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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.

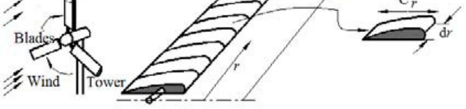

Fig.1. Blade element model

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:

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

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

Then the forces in the flow direction F$_N$ and perpendicular to the flow direction F$_T$ are obtained:

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

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

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:

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

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

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.

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

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:

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

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

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