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# Effects of vortex generators on aerodynamic performance of thick wind turbine airfoils

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ABSTRACT

The effects of vortex generators (VGs) on aerodynamic performance of thick wind turbine airfoils CAS-W2-350, CAS-W2-400, and CAS-W1-450 are presented. The measurements were carried out at a Reynolds number of 1 million with two experimental setups. Aerodynamic performance of testing models is obtained by measuring the surface pressure. The effects of height, chordwise position, and spanwise spacing between neighbor VGs are investigated, as well as the effect of a second row of VGs. The results show that the maximum lift coefficient increases with VGs installed towards the leading edge of airfoils but the lift at small angles of attack decreases when the chordwise position of VGs is smaller than 20% chord. The spanwise spacing between neighbor VGs has small effects on lift coefficient of CAS-W2-350, but strongly affects that of CAS-W2-400 before stall. The second row of VGs could further increase the lift coefficient at large angles of attack depending on the install positions and size of VGs.


## 1. Introduction

Thick airfoils are generally applied on the inboard section to enhance blade structure for large scale wind turbine blades. However, this kind of airfoils tends to have poor aerodynamic performance because of the boundary layer separation due to large curvature of the upper surface and high adverse pressure gradient at the rear part of the airfoil. For example, the maximum lift coefficient of DU00-W-401 is about 1.1 which is much smaller than that of DU00-W-350 due to flow separation (van Rooij and Timmer, 2003). Another version of 40%$c$ thick airfoil, DU00-W2-401 (Grasso, 2013), also has a small maximum lift coefficient of about 1.1. Moreover, very thick airfoils often work at large angles of attack (AOA), e.g., 15–30° (Li et al., 2014) and experience earlier flow separation (e.g. Paulsen et al., 2010). Therefore, aerodynamic flow separation control devices are necessary to improve aerodynamic performance of thick airfoils.

Vortex generators (VGs) are effective aerodynamic flow separation controlling devices (Taylor, 1947), and gradually used on wind turbines to improve aerodynamic performance. The improvement of power output due to VGs depends on the type of wind turbines. For example, the increase of power due to installation of VGs is up to 25% for a 1000 kW stall-regulated wind turbine (Øye, 1995), and it is 15% for a 2.5 MW tip-controlled wind turbine (Miller, 1995). For modern variable speed and pitch controlled (to feather) wind turbines, there is still benefit of increasing the annual energy production (AEP) (Mueller-Vahl et al., 2012; Seidel and Rische, 2004), especially when the annual-averaged wind speed of wind farms is low. As a good solution to suppress flow separation and improve the aerodynamic performance, the effect of VGs on wind turbine airfoils was investigated (e.g. van Rooij and Timmer, 2003). VGs can dramatically increase the lift coefficient of airfoils and reduce the sensitivity to surface roughness.

The efficiency of VGs depends on chordwise position, spanwise spacing, and the type of VGs. For a 0.6 m chord model, the optimized height of VGs is 5 mm placed at 20%$c$ and 30%$c$ chord position (Timmer and van Rooij, 2003). The VG size and layout should be changed for difference chord model and difference airfoil family. Therefore, it is worth investigating the influence of these parameters to supplement knowledge of the effect of VGs on thick airfoils. In addition, Godsk (2010) published an interesting multi-row installation of VGs and showed good prospect of application. The VGs downstream should experience the turbulent flow from upper VGs; therefore, the chordwise spacing of downstream VGs to upstream VGs should be studied. The investigation is carried out experimentally in two wind tunnels at Reynolds

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number of 1 million. Airfoils CAS-W2-350 and CAS-W2-400 were tested in a wind tunnel with a testing section of $1.5 \times 3 \times 4.5\ m^3$ and airfoil CAS-W1-450 was tested in another wind tunnel with a testing section of $1.5 \times 1.5 \times 2.5\ m^3$.

## 2. Property of the airfoils

The shape and design characteristics of the airfoils are shown and compared in Table 1 and Fig. 1. The chordwise position of the maximum thickness is set at about 30%$c$ to keep good geometric compatibility. Trailing-edge thickness is applied to improve aerodynamic performance because incorporation of trailing-edge thickness alleviates the tendency toward premature boundary layer separation for both clean and soiled conditions due to the reduction of the adverse pressure gradient on airfoil surfaces (Baker et al., 2006).

