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A new aero-structural optimization method for wind turbine blades used in low wind speed areas

Han Yang*, Jin Chen, Xiaoping Pang, Gang Chen

State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing 400044, China

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ABSTRACT

The wind turbine blades used in lower quality wind resources have been recently designed. The designed blades for low wind speed areas are scaled version of blades used in high wind speed sites with longer blade lengths, same chord length and same airfoils series. A discrete optimization method for wind turbine blade used in low wind speed sites is proposed. In the optimization process, both aerodynamic and structural parameters are considered as design variables. The airfoil design is also considered in the optimization process to improve the aerodynamic and structural performance by the method of airfoil integrated theory. The Blade Element Momentum theory is used to evaluate the blade aerodynamic performance and the Classical Laminate Theory is used to estimate the stiffness and mass per unit of each blade section. Finally, a Finite Element Method structural analysis is used to verify the strength under the extreme loading conditions. To prove the efficiency and robustness of the design, a commercial 2.1 megawatt HAWT blade is used as a case study. The results show that the aerodynamic and structural performance of the new blade is improved compared with that of the original one.

1. Introduction

Wind energy is one of the most promising energy production technologies. With more and more wind turbines installed, the high-quality wind resources are few and far between. Compared to the high-quality wind resources, low wind speed areas have some advantages since they are closer to the urban electrical grid and easier to transport and install. The development of low wind speed wind turbines can enable wind power resources to be more geographically dispersed and reduce the variability of wind power generation [1]. Thus, there has been a big potential to develop the wind energy in the areas of lower quality wind resources. The wind turbines applied in high wind speed sites have progressively lost share in favor of that applied in low wind speed locations. The low wind speed turbines have been developed greatly since 2010 [2]. The increasing market penetration of wind turbines in low wind speed areas is consistent with the trend towards lower specific power. The low wind speed turbines are equipped with larger and slender rotors to balance the capital expenditures and the electricity output. For instance, the Asian wind energy market has been dominated by low wind speed turbines in the last decade mainly due to the lower quality wind resources in most places of China and India [2].

The modern wind turbines with megawatt scale have large volume, complex external shape and various composite materials configurations. The IEC 61400-1 standard [3] defined wind classes according to wind speed. Currently, the Classes III, II and I of wind turbines correspond to low, medium and high wind speed locations, respectively. In comparison with the wind turbines used in the Class I region, the design method for blade used in the Class III region always follows that of the wind turbine used in the Class I region. The wind turbines used in the Class III region usually have 130–140% blade length longer and the structural parameters of the blade such as blade geometry and structural lay-out are designed by increasing linearly from the baseline blade used in the Class I region. Thus, there are more challenges such as increased mass, larger deflections and aerodynamic loads. Although there are many researches [4–7] on aerodynamic performance of low wind speed turbines, they focus on small scale turbines. The studies on external shape for large scale low wind speed turbine blades are very few. The work in [8] focused on aerodynamic performance analysis and AEP enhancement of 3 MW wind turbine blade for low wind speed areas. In their work, the optimization objective is to improve AEP and to minimize the thrust based on blade element momentum theory, but the design variables of blade geometry are selected by existing wind turbine blade groups. The work in [9] proposed a method to quantitatively compare wind turbine operating in wind Class I and Class III. Their results showed that the traditional design method for low wind speed blade structures is not efficient.

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* Corresponding author.
E-mail address: yh098@126.com (H. Yang).

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Generally, most of the large scale wind turbine blades for low quality wind resources follow the baseline of the modern wind turbine blades used in the Class I region [10,11].

Currently, the design method for large scale wind turbine blade is separated in two stages, the aerodynamic performance design and structural performance design. In fact, the aerodynamic performance is affected by the external shape of a wind turbine blade and the structural performance by the internal configurations. Generally, the common design method is to design the external geometry aiming to maximize the power extraction first and then the structural efficiency. The aerodynamic and structural optimization methods have been proposed widely in several studies. Benini and Toffolo [12] proposed a method to optimize the wind turbine blade coupling the BEM Theory and a multi-objective evolutionary algorithm. Their purpose is to best trade-off between AEP (Annual Energy Production) and cost of energy. Xudong et al. [13] performed a blade optimization based on the BEM theory and an aero-elastic code to reduce the cost of energy. The design variables are the blade geometric parameters including chord, twist and thickness distribution with fixed rotor diameter. The structural optimization design for wind turbine blades should consider strength, stability, cost and vibration [14]. In general, the most common analysis method is FEM (Finite Element Method), which can easily modify the parameters such as materials properties, various layer thicknesses, fiber angle and even the blade internal shape configurations by using parametric modeling. One way to optimize wind turbine blades is to reduce its mass. A lighter blade will not only reduce the loads for whole wind turbine system, but also has economic benefits. Hu et al. [15] studied on structural optimization to reduce both material cost and blade weight. The study by Liao et al. [16] used the FAST software to estimate structural performance and combine particle swarm optimization (PSO) algorithm to reduce the blade mass. Cai et al. [17] combined the FEM and PSO algorithm to reduce the mass of 1.5 MW wind turbine blade. Very few researchers study on optimization method integrated aerodynamic and structural model. Zhu et al. [18] used BEM theory for aerodynamic analysis, FEM method for structural analysis and a multi-objective genetic algorithm to prove the efficiency of their optimization method. The objective was to maximize the AEP and minimize the mass of the blade. The design variables were chord and twist distribution, width of the spar cap, the number of layers in the spar cap, and the location of shear webs. Monte et al. [19] proposed an advanced design algorithm for the AOC 15/50 wind turbine. The design algorithm coupled BEM theory and FEM analysis. Both structural and aerodynamic performances were considered as the design variables. Most of the integrated aero-structural optimization method set the chord and twist distributions as the variables for aerodynamic optimization, and the internal configuration and layout of the blade composite skin as the variables for structural optimization.

