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A Direct Approach of Design Optimization for Small Horizontal Axis Wind Turbine Blades

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Abstract

The performance of a wind turbine rotor depends on the wind characteristics of the site and the aerodynamic shape of the blades. The blade geometry determines the torque and the power generated by the rotor. From aerodynamic point of view, an economic and efficient blade design is attained by the maximization of rotor power coefficient. For small wind turbine blade design, there are some factors different from large blade. Such as, the small ones experience much lower Reynolds number flow than the large ones, thus large wind turbine airfoils may perform very poorly in small applications. The small turbines are self-started at lower wind speed, thus the hub and tip parts are vital for the starting-up torque which should be able to conquer the resistance of the generator and the mechanical system. This paper presents a direct method for small wind turbine blade design and optimization. A unique aerodynamic mathematical model was developed to obtain the optimal blade chord and twist angle distributions along the blade span. The airfoil profile analysis was integrated in this approach. The Reynolds number effects, tip and hub effects, and drag effects were all considered in the design optimization. The optimal chords and twist angles were provided with series of splines and points and three-dimensional blade models. This approach integrates blade design and airfoil analysis process, and enables seamless link with computational fluid dynamics analysis and CNC manufacturing.

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Keywords: Small wind turbine blade design; Blade Element Momentum theory; Optimization; Reynolds;Airfoil

Nomenclature

C_l	Lift coefficient
C_d	Drag coefficient
C_P	Power coefficient
C_r	Local chord in m
F	Tip-hub loss factor
F_l	Lift force
F_d	Drag force
F_N	Thrust force
F_T	Force of torque
R	Rotor radius in m
r	Local radius in m
φ	Relative angle of attack in rad
φ_r	Local relative angle of attack in rad
λ_r	Local tip speed ratio
U_{rel}	Relative wind speed in m/s
v	Kinematic viscosity of air in m²/s

1. Introduction

Wind energy is one of the most popular renewable energy resources all over the world. Wind turbine technology has gained great development over the last decades. The efficiency of the wind turbine blade determines the power performance of the wind turbine rotor. Wind turbine blade design optimization is generally a heuristic process, which cannot be finished in one single step. Iterations are needed for most cases. For the design optimization of a wind turbine blade, an aerodynamic criterion, such as maximum power coefficient, maximum annual energy production or minimum cost of energy is often considered as the objective. Until an optimal blade is obtained according to the criterion, the blade aerodynamic design task is finished. In wind turbine

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aerodynamics, it was reported by many researchers that the Blade Element Momentum (BEM) method [1; 2] is the most widely used and acceptably efficient approach for wind turbine blade design and analysis [3]. Maalawi [4] presented an approach to obtain the optimal relative angle of wind given a rotor diameter and rotor solidity. Vitale [5] developed a code to obtain the optimum blade shape for HAWT with optimum rotor power efficiency. The heuristic process of blade design based on the Blade Element Momentum theory was accelerated by involving advanced computing algorithms, such as evolutionary algorithm [6], etc. These methods showed advanced computing efficiency and reduced work load and rapid process of blade design. In the design of small blades, there are more factors to be considered, such as, the small wind turbines experience much lower Reynolds number flow than the large wind turbines, and the hub and tip area is vital for the starting-up torque which should be able to conquer the resistance of the system.

This paper presents a direct method for small wind turbine blade design and optimization. The airfoil profile optimization is integrated in this approach. A unique aerodynamic mathematical model was developed to obtain the optimal blade chord and twist angle distributions along the blade span. The Reynolds number effects, tip and hub effects, and drag effects were considered in the design optimization. The optimized chords and twist angles were then converted into series of splines and points. The three-dimensional blade surface and solid model were directly constructed from the output of the optimization process, which can be efficiently used in later computational fluid dynamics analysis and CNC manufacturing.

