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Aerodynamic shape optimization of non-straight small wind turbine blades

Xin Shen *, Hong Yang, Jinge Chen, Xiaocheng Zhu, Zhaohui Du

School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

Small wind turbines usually operate in sub-optimal wind conditions in order to satisfy the demand where it is needed. The aerodynamic performance of small horizontal axis wind turbines highly depends on the geometry. In the present study, the geometry of wind turbine blades are optimized not only in terms of the distribution of the chord and twist angle but also with 3-dimensional stacking line. As the blade with 3-dimensional stacking line is given sweep in the plan of rotation and dihedral in the plan containing the blade and rotor axis, the common used blade element momentum method can no longer provide accurate aerodynamic performance solution. A lifting surface method with free wake model is used as the aerodynamic model in the present work. The annual energy production and the starting performance are selected as optimization objective. The starting performance is evaluated based on blade element method. The optimization of the geometry of the non-straight wind turbine blades is carried out by using a micro-genetic algorithm. Results show that the wind turbine blades with properly designed 3-dimensional stacking line can increase the annual energy production and have a better starting behavior compared with 2-dimensional-optimized blade geometries.

1. Introduction

Most modern wind turbines are used for generating electricity for both large commercial wind turbines and small wind turbines. The basic design principles, such as maximum AEP and minimizing the cost of energy (COE), are the same for wind turbines of all sizes. On the other hand, there are operational issues that do depend on size; for example starting performance and cut-in speed, i.e. the lowest wind speed at which power can be extracted [1].

The working sites for large commercial wind turbines are usually specifically chosen to take advantage of high quality wind resources such as those that have a high average wind speed as well as small wind speed fluctuation throughout the year. On the other hand, small wind turbines are usually used as distributed power sources in individual homes, communities or by other users that cannot access an electricity grid and sometimes can only rely on wind power for generating their electricity. In such circumstances small wind turbines need to be able to work within a wider range of wind speeds. In many circumstance, small wind turbines could be much competitive with large wind turbines applying in distributed arrangement [2]. According to the performance analysis from previous similar studies Ozgener [3] and Al-Hadhrami [4], it is shown that the small wind turbines could be suitable tools for generating of electricity. Furthermore, the horizontal axis types of small wind turbines are demonstrated to be more efficient than vertical types of small wind turbines [4].

Unlike large wind turbines, small wind turbines often do not have a pitching control system meaning that it is not possible for small wind turbines to adjust blade pitch to suit wind conditions. In order to extract as much wind energy as possible, small wind turbines are often designed with a high tip-speed ratio that results in a large twist angle distribution along the blade in order to present high angles of attack when the rotor is stationary [1]. The high angle of attack along the blades, especially at the tip of the blade, makes it difficult to generate efficient torque to turn the blades. It is therefore important and difficult for small wind turbines to have both good starting behavior at low wind speeds and maximum AEP. Furthermore, there is increased interest in the study of blades with 3D stacking lines (swept and leaned blades) to improve aerodynamic efficiency, reduce the air-loads [5] and the noise of the rotor [6]. A wind turbine rotor blade, based on the U. S. National Renewable Energy Laboratory (NREL) 5 MW reference turbine, is optimized for minimum cost of energy through simultaneous consideration of aerodynamics and bend-twist coupling by Vesel and McNamara [5]. The authors noted that successive

* Corresponding author.
E-mail address: shenxin@sjtu.edu.cn (X. Shen).

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Nomenclature

a	axial induction factor
a'	tangential induction factor
c	chord
C_n	normal force coefficient
C_t	tangential force coefficient
I_{rotor}	rotational moment of inertia of the rotor
n	blade number
$\vec{r}$	position vector of vortex collocation point
r_h	hub radius
t	time
$T_{machine}$	resistive torque
T_{shaft}	aerodynamic torque generated
$\vec{V}$	velocity vector
$\vec{V}_B$	the induced velocity from blade
$\vec{V}_{FW}$	the induced velocity from far wake
$\vec{V}_{indv}$	induced velocity
$\vec{V}_{NW}$	the induced velocity from near wake
V_{rel}	relative velocity to airfoil
V_x	axial velocity
V_∞	free stream velocity
$\vec{w}$	the induced velocity on the blade
α_g	geometric angle of attack
α_e	effective angle of attack
Φ	flow angle
Γ	circulation
θ_P	blade tip pitch angle
ψ	azimuth angle
Ω	rotor rotational speed
ψ_b	blade azimuthal angle
ζ	vortex age

