point corresponds to the sharp trailing edge of the airfoil. The shape of the airfoil is determined combining Eqs(1) and (3).

2 Aerodynamic model of roughness of airfoil

The aerodynamic model of airfoil is always developed and solved using N-S (Navier—Stoke) equation based on the boundary layer theory. When the air flow turns around the airfoil surface, the surface pressure will go down from the stagnation point along the chordwise of the airfoil. After the air flow passes through the front part of the airfoil, the surface pressure will start increasing from the lowest point again.

The boundary layer equation of flow around airfoil surface is written as

$$\left.\begin{aligned}\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} &= 0 \\ \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} &= -\frac{1}{\rho}\frac{\partial p}{\partial x} + \upsilon\frac{\partial^2 u}{\partial y^2}\end{aligned}\right\} \quad (4)$$

where u is the velocity at x direction, v is the velocity at y direction, p is surface pressure; ρ is medium density.

At the surface of airfoil, it is known that $u = v = 0$, then Eq. (4) becomes

$$\frac{\mathrm{d}p}{\mathrm{d}x} = \mu\left(\frac{\partial^2 u}{\partial y^2}\right)_0 \quad (5)$$

From Eq. (5), it can be seen that the flow will start accelerating after acrossing the front stagnation point on the surface of airfoil, that is

$$\frac{\mathrm{d}p}{\mathrm{d}x} < 0,\ \frac{\partial^2 u}{\partial y^2} < 0 \quad (6)$$

And the curvature of velocity distribution is negative.

On the contrary, after the pressure on airfoil surface reaches the lowest point, that is

$$\frac{\mathrm{d}p}{\mathrm{d}x} > 0,\ \frac{\partial^2 u}{\partial y^2} > 0 \quad (7)$$

then the curvature of velocity distribution is positive.

At the point with the lowest pressure, these is

$$\frac{\mathrm{d}p}{\mathrm{d}x} = \mu\left(\frac{\partial^2 u}{\partial y^2}\right)_0 = 0 \quad (8)$$

At the moment, there is a turning point of velocity distribution on the surface of airfoil. Then the turning point of velocity distribution will move along the y direction of the boundary layer. When

$$\left(\frac{\partial u}{\partial y}\right)_0 = 0 \quad (9)$$

that is the flow separation point.

In this paper, the fixed separation point on the upper surface of airfoil is chosen at 5% position from the leading edge. And similarly, the fixed separation point on the lower surface of airfoil is chosen at 10% position. Then the aerodynamic model with roughness of airfoil is carried out based on the separation model.

3 Shape optimization design of wind turbine airfoils

The optimization design of airfoil profiles is achieved by solving the function expression model using MATLAB. The design objects are maximum lift-drag ratio and low roughness sensitivity. As it is known that high roughness on an airfoil can cause earlier transition to turbulence, and keeping the airfoil shape smooth is essential in the optimization. From the previous sections, it was shown that the shape of an airfoil could be expressed analytically using the integrated expression, which also implies that analytical expression results in a smooth airfoil shape. The design variables here are the coefficients of Eq. (3) which are used to control the airfoil shapes.

In order to design airfoils, the basic structural features of the airfoil shape needs to be satisfied. The airfoil thickness-to-chord ratio is one of the most important parameters to determine the basic structure. Besides, the location of the maximum thickness is also important. The location of the maximum thickness is always controlled to be located between 20% and 40% of the airfoil chord, measured from the leading edge. Therefore, the constraint of the location of the maximum thickness is applied as

$$0.2 \leqslant x/c \leqslant 0.4 \quad (10)$$

The aerodynamic performance of airfoils is simulated using XFOIL[9] because of its fast running and accurate results. To save the optimization time and improve the solving efficiency, the expression equation of airfoil profiles and XFOIL are coupled to make the aerodynamic characteristics of airfoils and parameter control of airfoil profiles much more direct and convenient.

By solving the optimization model, three airfoils with different relative thickness 15%, 18% and 21% are obtained. The three airfoils are mainly applied at the tip part of the wind turbine blade to produce the greatest power of wind turbine, so the higher lift-drag ratio at the working angle of attack $\alpha \in [2°, 10°]$ is required during the optimization process.