2. Aerodynamic principles of wind turbine

As the classical theory of wind turbine rotor aerodynamics, the BEM method (also known as Strip theory or Glauert/Wilson method) combines the Momentum theory and Blade Element theory. As shown in Fig.1 [2], the blade is divided into several sections and each section sweeps an annular area when the rotor rotates. These annuli are separated and no interaction between each other. In other words, the stream tube is decomposed along different radius positions and each annulus has its own momentum balance. By dividing the wind turbine blades into annular blade elements and applying one-dimensional linear momentum conservation to the annular elements, the forces and power are calculated and integrated based on the sectional airfoil lift and drag coefficients, the chords and twist angles of the blade geometry. The airfoil aerodynamic characteristic data i.e. the lift drag and moment coefficients are often obtained from wind tunnel measurements.

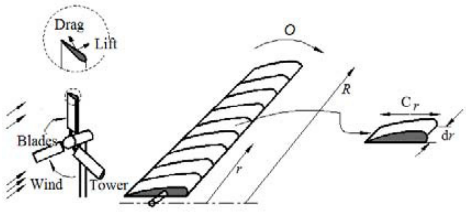


Fig.1. Blade element model

The lift and drag forces of a blade element are calculated by the lift and drag coefficients from wind tunnel test, which are defined as:

$$dF_L = \frac{1}{2} C_l \rho {U_{rel}}^2 c_r dr \tag{1}$$

$$dF_D = \frac{1}{2} C_d \rho {U_{rel}}^2 c_r dr \tag{2}$$

Then the forces in the flow direction F_N and perpendicular to the flow direction F_T are obtained:

$$dF_N = \frac{1}{2} Z \rho {U_{rel}}^2 (C_l \cos\varphi + C_d \sin\varphi) c_r dr \tag{3}$$

$$dF_T = \frac{1}{2} Z \rho {U_{rel}}^2 (C_l \sin\varphi - C_d \cos\varphi) c_r dr \tag{4}$$

This is a great development in the history of the wind turbine aerodynamics, which relates the blade geometry to power and thrust forces using lift and drag coefficients. It provides a principle to design optimal blade geometry.

3. Design optimization method

3.1. Mathematical model

According to the BEM method, the total power produced by a rotor was integrated from the root sections to the tip sections in the form of local speed ratio:

$$\begin{aligned} C_p = (8/\lambda^2) \int_{\lambda_h}^{\lambda} & F \sin^2\varphi (\cos\varphi - \lambda_r \sin\varphi) \\ & (\sin\varphi + \lambda_r \cos\varphi) \lambda_r^2 \left[1 - (\frac{C_l}{C_d}) \cot\varphi \right] d\lambda_r \end{aligned} \tag{5}$$

$$F = \left[2ar\cos(e^{-\frac{Z(R-r)}{2R\sin\varphi}}) / \pi \right] * \left[2ar\cos(e^{-\frac{Z(r-r_h)}{2r_h\sin\varphi}}) / \pi \right] \tag{6}$$

Here, the subscript r indicates local properties; the subscript h indicates hub properties.

In equation (5), if the C_P of each section along the blade span is maximized, as shown in equation (7), the maximum power coefficient of the whole blade is achieved.

$$\begin{aligned} & F \sin^2\varphi (\cos\varphi - \lambda_r \sin\varphi)(\sin\varphi + \lambda_r \cos\varphi) \lambda_r^2 \\ & \left[1 - (C_d/C_l) \cot\varphi \right] \to Max \end{aligned} \tag{7}$$

Ignoring the tip-hub loss and drag effect, i.e. F is equal to 1 and C_d / C_l is equal to zero, with the partial derivative being zero, the optimal blade chords and twist angles are obtained:

$$\varphi_r = (2/3) \tan^{-1}(1/\lambda_r) \tag{8}$$

$$\mathrm{C_r} = \frac{8\pi \mathrm{r}}{\mathrm{ZC_l}} (1 - \cos\varphi_\mathrm{r}) \tag{9}$$

To include the tip-hub loss and drag effects in the optimal blade design equations, a new strategy is introduced. Given a design tip speed ratio, an optimal blade is optimal at each section to have a maximum power coefficient. Thus, the axial and tangential induction factors (a and a') are optimal at these sections. According to this principle, if the optimal induction factors are solved to give a maximum C_P in power prediction equations including the tip-hub loss and drag effects, then the optimal blade sectional chord and twist angle can be calculated. Then the problem of searching for an optimal blade is converted to searching for the sectional optimal induction factors.