Abbreviations

AEP	annual energy production
BEM	blade element momentum
COE	cost of energy
HAWT	horizontal-axis wind turbine
MOEA	multi-objective evolutionary algorithm
NURBS	non-uniform rational basis spline
NREL	U.S. National Renewable Energy Laboratory

decreases in cost of energy were observed with the coupling of bend-twist. A winglet for a HAWT rotor blade is optimized by using CFD, GA and ANN for a selected wind speed range by Elfarra et al. [6]. The results showed that the winglet affected the flow characteristics by making it more attached at the tip.

An experimental study of the starting behavior of small wind turbines was made by Ebert and Wood [7] with a 5 m diameter, two-bladed small wind turbine. The observations showed that there are two main stages in the starting sequence of a 5 kW turbine. During the first stage, which was termed the 'idling' acceleration stage, the rotor accelerated slowly with large blade angles of attack. As the rotating velocity of the rotor increased the angles of attack of the blade decreased. During the second stage, the rotor accelerated rapidly to reach its operating rotating velocity.

Starting behavior was further studied by Mayer et al. [8] using a 5 kW small turbine platform with an adjustment of the pitching mechanism connecting the blades to the rotor hub. The research was focused on the relationship between the pitch angle of the blade and the starting behavior of the turbine. The results showed that with the increase of the pitch angle the 'idling' stage was shortened due to the decreasing of the angles of the attack of the blade.

Wright and Wood [9] studied the starting performance of a three-bladed, 2-m diameter HAWT via comparison of field tests measurements and calculations that employed a quasi-steady blade element analysis. The authors suggested that the blade near the hub provided most of the starting torque and that the torque for power production was generated near the tip of the blade.

Recently Pagnini et al. [10] tested the power production of two small-size commercial wind turbines. The authors noted that the overall energy production of the HAWT is higher than the VAWT. However the HAWT showed to be strongly affected by gust and large mean wind speed and direction fluctuations.

In literature there are three methods used in the analysis of the aerodynamic performance on horizontal axis wind turbines, the blade element momentum (BEM) theory, the vortex method and the computational fluid dynamics (CFD) methods.

Pourrajabian et al. [11] use BEM method as the aerodynamic model for the optimization of micro wind turbine blade with the objectives of both power coefficient and starting behavior at low wind speeds. Both starting time and the power coefficient of the rotor were included in the objective function. The results emphasized that the larger values of the chord and twist at the root part of the blades are indispensable for the better performance when the wind speed was low.

Sharifi and Nobari [12] developed a code based on BEM theory to predict the aerodynamics of wind turbine blades which can make possible the prediction of the best section pitch angle distribution for several sites. The BEM theory uses a simple two-dimensional analytical approach with analytical or empirical three-dimensional wake correction terms. This makes BEM theory unsuitable for the prediction of the aerodynamics of non-straight blades since this non-straight blade geometry violate some of the BEM 2D assumptions.

Vortex methods (such as lifting line and lifting surface method) represent the wind turbine blades as a series of bound vortices and trailing vortices. This capability provide flexibility that allows the vortex methods can handle 3D aerodynamic features or blade with non-straight geometry. The released root and tip vortices can be modelled with prescribed wake of free wake model. As the free wake methods do not require priori specification of the position of the vortex elements it is useful to predict transient loads and power output of wind turbine. A doubly fed induction generator (DFIG) based dynamic wind turbine model was developed by Liang et al. [13] to predict the dynamic behaviors of wind turbines both in mechanical and electrical parts. A lifting line method was used as the aerodynamic model.

CFD methods solve the full Navier–Stokes equations using standard numerical techniques for partial differential equations such as finite difference, finite volume of finite element methods. Sayed et al. [14] also used CFD method to study the aerodynamics of wind turbine airfoil to find the suitable airfoil for the wind conditions in Egypt. A full scale wind turbine unsteady aerodynamic simulations including effects of wind shear, tower shadow and yaw regulation were carried out using CFD numerical method by Cai et al. [15]. Although the CFD methods can provide more precision prediction results than both BEM and vortex methods, such methods require huge amount of computation resource. The capabilities of such methods have not yet been validated sufficiently to be assigned the confidence levels that are necessary for design purpose.