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Effects of vortex generators on a blunt trailing-edge airfoil for wind turbines

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A B S T R A C T

Vortex generators (VGs) are commonly-used effective flow separation control devices, and are proved to have potential to improve the aerodynamic performance of large wind turbines. In this paper, the flow physics of VGs and how their size affects the aerodynamic performance of a blunt trailing-edge airfoil DU97-W-300 have been investigated using CFD simulations. Based on wind turbine dedicated airfoil with and without VGs respectively, three-dimensional numerical models were established and further validated through the comparisons between the numerical results and the experimental data. The effects of VGs' size were analyzed from several perspectives, such as trailing-edge height, length, short and long spacing between an adjacent pair of VGs. The results indicate that drag penalty is more sensitive to the increase of VG height than lift; an increment of VG length leads to negative effects on both lift and drag; increases of the spacing between an adjacent pair of VGs have positive impact on suppression of separated flow. Additionally, the flow field characteristics were further revealed by the analysis of streamlines and vortices in the wake region.

1. Introduction

In order to achieve strong structure for large wind turbine blades, thick airfoils have been designed and researched to absorb large bending loads, which are applied from middle to the root sections of blades in recent years [1,2]. Compared with normal thick airfoils, blunt trailing-edge airfoils are dedicated wind turbine airfoils, which are able to be adopted in larger section area, to produce more lift, and to be less sensitive to leading edge roughness [3]. Therefore, blunting trailing-edge airfoils could further improve both the structural strength and the aerodynamic performance of large wind turbine blades.

However, the comparatively high airfoil thickness simultaneously increases drag penalty, which is mainly caused by flow separation at large angles of attack. Due to increasing angles of attack, adverse stream-wise pressure gradients increase correspondingly and lead to a separation of flow. Airfoil thickness increases from tip to root, as well as the reduction of wind velocity, which is not ideal for low Reynolds number flows [4]. It is particularly problematic for flow separation in the region near the hub [5]. Consequently, the efficiency of wind turbines is diminished by the drag penalty resulting from flow separation [6]. Thus, it is a crucial objective to study the flow separation control methods for better aerodynamic performance of wind turbines.

Vortex generators (VGs), first documented by Taylor [7], are widely-used effective flow separation control devices. In 1990, Afjeh [8] predicted the aerodynamic performance of a horizontal-axis wind turbine equipped with VGs. In 1995, Øye [9] indicated that a stall-regulated wind turbine power increased nearly 24% by using VGs (from 850 kW to 1050 kW) through field tests. The first industrial application was implemented by UpWind Solutions, Inc. [10] in 2012 and the result showed that the mean Annual Energy Production (AEP) increase experienced within the 3 month time period was in the range of 2.1–2.5%. And then, a relation between wind speeds and the impact of VGs on AEP was pointed out. Therefore, VGs are effective devices for wind turbines to increase power output and studies are required for VGs to further improve wind turbine performance.

Many researches have been carried out towards VGs on wind turbines. Lin [11] reviewed the research on low-profile VGs to control boundary separation, and summarized the features of different types of VGs and their applications. He also pointed out that VG is applicable to control flow separation at a relatively fixed point, and its installation location should not far away from the

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Nomenclature

Latin symbols

a	short spacing between adjacent vortex generators (mm)
b	long spacing between adjacent vortex generators (mm)
c	airfoil chord length (m)
C_d	drag coefficient (dimensionless)
C_l	lift coefficient (dimensionless)
$C_{l,max}$	maximum lift coefficient (dimensionless)
d	length of vortex generator (mm)
ds	the height of first grid layer (m)
h	trailing-edge height of vortex generator (mm)
l	span-wise length (m)
C_l/C_d	lift-to-drag ratio (dimensionless)
Re	Reynolds number (dimensionless)
U_∞	wind speed (m/s)
x, y, z	Cartesian coordinate system
$y+$	dimensionless wall distance

Greek symbols

α	angle of attack (°)
β	angle of incidence of VG vanes (°)
ρ	air density [assumed 1.225 kg/m^3]
μ	dynamic viscosity (Pa s)