Since induction factors are within the range from 0 to 1, it is able to search optimal values towards maximum C_P using the Nonlinear Constrained Minimization Function in MATLAB. The axial induction factor and tangential induction factor are the two variables. The objective function is a minus power coefficient including tip-hub loss factor F.

$$Obj : Function = -C_{\mathrm{p}} = -(8/\lambda^2)\int_0^{\lambda} a'(1-a)\lambda_r^3 F d\lambda_r \quad (10)$$

$$NonLConstr : a'(a'+1)\lambda_r^2 = a(1-a)F \quad (11)$$

Then, the optimal blade chords and twist angles are obtained as equations from (12) to (14):

$$\varphi_{r,op} = \tan^{-1}\left[\frac{U(1-a_{op})}{\omega r(1+a'_{op})}\right] = \tan^{-1}\left[\frac{1-a_{\mathrm{op}}}{(1+a'_{op})\lambda_{op}}\right] \quad (12)$$

$$\theta_{r,op} = \varphi_{r,op} - \alpha_{op} \quad (13)$$

$$C_{r,op} = \frac{8\pi a_{op} F r(1-a_{,op}F)\sin^2\varphi_{r,op}}{N(1-a_{op})^2(C_l\cos\varphi_{r,op}+C_{\mathrm{d}}\sin\varphi_{r,op})} \quad (14)$$

Here, the subscript *op* represents the optimal value.

3.2. Airfoil analysis

Small wind turbines experience much lower Reynolds number flow than the large ones, for wind turbine blade design and analysis, it is essential to have the aerodynamic data of the selected airfoil at the corresponding flow conditions, i.e. Reynolds (*Re*) numbers. The Reynolds number is defined as:

$$\mathrm{Re} = \frac{U_{rel}c}{\upsilon} \quad (15)$$

For a rotor radius of 5m and TSR of 8, the Reynolds numbers of a typical 10kW wind turbine blade are tabled as following:

Table 1. *Re* numbers of a typical 10kW wind turbine blade.

Blade span position	0.1r	0.3r	0.5r	0.7r	1r
Chord length	0.5	0.3	0.2	0.15	0.1
Wind speed 5m/s	135000	243000	27000	283000	270000
Wind speed 8.5m/s	230000	4135000	459000	482000	459000

As shown in the Table 1, the Reynolds number is from 135,000 to 459,000 at the wind speeds from 5m/s to 8.5m/s. Due to the variation of the Reynolds number at different wind speeds and different blade span sections, the power coefficient is different at different wind speed with the same tip speed ratio. At the wind speed of 8.5m/s, the Reynolds number for the main part (0.3r/R to 1R) of the 5m blade varies from 4.13×10^5 to 4.82×10^5. These Reynolds numbers are much lower than large wind turbines (*Re*>2×10^6). To calculate the aerodynamic date at the corresponding Reynolds numbers, the airfoil analysis code XFOIL was integrated in the blade design code as shown in Fig.2. Providing basic parameters, i.e. the airfoil coordinate data, the Reynolds number and Mach number, the range and step of the angle of attack, the corresponding lift and drag coefficients were obtained. With this integrated airfoil analysis tool, airfoils can be customized in wind turbine applications.

