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A new optimization approach to improve the overall performance of thick wind turbine airfoils

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ABSTRACT

A crucial problem of designing thick airfoils is balancing structural and aerodynamic requirements. This paper documented a new idea to deal with the thick airfoil's design. Firstly, the relative thickness of the original airfoil was increased to enhance its structural property. Then the overall aerodynamic performance was improved by the optimization design method. Specifically, this paper put forward a mathematical model of the overall optimization employing airfoil's performance evaluation indicators which represent modern rotor blades' aerodynamic requirements of "high efficiency, low extreme load, wide range of operating angle of attack and stability with varying operating conditions". Based on this model, an integrated optimization platform for thick airfoils' overall design was established. Through an optimization experiment, a new 35-percent relative thickness airfoil was obtained. The new airfoil was predicted with high design lift coefficient, acceptable maximum lift to drag ratio, moderate stall parameter, and desirable stability parameters. These characteristics contribute to a high overall performance which could be competent with commonly used thick DU airfoils. Lift characteristics of the new airfoil have been validated by tests. These results confirmed the proposed method has effectively balanced airfoil's complicated requirements and successfully improved the new airfoil's overall performance.

1. Introduction

Much research in recent years has focused on dedicated airfoils, especially on thick airfoils used in mid span of rotor blades. Because the use of thick airfoils with high performance help to reduce the cost of rotor blades. The airfoil is the cross section of a blade, and its characteristics essentially determine blades' performance. For 'thick' is a relative concept, thick airfoils in this paper, are not just judged by the relative thickness, but specifically defined as sections used in blades' mid span of current multi-MW horizontal axis wind turbines (HAWTs). The regional classification of the blade is based on aerodynamic and structural functions [1]. For natural requirements of blades with increasing size, the development of wind turbine airfoils could be considered as the history of courting thicker airfoils with high performance compared with traditional aviation airfoils. Thicker airfoils offer higher structural strength and stiffness which benefit reducing the chord of the blade. High aerodynamic efficient and $c_{l,design}$ also help to reduce the chord of the blade. Both of these features contribute to the reduction of used material and weight load of the blade. Therefore, design high performance thick airfoils used in mid span to replace old airfoils has been investigated as a key way to solve contradiction requirements of geometrical compatibility, structure integrity and aerodynamic efficiency [1]. However, it has been found that simple increase of the relative thickness by scaling the airfoil along the camber line generally results in deteriorated aerodynamic performance [2].

One way to obtain airfoil with desirable performance is the inverse design method, which is to regulate the velocity or pressure coefficient distributions around the scaled airfoil [3,4]. Successful use of the inverse method depends on experiences of designers. By this method, NREL S airfoil families [5] and DU airfoil series [6] dedicating to wind turbine blades were designed, and most of these airfoils' relative thicknesses were larger than 21%. Detailed design considerations of wind turbine airfoils were introduced considerably in Ref.6. For inboard airfoils, Timmer [7] suggested

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Nomenclature

α	angle of attack
α_{design}	design point, angle of attack related to maximum lift-to-drag coefficient
α_{stall}	stall point, angle of attack related to maximum lift coefficient
$\Delta\alpha$	range of angle of attack between design point and stall point
Re	Reynolds number
$Redesign$	Reynolds number at which an airfoil is designed
c_l	lift coefficient
$c_{l,max}$	maximum lift coefficient
c_d	drag coefficient
l/d	lift-to-drag ratio
$l/d_{\max}$	maximum lift to drag ratio
M_{stallx}	stall parameter
R_{cl}	change rate of c_l in $\Delta\alpha$
R_{ld}	change rate of l/d in $\Delta\alpha$
S_{sf}	stability parameter to surface roughness
S_{re}	stability parameter to Reynolds number
C_{am}	relative camber of an airfoil
R_{le}	radius of leading edge of an airfoil
T	relative thickness of an airfoil
T_{tr}	relative thickness of trailing edge
X_{cam}	chord position of maximum camber
X_t	chord position of maximum relative thickness