Abbreviations

CFD	computational fluid dynamics
VG	vortex generator
DUT	Delft University of Technology

point of separation. The performance of VGs on DU91-W2-250 was experimentally evaluated by Velte et al. [5] using Stereoscopic particle image velocimetry (PIV). Velte and Hansen [12] also investigated the flow behind VGs by Stereoscopic PIV near the stall. Mueller-Vahl et al. [13] investigated the optimization of VG configuration in both experimental and numerical way. Their conclusions were drawn through their observations on force measurements and PIV measurements. Advanced CFD models were established by Xue et al. [14] to capture the micro-scale physics of VGs, and their models were proved to be suitable to uncover the performance of tiny VGs. Yang et al. [15] conducted simulations of aerodynamic performance affected by VGs on blunt trailing-edge airfoils, and they indicated that VGs could also function efficiently on a DU airfoil.

However, the above investigations only focus on blunt trailing-edge airfoils or performance of VGs on sharp trailing-edge airfoils. The present researches on blunt trailing-edge airfoils equipped with VGs are limited and rare, particularly for parametric study. Therefore, it is significant to have parametric investigations of VGs on blunt trailing-edge airfoil for wind turbines.

To solve the above problem, the study on effects of VGs on airfoil DU97-W-300 has been carried out using CFD simulations in this paper. The organization of the rest of paper is as follows. Section 2 describes the geometric considerations for the blunt trailing-edge airfoil and VGs. Section 3 illustrates the CFD simulations. In Section 4, the impact of VGs' sizes, including trailing-edge height, length, and short and long spacing between adjacent VGs, on DU97-W-300 has been discussed. Section 5 presents the final conclusions.

2. Geometric description

2.1. Blunt trailing-edge airfoils

Blunt trailing-edge airfoils (DU series) were developed by DUT for wind turbines using RFOIL, a modified version of XFOIL [16]. A representative and base airfoil DU97-W-300 with a thick trailing edge of about 1.74% chord has been adopted in this paper, and its maximum thickness locates around 30% chord. Airfoil DU97-W-300 is widely suited to 40% span-wise position of a wind turbine blade, and could smoothly transit to the other airfoils. Additionally, its design goal of the maximum lift coefficient $C_{l,max}$ is in the range of 1.5–1.6 at a Reynolds number of 3×10^6 [17,18].

2.2. Vortex generators

Vortex generators are utilized to suppress the flow separation caused by adverse pressure gradients and turbulence [19], increase lift [20,21] and reduce drag [4] through generating discrete streamwise vortices to energize the slower moving boundary layer with the high-momentum fluid in free stream and in the outer part of the boundary layer [22,23].

Optimization of VGs has been investigated by several authors with the consideration of following variables, but not limited to: type, shape, size, patterns (orientation of adjacent VGs) and location. In this paper, size parameters, including height, length, short and long spacing between adjacent vortex generators, are the key research objectives. Other govern variables were determined according to the optimal solutions in Refs. [11,13,17,24].

Fig. 1 portrays two main configurations of VGs, the counter-rotational configuration and the co-rotational configuration. The adjacent VGs in the co-rotational configuration have all equal angles of incidence to the flow, while the adjacent VGs in the counter-rotational configuration possess equal, but opposite angles of incidence. The rotational directions of vortices generated by a pair of VGs depend on their array configurations. The counter-rotational configuration has been proved to be more effective to suppress the flow separation in several aerodynamic applications [24–26]. The same result for wind turbines was obtained by our early study [27].

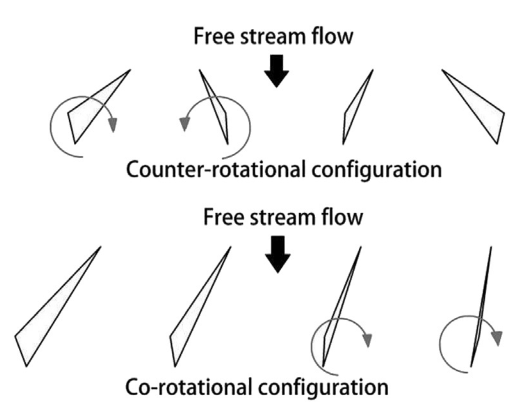

Fig. 1. Schematic of the counter-rotational configuration and the co-rotational configuration.