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Shape design and performance test for small wind turbine blade①

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Abstract

Based on the 1D-blade element momentum theory (BEM) with the improved tip loss correction introduced, a new aerodynamic model of wind turbine is developed. Using one high aerodynamic performance airfoil with 18% relative thickness, one small wind turbine blade is designed and the distribution of the chord and twist angle of the blade are determined. According to the shape parameters of the blade, a method to set up the 3D model is presented by investigating the coordinate position of each section of the blade. Based on the fiber reinforced polymer (FRP) molding technology, the manufacturing process of wind turbine blade is put forward. Using fiber reinforced polymer, the wind turbine blades are manufactured by the mold making and layer process. A test platform and method of wind turbine output power are carried out, the output powers at different speeds of the wind turbine are obtained and discussed. The comparison between the designed and one existing wind turbine rotor is completed to show the reliability and superiority of the design and test method presented in this paper.

Key words: wind turbine blade, aerodynamics, molding process, performance test

0 Introduction

Design and manufacture of blade is a very basic and important task for wind turbine rotors. Innovative research of design and manufacture methods for wind turbine blades and airfoils can not only increase wind power coefficient, but also improve operation reliability of wind turbine.

The design of small wind turbine blades is usually based on a single airfoil and the aerodynamic performance is mainly considered. Taking the maximum wind energy utilization as the target, the traditional aerodynamic theory of the wind turbine is applied to complete the design of blade[1-3]. However, the making method of small wind turbine blade is now mainly based on fiber composite materials. The manufacturing processes mainly include the hand lay-up molding, compression molding, prepreg molding, resin transfer molding and vacuum infusion molding. There are also a number of recently published papers dealing with the design of wind turbine airfoils and blades. Iva et al. [4] presented a design method for wind turbine thick airfoils based on a direct method using shape perturbation function. Two new airfoils with thickness to chord ratios of 30% and 36% are presented and the optimization algorithm is coupled with the viscous/inviscid flow solver XFOIL. Anand and James[5] presented an integrated approach to achieve system-optimal wind turbine designs using co-design, a design methodology that accounts directly for the synergistic coupling between physical and control system design. Salih et al. [6] presented a methodology to optimize the blade geometry for average wind speed of 5 m/s based on operational Reynolds number. And a prototype was built using 3D printer and tested in open air environment to validate the simulation results. In this paper, a new design method for wind turbine blade is described. Using one designed airfoil, a small wind turbine blade is designed and manufactured. The power of designed wind turbine rotor is tested and compared with one existing wind turbine rotor.

1 Shape design of the wind turbine airfoil

The wind turbine airfoil used in this paper is designed with an integrated design method[7]. The integrated design method is an optimization design method which includes an optimization process using the shape expression to represent the profiles of the airfoil. The

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shape expression of airfoil profile is one trigonometric function from the earlier Joukowsky transformation investigations on airfoils. The coefficients of the trigonometric expression are chosen as design variables to represent the shape of the airfoil. The lift-drag ratio, which is the main design objectives, is calculated using the fast and robust XFOIL.

The optimization design of airfoil profiles is achieved by solving the function expression model using Matlab. Airfoils with 0.18 thickness-chord ratios are used for constructing the outboard part of a wind turbine blade and play an important role for the output power. By solving the optimization model, one airfoil with max relative thickness of 18% is obtained. The designed airfoil is mainly applied at the tip part of wind turbine blade which produces the most 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.

Fig. 1 shows the shape of the A18 airfoil with thickness-chord ratio of 0.18. The location of the maximum thickness of this airfoil is at 0.25 chords from the leading edge. The airfoil has a maximum lift coefficient of 1.87 and a maximum lift-drag ratio of 150.09 at a Reynolds number $Re = 1.6 \times 10^6$. The maximum lift coefficient is found at an attack angle of about 18° and the maximum lift-drag ratio is located at an attack angle of about 5.5°.