that the roughness sensitivity may be reduced by rotational effects, and therefore, inboard airfoils' design objective could be focused on increasing c_l to deliver enough torque of rotor blades. Using RFOIL code [8], Institute of Engineering Thermophysics (IET) developed a family of root airfoils with large thickness [9] and the new 45% relative thickness airfoil exhibits competitive lift characteristics in high α values compared with DU 00-W2-401 (40% relative thickness). For thick airfoils used in mid span of the blade, the design is a complicated balance problem among multi-objectives of aerodynamic and structural performance. Therefore, the numerical optimization method on which researchers have made great efforts was used. The optimization method is a way to design airfoils with more comprehensive objectives. Combining the CFD method and optimization method, Fuglsang [10], van Dam [11], Grasso [12] improved both airfoils' aerodynamic efficiency and structural inertia moment.

The capacity of state-of-the-art HAWT nearly reaches 10 MW with the scale of the rotor exceeding 100 m [13]. In order to reduce the cost, increasing wind energy captured by mid span of the blade becomes significantly important. Aerodynamic requirements for thick airfoil used in mid span cannot focus only on a single coefficient like $l/d_{\max}$ or $c_{l,max}$. A more overall performance requirement including design performance, off-design performance and stability in varying operating conditions [14] should also be placed on thick airfoil designs. IET established an evaluation method on the airfoil's overall performance [15]. However, there remains a need for an efficient method that can improve the overall aerodynamic performance for thick airfoils.

Therefore, this paper presents an optimization method to improve the overall aerodynamic performance of thick airfoils specifically for the use in mid span of rotor blades. Based on complex flow characteristics and different requirements along spanwise of a blade, the airfoil's design principles will be firstly investigated, and the aerodynamic design philosophy satisfying blades' requirements of "high efficiency, low extreme load, stability and wide range of operating α" will be put forward. Then, the paper will build a mathematic model of the multi-objective optimization on thick airfoils and establish an integrated design platform. At last, an optimization of experiment of an airfoil with 35-percent relative thickness will be performed to validate the method.

2. Design considerations and prediction methods

This study is to present a new way to increase both the airfoil's structural property and overall aerodynamic performance. Specifically, the new airfoil is aimed to be used in mid-span. The relative thickness of primary airfoil used in this part is around 30%. Thus, the relative thickness is firstly scaled to 35% to replace its original airfoil. Then the overall aerodynamic performance will be improved to the level that can be competent with the original airfoil by numerical optimization method based on the parameterization of airfoil's performance.

For the design of airfoils, the first problem is to determine design objectives. The airfoil's design principle depends on the development of wind turbines. General performance requirements of different parts of a blade and related airfoil design objectives have been discussed in detail in the early designs. However, the capacity of related wind turbines was relatively small. Therefore, this paper will firstly summarize general performance requirements of blades and present new considerations for large wind turbine blades.

2.1. Performance requirements for rotor blades

HAWTs are large rotational machines to generate power by capturing the kinetic energy of the wind. The investigation of wind farms shows that accidents of wind turbines due to extreme wind conditions (e.g. typhoon) mainly occurred in the blades. It demonstrates the structural strength and stiffness of blades play critical roles in the safe operation. On the other side, the blade's rotation is motivated by the aerodynamic lift force which is generated by the relative motion between the air and blade. Therefore, it is widely accepted that the main design considerations for airfoils include both aerodynamic performance and structural property. For the part closer to the blade root, structural property is more highly weighted, but for that closer to tip region, aerodynamic characteristic is more highly weighted [1,6]. Besides, noise produced by turbines is the main negative effect to the environments. Except the noise produced by the nacelle, the aerodynamic noise is the leading source of the wind turbine noise. Thus, the design of wind turbine blade is naturally a multi-discipline problem concerning aerodynamic, structural, and acoustical issues.

To reduce the cost, the capacity of HAWTs increases year by year. The significant increase in scale makes the blade more flexible, and brings great challenge to operation safety. This indicates that the structural property for the whole blade, not just for the root part, must be taken seriously into account. Employing thicker airfoils is definitely an effective way, because thicker airfoils generally provide higher strength and larger stiffness. Therefore, this study presents a way to enhance the structural property of blade's sections by using thicker airfoils to replace previously used airfoils. However, as is presented before, simply thickening the airfoil