The shapes of three design airfoils are shown and plotted in Fig. 1. It can be seen that the largest thickness of the three airfoils are all located at the 25% chordwise direction. The Reynolds number in this paper is chosen as $Re = 1.6 \times 10^6$ based on the actual working condition of wind turbine blades. Under this Reynolds number, the aerodynamic performances of design airfoils are simulated. The maximum lift coefficient of 15% airfoil is 1.86 at the angle of attack 18° and the maximum lift-drag ratio is 143.92 at the angle of attack 6.5°. Similarly, the maximum lift coefficient of 18% airfoil is 1.87 at the angle of attack 18° and the maximum lift-drag ratio is 150.09 at the angle of attack 5.5°. The maximum lift coefficient of 21% airfoil is 1.96 at the angle of attack 18° and the maximum lift-drag ratio is 130.10 at the angle of attack 6°.

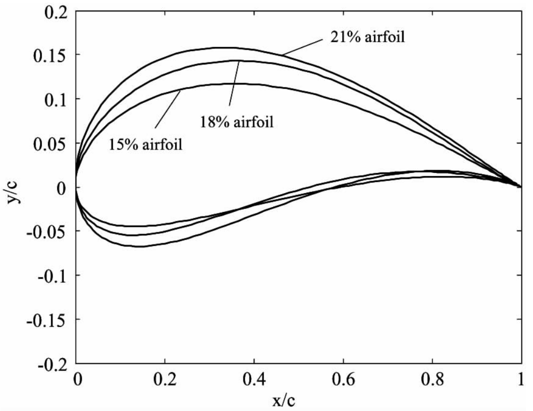

Fig. 1 The three design airfoils with different relative thickness

4 Roughness sensitivity performance of designed airfoils

To know the aerodynamic characteristics of designed airfoils, both airfoils with clean and rough surfaces should be selected and compared because roughness can influence the aerodynamic characteristics of airfoils. While the surface of airfoils is rough, the transition position on the boundary layer will go forward and the thickness of boundary layer will increase, then the maximum lift coefficient of airfoils is reduced. On the other hand, the roughness of airfoil surface can make the laminar flow on the boundary layer to be turbulent flow that the friction and resistance around the airfoil is going to increase. Therefore, the low roughness sensitivity is required during the design of new airfoils to gain higher output power of wind turbine rotors.

The aerodynamic model with roughness of airfoils is set up in which, the fixed separation point on the upper surface of airfoil is chosen at 5% position from the leading edge. And similarly, the fixed separation point on the lower surface of airfoil is chosen at 10% position. As an example, the design airfoils of relative thickness of 15% is selected, and the roughness sensitivity and aerodynamic characteristics of the airfoil is simulated at Reynolds number $Re = 1.6 \times 10^6$. The lift and drag coefficients of the airfoil with clean and rough surfaces are plotted and compared in Fig. 2 and Fig. 3. Obviously the aerodynamic performance of the design airfoil with clean surface is a little better than the design airfoil with rough surface.