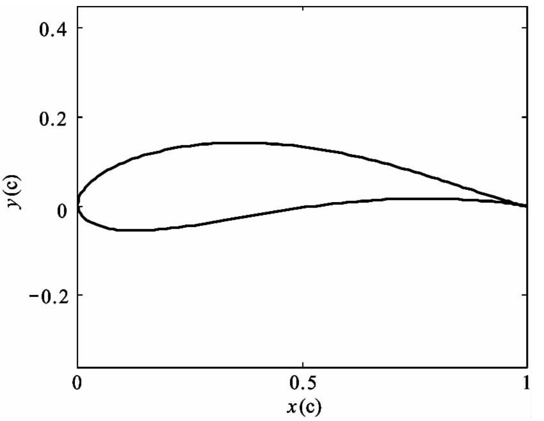

Fig. 1 The new designed airfoil with a thickness-chord ratio of 0.18

2 Design model of small wind turbine blade

To design the wind turbine blade, the basic parameters of the designed rotor are defined firstly. The power of small wind turbine rotor is designed as 2 kW at the rated wind speed of 9 m/s. And the tip speed ratio is determined as 7. Then the shape parameters of wind turbine blade are studied and carried out.

The shape of wind turbine blade is defined by the parameters of airfoil, chord and twist angle. The airfoil used for the designed blade is new A18 airfoil in last section. So another important thing is to determine the chord and twist angle distribution of blade that directly affects the efficiency of wind power.

The aerodynamic model used is based on the 1D-blade element momentum theory (BEM) with the improved tip loss correction, and the principal points are summarized[7-11].

Employing the momentum theory, the axial load and the torque are written as

$$dT = 4\pi\rho V_0^2 aF(1 - aF)rdr \tag{1}$$

$$dM = 4\pi\rho\Omega V_0 bF(1 - aF)r^3 dr \tag{2}$$

where, ρ is the air density; V_0 is the wind speed; a is the axial interference factor; Ω is the rotating speed of wind turbine rotor; b is the tangential interference factor and F is the Prandtl tip loss function given as

$$F = \frac{2}{\pi}\cos^{-1}\left[\exp\left(-\frac{B(R - r)}{2r\sin\phi}\right)\right] \tag{3}$$

Employing the blade element theory, the axial load and the torque are written as

$$dT = \frac{1}{2}B\rho cV_{rel}^2 F_1 C_n dr \tag{4}$$

$$dM = \frac{1}{2}B\rho cV_{rel}^2 F_1 C_t rdr \tag{5}$$

where, B is the number of blades; c is the chord of blade; V_{rel} is inflow wind speed; (C_n, C_t) are the 2D force coefficients and F_1 is the correlation between the 2D force coefficients and the 3D force coefficients on the blade. The F_1 function is given as

$$F_1 = \frac{2}{\pi}\cos^{-1}\left[\exp\left(-g\frac{B(R - r)}{2r\sin\phi}\right)\right] \tag{6}$$

$$g = \exp[-0.125(B\lambda - 21)] + 0.1 \tag{7}$$

where, R is the radius of the wind turbine rotor; λ is the tip speed ratio.

Equating Eq. (1) to Eq. (4), and Eq. (2) to Eq. (5), the final formulas of the interference factors become:

$$a = \frac{2 + Y_1 - \sqrt{4Y_1(1 - F) + Y_1^2}}{2(1 + FY_1)} \tag{8}$$

$$b = \frac{1}{(1 - aF)Y_2/(1 - a) - 1} \tag{9}$$

where, $Y_1 = 4F\sin^2\phi/(\sigma C_n F_1)$, $Y_2 = 4F\sin\phi\cos\phi/(\sigma C_t F_1)$ and $\sigma = Bc/(2\pi r)$.