## 3. Vortex generators

The shape of VGs can be rectangular or triangular plates (i.e., delta wing). Other short wings that create strong tip vortices can also be used as VGs, e.g., the sectional profile of VGs is a specific airfoil (Hansen et al., 2015). Delta wing shaped VGs are studied in this paper, as shown in Fig. 2. Two VGs in a pair are placed opposite with an angle of attack ($\alpha_{VG}$) with respect to the chordwise direction. Pairs of VGs are arrayed periodically along the spanwise direction with a spacing $S$. To distinguish flow passages at both sides of the VG, the authors define the flow passage at the suction side of the VG as "expanding passage." By the same way, define the adjacent flow passage as "contracting passage." The rotational directions of vortices from adjacent VGs are opposite, so-called counter-rotating layout (Dayton, 1996). The height and length of VGs are respectively $h$ and $l$. The strength of vortices is a function of $h$, $l$, $\alpha_{VG}$, and the local velocity ($V_{VG}$), as given by Eq. (1) (Zhang et al., 2011)

$$\Gamma = V_{VG} l \sin \alpha_{VG} \cos \alpha_{VG} \left( \frac{2h}{l} + \frac{1}{2} C_{Dp} \sin \alpha_{VG} \right) \quad (1)$$

in which $C_{Dp}$ is the drag coefficient of a plate with infinite length, i.e., $C_{Dp} \approx 1.95$. Effective VGs should create strong vortices but low additional drag that leads to researches of sub boundary-layer VGs (Mueller-Vahl et al., 2012). The parameters of VGs in this paper are primarily from reference (Timmer and van Rooij, 2003) and then changed according to the specific application in this paper.

The multi-row installation of VGs is considered as more efficient than the single-row layout (Godsk, 2010); therefore, the two-row layout was measured to validate whether it affects and further improve aerodynamic performance of very thick airfoils.

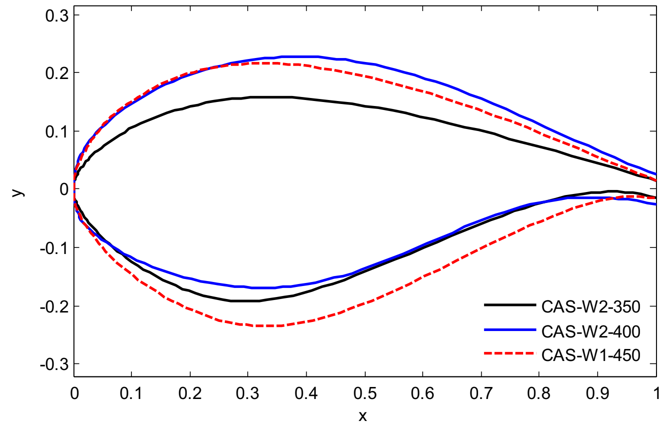


**Fig. 1.** Profiles of the newly designed airfoils.

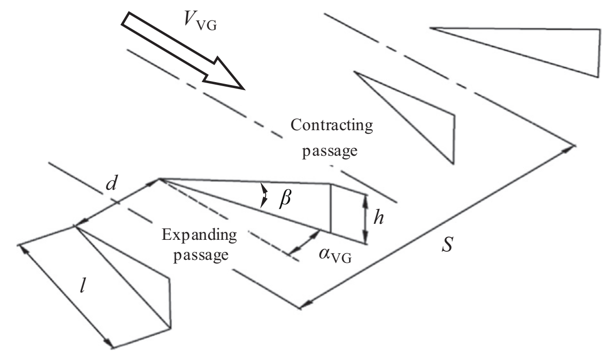


**Fig. 2.** Sketch of VGs: $V_{VG}$ is the local velocity; $d$ is the leading edge spacing in a pair of VGs; $l$ is the length of VGs; $\alpha_{VG}$ is the angle of attack of VGs with respect to the local velocity; $h$ is the height of VGs; $S$ is the spacing of adjacent pairs of VGs; $\beta$ is the leading edge angle of a VG equaling to $\alpha_{VG}$ in this study.

## 4. Experimental methods

### 4.1. Experimental set-up one

This experimental set-up was introduced in the authors' previous paper (Zhang et al., 2016). Some key points are represented in this paper, and the set-up of VGs is introduced.

The wind tunnel is named D4 in Beijing University of Aeronautics & Astronautics (BUAA). It is a low-speed wind tunnel with a closed circuit, and the turbulence level is 0.085%. The test section has a cross-sectional dimension of 1.5 m × 1.5 m and a tunnel length of 2.5 m. The wind speed in the experiments is 48.7 m/s, considering the capacity of the wind tunnel. The testing model is 1.5 m long in spanwise direction, which vertically bisects the test section of the wind tunnel, extending from the floor to the ceiling. The chord length of the model is specified as 0.3 m that creates a minimum solid blockage of 8%. The testing model is assembled with three parts but the slits at connections were covered with transparent tape in the experiment, as shown in Fig. 3(a). Three lines of pressure taps are placed on the middle part with stagger layout at the leading edge to avoid too small spacing between neighbor pressure taps.

**Table 1**
Design characteristics of the airfoils.

| Airfoil | Relative thickness | Chordwise position of maximum thickness from leading edge | Maximum camber | Chordwise position of maximum camber from leading edge | Trailing edge thickness with respect to chord |
|---|---|---|---|---|---|
| CAS-W2-350 | 0.35 | 0.319 | 0.0200 | 0.842 | 0.02 |
| CAS-W2-400 | 0.40 | 0.327 | 0.0192 | 0.831 | 0.05 |
| CAS-W1-450 | 0.45 | 0.322 | 0.0204 | 0.807 | 0.03 |