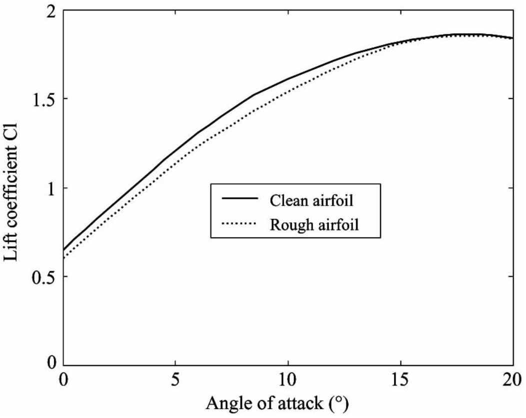

Fig. 2 Lift coefficient of design airfoil with clean and rough surface

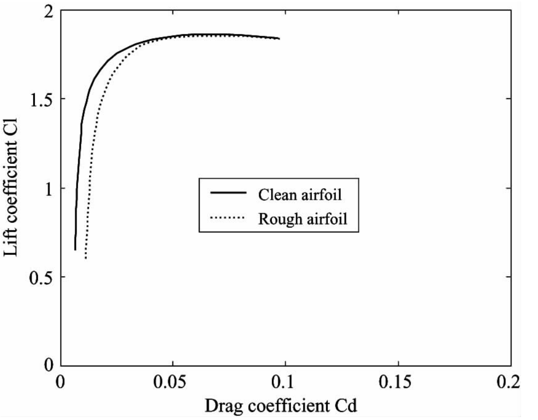

Fig. 3 Lift-drag chart of design airfoil with clean and rough surfaces

Besides the flow separation, the roughness of airfoil surface can also make the laminar flow on the boundary layer to be turbulent flow. The aerodynamic characteristics of design airfoils with turbulent flow is simulated using XFOIL which can control the transition condition of boundary layer. The lift coefficients and lift-drag ratios of the design airfoil in the condition of laminar and turbulent flow are plotted and compared in Fig. 4 and Fig. 5 at the same Reynolds number of $Re = 1.6 \times 10^6$. From Fig. 4, we can see that the lift coefficients basically remain unchanged between laminar flow and turbulent flow. And in Fig. 5, the maximum lift-drag ratio of the design airfoil is decreased from 143.92 to 116.76 because the turbulent flow on the boundary layer around the design airfoil makes the friction and resistance increased.

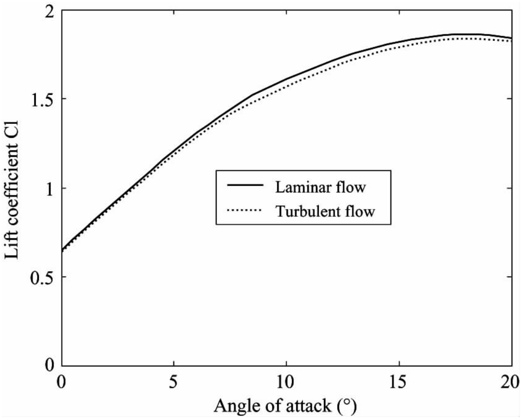

Fig. 4 Lift coefficient of design airfoil with laminar and turbulent flow

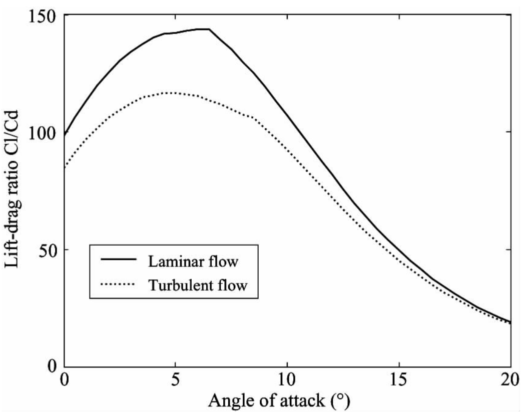

Fig. 5 Lift-drag ratio of design airfoil laminar and turbulent flow

In order to demonstrate the performance of the designed airfoils, a comparison is made between the design airfoils and one existing NACA wind turbine airfoil[10]. Fig. 6 shows the lift and drag coefficients of the design airfoil with relative thickness of 15% and the NACA 63215 airfoil at $Re = 1.09 \times 10^6$. From Fig. 6, it is seen that the lift coefficients of the design airfoil is much larger than NACA airfoil. And the drag coefficients are similar for both airfoils. Due to the higher lift coefficient of the design airfoil, the lift-drag ratio is also much higher than that of the NACA 63215 airfoil.

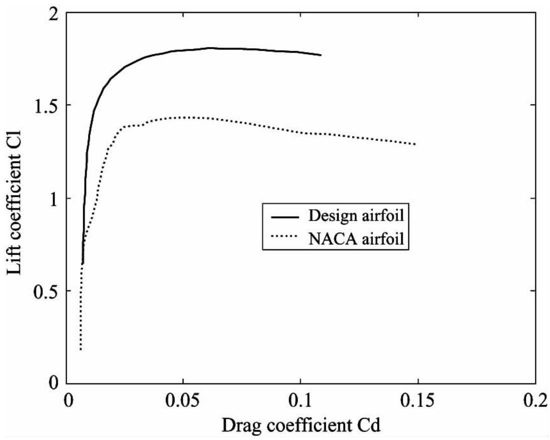

Fig. 6 Comparison of lift and drag coefficients between design airfoil and NACA airfoil

5 Conclusions

1) Based on the shape characteristics of wind turbine airfoil, the integrated expression equation for airfoil profile is presented. Using the boundary layer theory, the aerodynamic model with roughness of airfoil is carried out.

2) The optimization design model of airfoil is founded that the design objects are maximum lift-drag ratio and low roughness sensitivity. Three wind turbine airfoils with different relative thickness 15%, 18% and 21% are obtained.

3) The aerodynamic characteristics of the design 15% airfoil is simulated and compared in different conditions including clean surface, rough surface, laminar flow and turbulent flow. The research method and results concluded in this paper are very useful for the design of new wind turbine airfoils with high performance.

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