By iterative solution of the aerodynamic model, interference factors a and b are both determined. Then the output power of the wind turbine rotor is

$$dP = 4\pi\rho\Omega^2 V_0 b(1 - a)r^3 dr \tag{10}$$

With the aerodynamic model, the load and power on each section of the blade can be calculated. The blade is divided in 35 sections from the blade bottom to tip. Through the iterative solution, the chord and twist angle distributions of all the 35 sections along the blade are gained. Fig. 2 shows the chord distribution of the designed wind turbine blade. It is seen that the maximum chord is 0.23 m at the 16% position close to the blade bottom. Fig. 3 shows the twist angle distribution of the designed wind turbine blade. It is seen that the change of the twist angle is very smoothl, and the largest twist angle is 12.4° at the bottom of the blade. The relative thickness of the deigned wind turbine blade remains unchanged as 18% from the starting point to the blade tip.

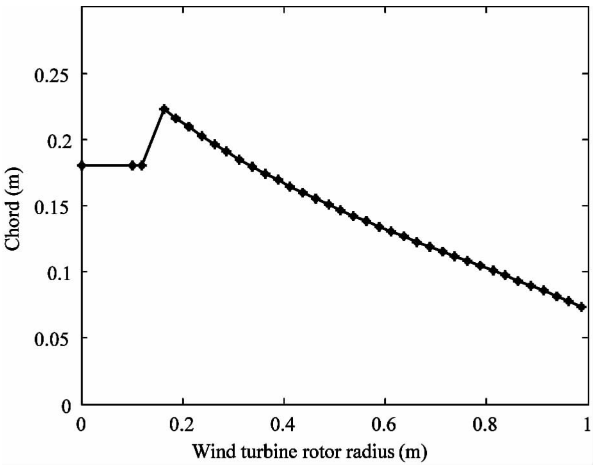

Fig. 2 Chord distribution of the designed blade

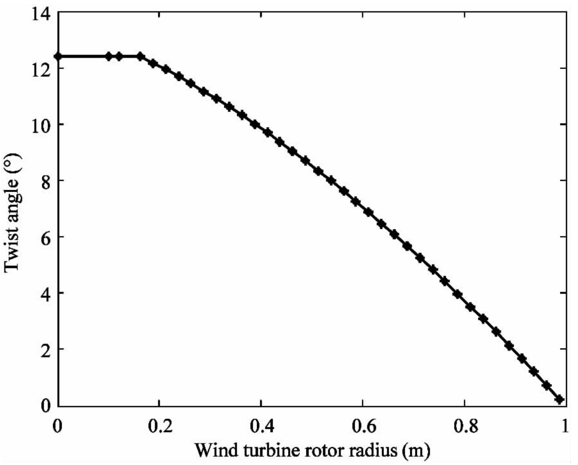

Fig. 3 Twist angle distribution of the designed blade

As an important performance parameter, the output power of the wind turbine rotor is simulated with the aerodynamic model. Fig. 4 shows the output power at the different wind speeds. When the wind speed is 9 m/s, the output power of the rotor is a rated power of 2 kW.

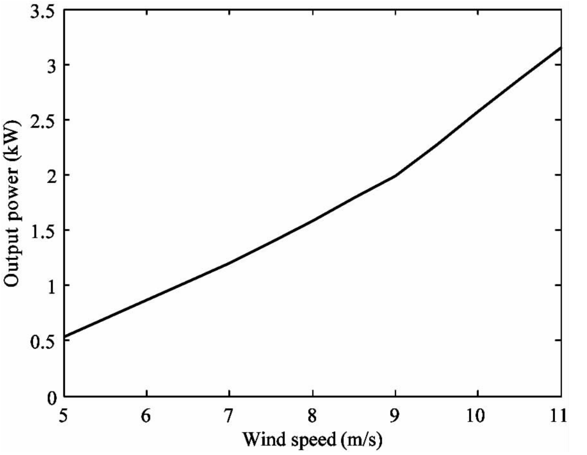

Fig. 4 The output power of designed wind turbine rotor at different wind speeds

3 Solid model of the wind turbine blade

The surface of wind turbine blade is complicated because not only the shapes of each section but also the twist angels of each section are different at the spanwise direction. It is very difficult to accurately express the geometric shape of the blade using the traditional two-dimensional three-view drawing method[12]. Therefore, studying the shape parameters of wind turbine blades is needed at x, y, z axis to finish the 3D model, and it is also the preparation for design and manufacture of the blades.