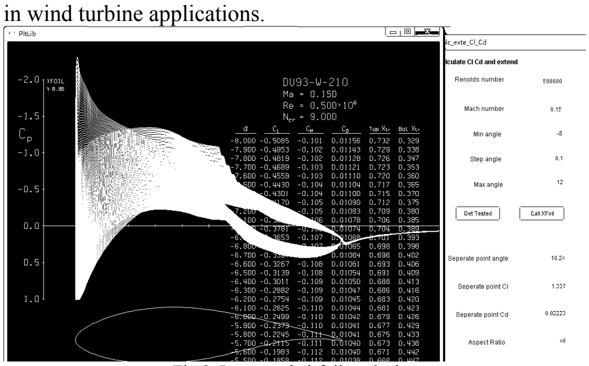


Fig.2. Integrated airfoil analysis

3.3. Workflow of design approach

The blade design flow chart is shown in Fig. 3. The fundamental rotor parameters of the wind turbine were defined in initialization and then the two optimal induction factors were calculated for each section by using nonlinear constrained minimization function. According to the equations from (12) to (14), the optimal chords and twist angles were obtained.

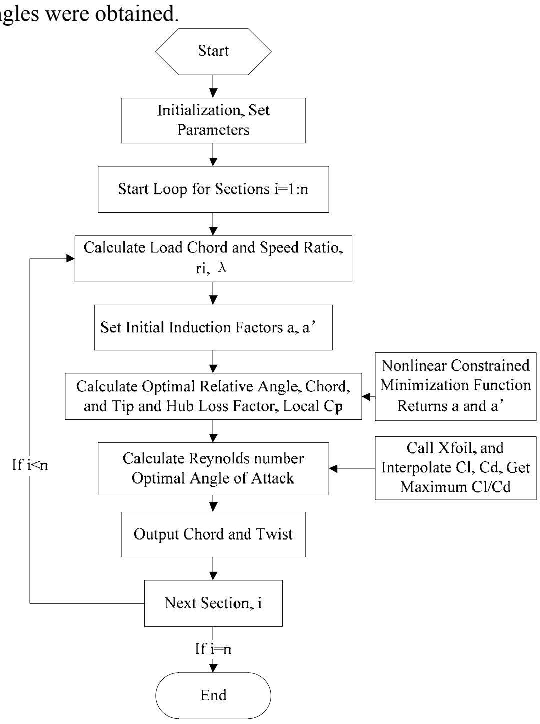


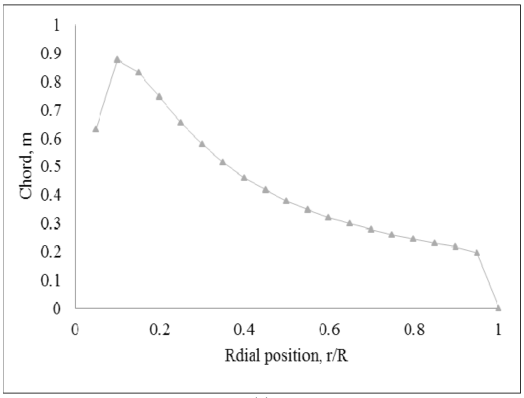
Fig. 3. Blade design flow chart

4. Results and discussion

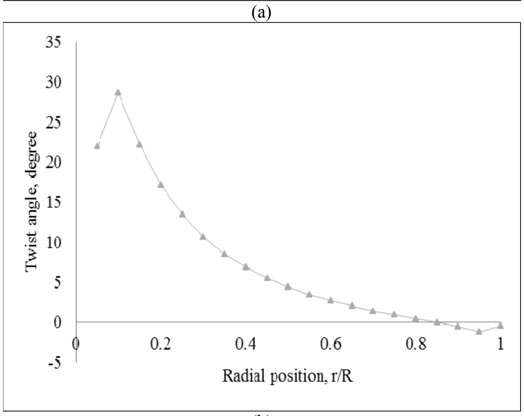
A case study for a 10kW wind turbine blade design was conducted. The results are presented and discussed below.