The blades of low wind speed turbines are longer and slender to balance the capital expenditures and the electricity output. It is not appropriate that the design method for low wind speed turbine follows that for high wind speed sites. The design challenges are not fully equivalent for two wind speed areas. Compared to wind turbine blade in Wind Class I, the blade length is increased while the other dimensions remain the same for the blade used in low wind speed areas. The aerodynamic design challenge is to capture more energy from the lower average wind speed areas. For the structural design challenge, the structural stability and tip deflection should be met with design constraints. The objective of this study is to propose a method integrating aerodynamic and structural optimization for wind turbine blade used in low wind speed areas. In order to improve the aerodynamic and structural performance of the blade, the geometric shape and lay-up scheme are set as design variables. More essentially, introducing airfoil design into the optimization process could contribute more to both aerodynamic and structural performance. The purpose is to trade-off the design process to obtain the optimum overall performance of the blades focusing on the airfoils. Each airfoil of the blade section has strong impact on its aerodynamic and structural performances of the blade section. For this reason, the optimization focuses on each blade section. The main objective is to improve the aerodynamic (higher torque and lower thrust) and structural (higher stiffness and lower mass per unit) performance for each blade section. This paper studies on airfoils and blade sections design simultaneously including aerodynamic and structural integrated optimization.

Table 1
Baseline blade geometry.

Span location (m)	Chord (m)	Twist (°)	Airfoil	Thickness (%)
0	2.4	18	Circle	100
1	2.4	18	Circle	100
13.4	3.42	9.6	DU00-W2-401	40
16.2	3.17	6.9	DU00-W2-350	35
24.9	2.36	2.7	DU97-W-300	30
49.8	1.02	−1.56	DU91-W2-250	25
59.8	0.02	−1.6	DU93-W-210	21

2. Methods

2.1. Wind turbine blade model

A commercial 2.1 MW HAWT wind turbine blade for low wind speed areas is used for a case study. The length of the blade is 59.8 m and the mass of it is 13240 kg. The blade is made of glass fiber reinforced plastic (GFRP). The core materials consist of the balsa wood and PVC. The blade baseline is described by the chord distributions, twist distributions and selected airfoils distributions. Details of each parameter are shown in Tables 1 and 2.

2.1.1. Materials

The blade is made of glass fiber reinforced plastic (GFRP), consisting of leading/trailing edge reinforcement and panel sections, two shear webs and spar cap. The spar cap is made of unidirectional glass fiber composite materials to withstand the aerodynamic loads on flap-wise. The shear webs are composed of sandwich panels to withstand the aerodynamic loads on edge-wise. The core materials comprise of glass fiber composite materials with balsa wood and PVC. The properties of materials are listed in Table 3.

2.1.2. Original blade layup schedule

Fig. 1 shows the distribution of the layup layers along the blade axis. The first two meters of span are circumferential reinforcement for blade root. The main material for this section is triaxial composite materials with large layers. The first thirteen meters of span are inner and outer surface reinforcement for blade root. Sections outboard of 5 m have thick caps and trailing edge layup by UD materials. The airfoil with thickness of 40% is set at the blade span location 13.4 m. The energy production by the sections inboard of the 13.4 m (location of airfoil with 40% thickness) are very limited. Thus, in this study, the main

Table 2
Wind turbine characteristics.

Wind class	III
Rated power	2.1 MW
Rated wind speed	9 m/s
Cut in wind speed	3 m/s
Cut out wind speed	20 m/s
Number of blades	3
Design tip speed ratio	10.6
Rotor diameter	122.3 m
Control type	Various speed – various pitch
Maximum power coefficient	0.483
Pre-bend at blade tip	2.5 m