All coordinate data of the points on the airfoil as shown in Fig. 1 can be acquired and denoted by x_0, y_0. According to the shape of wind turbine blade, the actual center of each section is the aerodynamic center which is at 1/4 chord to the leading edge of airfoil, and the coordinate data of the aerodcynamic center is denoted by (X, Y). Then in the new frame of axes in which the aerodynamic center is defined as the origin of coordinate, the coordinate data of the airfoil can be expressed as

$$(x_1, y_1) = (x_0, y_0) - (X, Y) \tag{11}$$

Using the 2D coordinate data of airfoil, based on the chords and twist angles of blade, the actual coordinates for all the points on blade surface can be written as

$$\begin{cases} x = c \times \sqrt{x_1^2 + y_1^2} \times \cos(\arctan \dfrac{y_1}{x_1} + \theta) \\ y = c \times \sqrt{x_1^2 + y_1^2} \times \sin(\arctan \dfrac{y_1}{x_1} + \theta) \\ z = r \end{cases} \tag{12}$$

where c is the chord, θ is the twist angle of blade.

The coordinate data of each blade section can be calculated by Eq. (2). In this work, the coordinate data of all 12 sections are obtained from blade bottom to tip. Each section profile of the wind turbine blade is drawn by importing the coordinate data in SolidWorks as shown in Fig. 5. Based on all the section profiles, the 3D model of wind turbine blade is established by lofting method. The model of the blade is finished (Fig. 6) by a traditional structure supplement to blade root.

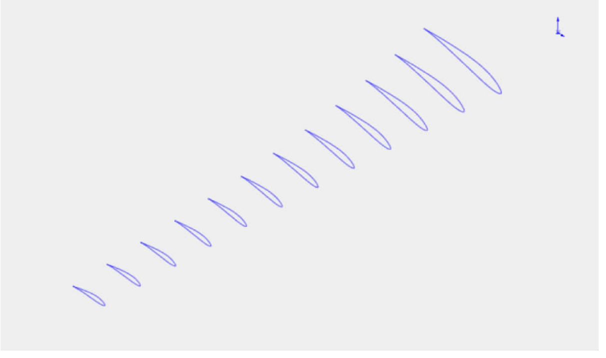

Fig. 5 Profile distribution of the blade sections

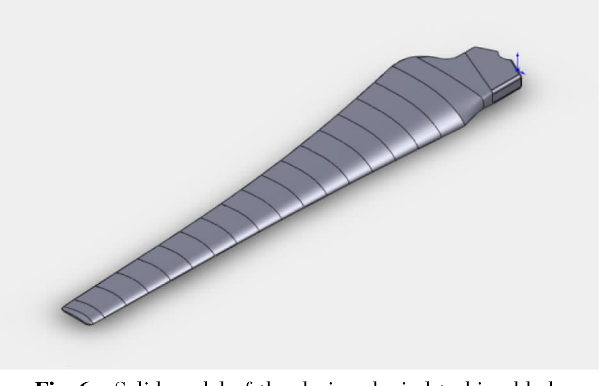

Fig. 6 Solid model of the designed wind turbine blade

4 Processing technology of wind turbine blades

As the main part of the wind turbine rotor, the blade should not only be affected by environmental factors such as sun and rain, but also bears the aeroelastic structural load caused by rotor rotation. Therefore, the fiber reinforced composites are generally used in the blade materials. Its advantages are high strength and small proportion, and it has good anti fatigue, shock resistance and creep resistance characteristics[13]. In this paper, the glass fiber composites are selected as the material of the blade model. The fiber reinforced polymer (FRP) moulding process is used to make the blade of the wind turbine. The main process is as follows.