4.1. Chord and twist angle distributions along blade span

The optimal blade chord and twist angle distributions with the tip-hub loss and the drag effects are presented in Fig.4. Apparent changes of chord and twist angle distributions occur at the *0.05R* hub position, and *0.95R* and *1R* tip positions. The chord reduces gradually from location *0.95R* to *1R* when *F* and drag are considered. In some cases, the blade tip needs to be modified due to manufacturing limits. However, the chord and twist angle distributions of main part of the blade (from *0.15R* to *0.9R*) are almost in a smooth spline manner. These results reveal the tip-hub loss brings visible effect on both blade chord and twist angles at the hub and tip sections.



(a)

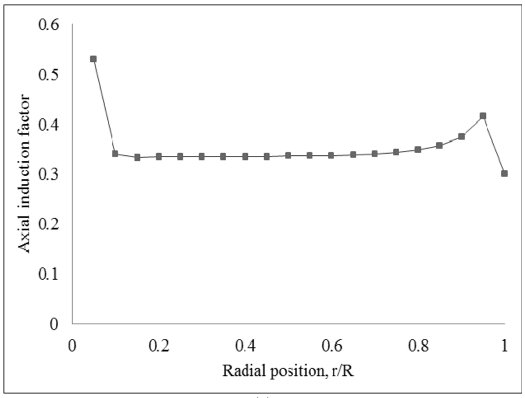


(b)

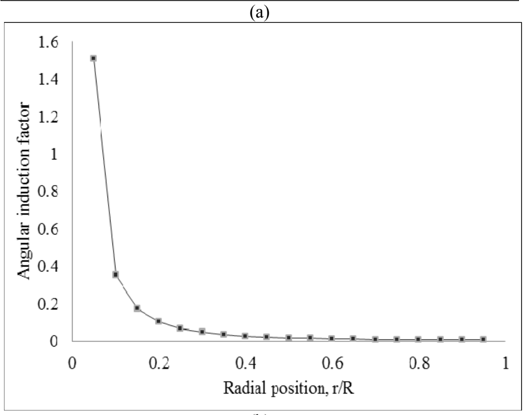
Fig.4. Blade chord and twist angle distributions

4.2. Axial induction and angular induction

Fig.5 and Fig.6 show the local optimum axial and angular induction factors of the blade. Without F and drag in the blade design, the optimum axial induction factor is almost constant along the blade span with an approximate value of 0.33 in standard BEM. Considering *F* and drag in the blade design, the optimum axial induction factor deviates from 0.33 at the hub and tip regions. And larger angular induction factor occurs at the hub region for the blade design with *F* and drag. It reveals that for maximum power coefficient design with *F* and drag consideration, the optimum axial induction factor does not necessarily remain constant at the theoretical value of 0.33.



(a)



(b)

Fig.5. Local axial induction factor (a) and angular induction factor (b)

4.3. Power coefficients

The power coefficient of each blade section was simultaneously calculated in the optimization process, thus a total rotor power coefficient was integrated. The power coefficient curve of the blade is plotted in Fig.6.

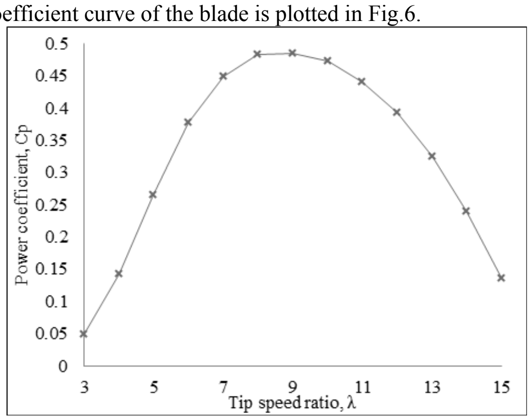


Fig.6. Power coefficient

4.4. Blade geometry construction and fluid analysis

The optimal chords and twist angles and airfoil profile were transferred into stacked section points and splines by coordinate transformation. Defining that the blade span is the *Z* direction, the blade section cross plane at the root positon is the *XOY* plane, the origin point is at the pressure center of the section airfoil, the coordinates of discrete points of each element airfoil are described as (x,y,z). Having the airfoil points (x_0,y_0), the coordinate transformation equations are described as following :