Firstly, the blade prototype should be processed, which is the same as the blade shape, namely the so-called blade male mould.

Secondly, according to the male mould, the female mould should be made, which is opposite to the outside and the inside of the blade male mould.

Thirdly, the female mould will be used to complete the forming process of blades, and finally the blade which meets the design requirements will be made.

As the first step of blade making, the processing quality of the blade male mould determines the final accuracy of the blade. The traditional blade male mould materials are generally the materials that are easy to form, such as the wood, paraffin, or nylon. Nylon materials are used in this study because they are easier to be processed and cheaper.

There are many methods to make the blade male mould. In this paper, the mode of numerical control machining is adopted to make the blade male mould to ensure the processing precision. According to the three-dimensional model of the blade established in the previous section, the model is converted to IGS format in SolidWorks software. Then the IGS format blade model is imported into the Mastercam software. After importing, the coordinates in the Mastercam software should be adjusted to align with the machine coordinates, then the blade male mould is completed as shown in Fig. 7.

Fig. 7 The processed blade male mould

The finished blade male mould is divided into upper part and lower part by sheet metal to make the blade female mould. And finally, the blade female mould making is completed by applying the coating parting agent, placing glass fiber and using curing process of polyester resin on the surface of the blade male mould, as shown in Fig. 8.

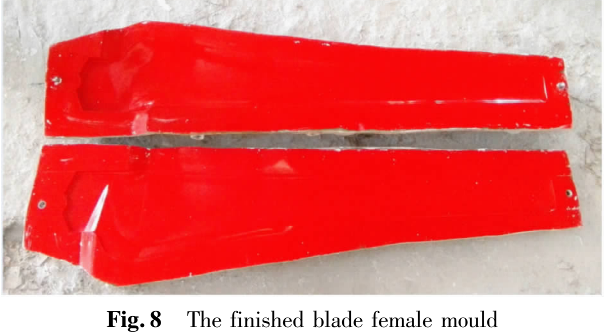

Fig. 8 The finished blade female mould

The coating of the glass fiber material is carried out on the upper and lower female moulds of the blade. After the upper and lower female moulds are all paved with glass fiber, the excess glass fiber materials on the edge of the female moulds are pruned. When the upper and lower female moulds are closed, they are fixed with the positioning bolt. After the material is fully solidified, the releasing operation is done for blade female mould. And finally, after the releasing operation, the production process of the blade is completed. The finished blade is shown in Fig. 9.

Fig. 9 The processed wind turbine blade

5 Performance test of the wind turbine rotor

According to the blade processing steps in the upper section, three same blades are processed to assemble the wind turbine rotor. As shown in Fig. 10, three blades should be distributed symmetrically and at an interval of 120 °. The tower height of the tested rotor is 4 m, the outdoor temperature is 19 ° (degree Celsius) and the air density is 1.226 kg/m^3.

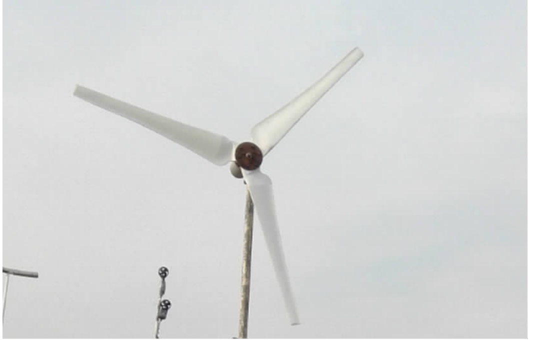

Fig. 10 Assembled wind turbine rotor

A test platform should be set up for the output power of the wind turbine. The principle is to test and control the wind speed of the natural wind first through the wind speed tester in order to ensure wind speed steady input. Secondly, the electric energy generated by the wind turbine passes through the three-phase rectifier bridge, and the voltmeter and ammeter are used to record the voltage and current output produced by the wind wheel. The measured current under different wind speeds multiplied by the voltage is the output power of the wind turbine rotor.