$$x = C_r \times \sqrt{x_0^2 + y_0^2} \times \cos\left(\arctan\frac{y_0}{x_0} + \theta_r\right) \tag{16}$$

$$y = C_r \times \sqrt{x_0^2 + y_0^2} \times \sin\left(\arctan\frac{y_0}{x_0} + \theta_r\right) \tag{17}$$

$$z = r \tag{18}$$

By importing the transferred section points or splines, an accurate parametric model of the blade was constructed in a general three dimensional CAD tool, as shown in Fig.7. For later fluid analysis and CNC cutting, the blade model can be exported into any neutral format, such as, .stl, .igs, .step, etc.

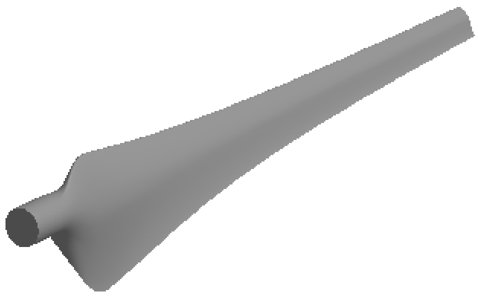
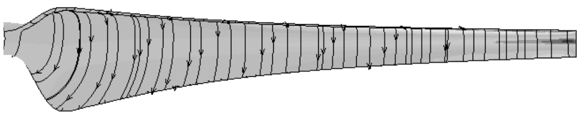
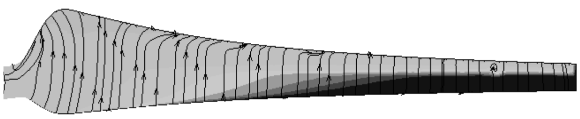


Fig.7. CAD parametric model of the blade

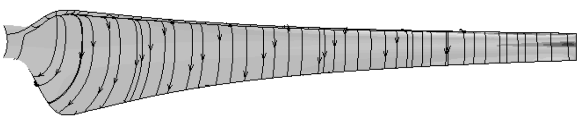
For this case, a detailed flow analysis was implemented in Fluent at the wind speeds of 8m/s, 10m/s and 12m/s. The surface flow streamlines of the blade pressure and suction sides are plotted in Fig.8.



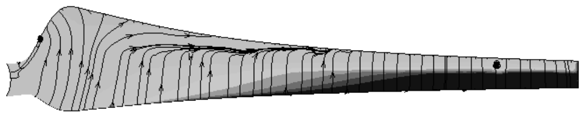
(a) Pressure side at 8m/s



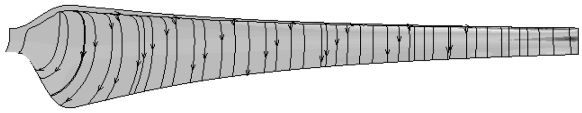
(a) Suction side at 8m/s



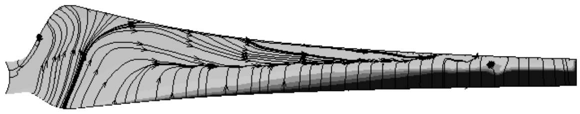
c) Pressure side at 10m/s



(d) Suction side at 10m/s



(e) Pressure side at 12m/s



(f) Suction side at 12m/s

Fig.8. Blade surface flow streamlines

5. Conclusions

A unique approach of searching optimal induction factors was developed to obtain the optimal blade chord and twist angle distributions in small wind turbine blade design. Blade performance evaluation with Reynolds number effect and the tip-hub loss effect was included in the design optimization. This approach integrates blade design and airfoil analysis process, provides optimal parametric blade design directly with series of splines or points or 3D solid models and enables seamless link with computational fluid dynamics analysis and CNC manufacturing. Further work will be undertaken in innovative design of small wind turbine blades with consideration of aerodynamics, structure and economics.

Acknowledgements

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