The output power of designed wind turbine rotor is measured at different wind speeds. The power-time change curves are shown from Fig. 11 to Fig. 14 at wind speed of 7 m/s, 8 m/s, 9 m/s and 10 m/s. It is seen that the change fluctuation of power is slightly obvious because of the instability inflow wind speed. Hence, to obtain more accurate testing results, the power data at several time regions are chosen and analyzed. The attained average output power at different wind speeds is shown in Table 1.

The rated wind speed of the designed rotor is 9 m/s, and the rated output power is 2 kW. Through the test, the output power of the assembled rotor is 1.87 kW at the rated wind speed of 9 m/s. The experiment test power is lower than that of the theoretical value by 6.5%,

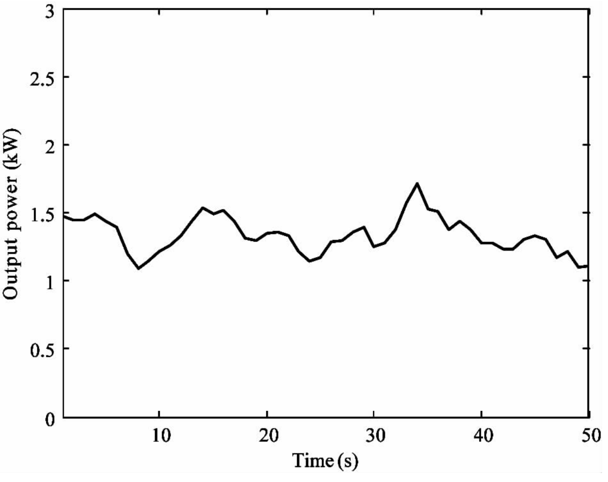

Fig. 11 Tested output power of designed wind turbine rotor at wind speed of 7 m/s

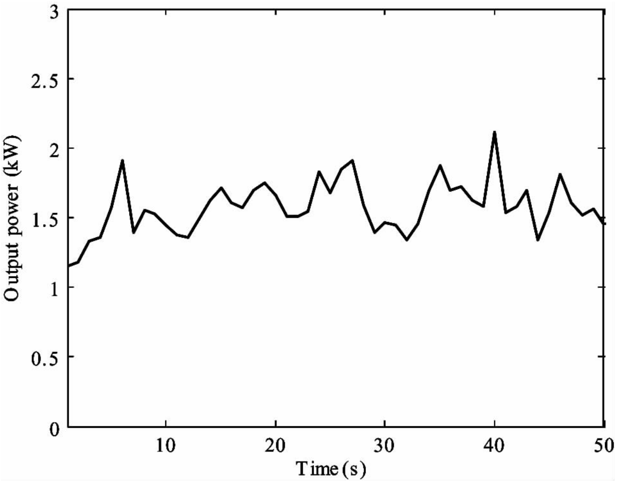

Fig. 12 Tested output power of designed wind turbine rotor at wind speed of 8 m/s

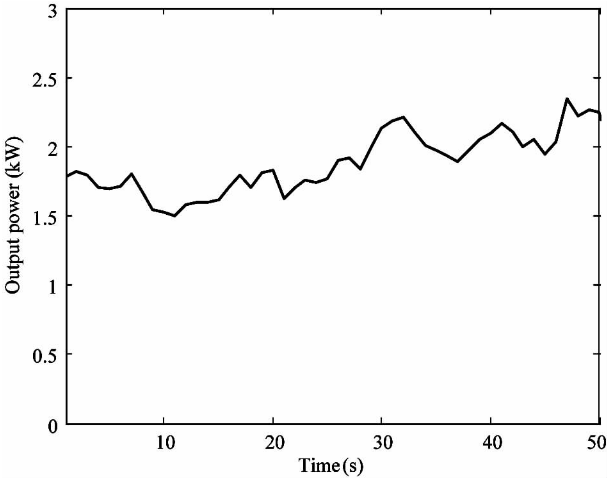

Fig. 13 Tested output power of designed wind turbine rotor at wind speed of 9 m/s

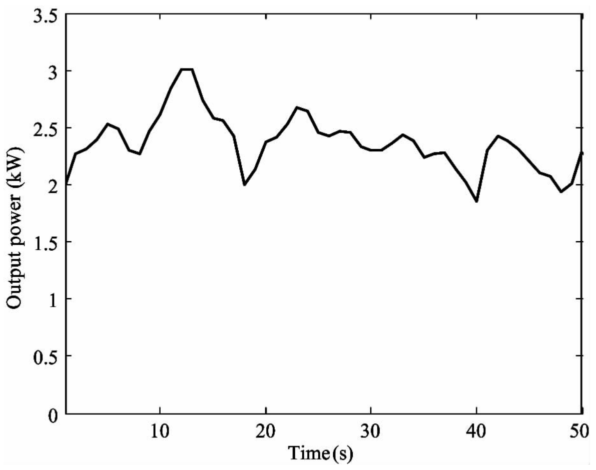

Fig. 14 Tested output power of designed wind turbine rotor at wind speed of 10 m/s

Table 1 Tested average power of designed wind turbine rotor

Average wind speed(m/s)	Average output power (W)	Number of data points
3.8998	330.1	65
4.7687	400.7	70
6.2878	984.3	68
7.2912	1335.8	75
8.2816	1592.1	70
9.0584	1882.8	68
10.1163	2281.7	75
11.0747	3259.2	72

which is mainly caused by the machining accuracy and the error during the test process.

In order to demonstrate the reliability of design method and results presented in this paper, a comparison of output power is carried out between designed rotor and one existing rotor that is widely used and accepted in the market. The rated power and diameter of the two compared rotors are the same, but the chords, twist angles and airfoils of the blades are all different. In Fig. 15, the comparisons of output power between two wind turbine rotors are shown. It is seen that the power of design wind turbine rotor is larger than that of the existing wind turbine rotor, especial at wind speed from 4 m/s to 8 m/s. At the rated wind speed of 9 m/s, the output power of design rotor is improved by 6.2%.

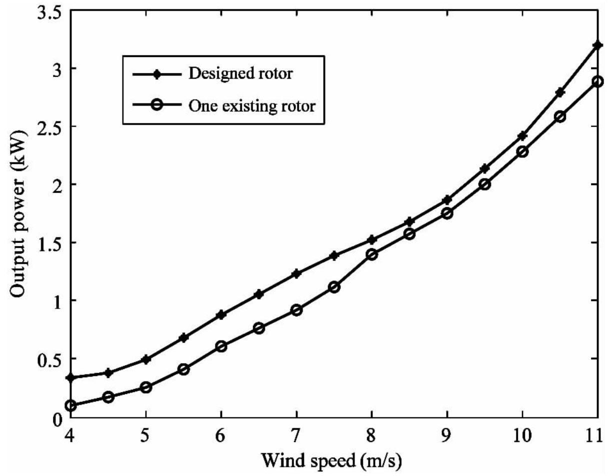

Fig. 15 Comparison of output power between designed and one existing wind turbine rotors

6 Conclusions

Using the trigonometric expression for airfoil profiles, a so-called integrated design method is developed for designing wind turbine airfoils. One airfoil with relative thickness 18% is designed and the performance is computed and compared with other popular airfoils. The airfoil has a maximum lift coefficient of 1.87 and a maximum lift-drag ratio of 150.09 at a Reynolds number $Re = 1.6 \times 10^6$. Based on the aerodynamic model presented in this paper, one 2 kW small wind turbine rotor is designed for testing using the 18% airfoil. The aerodynamic and structural characteristics of designed wind turbine rotor are calculated. The output power of designed wind turbine rotor is tested at different wind speeds. Compared with one existing 2 kW wind turbine rotor, the output power of design rotor is improved by 6.2% at the rated wind speed of 9 m/s.

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