Flow analysis of the deep dynamic stall of wind turbine airfoil with single-row and double-row passive vortex generators

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Abstract: This paper aims to understand the influence of vortex generators (VGs) on deep dynamic stall of the NREL S809 airfoil. The fully-resolved URANS method is used to predict aerodynamic responses of the airfoil with both single-row and double-row VGs. On one hand, single-row and double-row VGs are found to attenuate the force fluctuation and postpone the extension of flow separation when the airfoil pitches up. The onset of deep dynamic stall is therefore significantly delayed with the maximum lift coefficient increased beyond 40%. This indicates that VGs are effective in controlling deep dynamic-stall behavior. On the other hand, single-row and double-row VGs are found to make a great difference in aerodynamic responses when the airfoil pitches down. Single-row VGs undermine the torsional aeroelastic stability and have the potential risk of making the airfoil flutter. Double-row VGs can accelerate the flow reattachment effectively, and quickly restore the decreased aerodynamic force near the maximum angle of attack. These findings also imply that deep dynamic stall with VGs becomes highly complicated, because VGs can be fully submerged in separation vortices. In general, double-row VGs perform better than single-row VGs to control deep dynamic stall. This study is believed to assess the VG performance in controlling highly unsteady aerodynamic loads on wind turbines.

Keywords: dynamic stall; passive vortex generators; wind turbine airfoil; URANS simulations; deep stall

1. Introduction

Passive vortex generators (VGs) can effectively suppress the separated flow and improve the aerodynamic performance of horizontal axis wind turbines (HAWTs) [1], although their geometry is very simple. Conventional VGs have some pairs of vanes protruding from the surface, angled to the incoming flow [2]. The underlying principle of flow control via VGs is to generate streamwise vortices. These vortices can reenergize the boundary layer and counteract the adverse pressure gradient.

The evolution of streamwise vortices mainly determines the effectiveness of VG designs. There are various VG parameters to impact on this streamwise vortex evolution. Godard and Stanislas [3] used hot film probes and stereo particle image velocimetry (PIV) to measure the boundary layer flow around a bump with VGs. The triangular VGs were found better than rectangular VGs in reducing the drag penalty at low angles of attack (AOAs). The counter-rotating configuration was also found better than co-rotating configuration in producing the wake of upwash and downwash regions. Mueller-Vahl * et al. [4] conducted force measurements and PIV measurements of the NACA 63(3)-618 airfoil with VGs.
They found that decreasing the spanwise spacing of VGs could not only delay the onset of static stall, but also lead to the high drag penalty. Baldacchino et al. [5] used wind-tunnel measurements to systematically study the influence of VG parameters on the performance of DU97-W-300 airfoil. The chordwise location and vane height of VGs were found to be determining factors in the airfoil performance. The chordwise location has a great effect on the airfoil post-stall behavior. If VGs are positioned too downstream, they are easy to be submerged in the separation vortices, and then an early abrupt stall will occur [4, 5]. Wang et al. [6] used URANS simulations to study aerodynamic responses of the NREL S809 airfoil with rectangular VGs. Double-row VGs were found to further suppress the separated flow and delay the onset of static stall in comparison with single-row VGs.

Although VGs have succeeded in aerospace engineering and have been practically applied in wind turbine engineering (Figure 1), the effect of VGs on the HAWT blade flow is still poorly understood. Most researches of VGs are about the two-dimensional steady flow around stationary airfoils with VGs. However, the blade flow is three-dimensional rotational, and often becomes unsteady due to the complicated environmental effects like turbulent inflow, yaw misalignment and wind gust [7, 8]. These unsteady conditions ultimately lead to the time-varying AOA from the blade-section view. If the AOA variation is wide and fast enough, the blade boundary layer cannot follow it instantaneously, and then dynamic stall occurs [9]. Dynamic stall is often accompanied by the pronounced aerodynamic hysteresis and unsteady loads, to which wind turbine failures, reduced machine life, and increased operating maintenance are all directly linked. However, the influence of VGs on dynamic stall has been rarely studied and thus remains unclear.

**Figure 1.** Applications of VGs on the aircraft wings and wind turbine blades [10, 11].

Previous works conducted by Zhu et al. [12, 13] indicated that VGs could effectively suppress the unsteady separated flow of the oscillating wind turbine airfoil, thereby reducing the aerodynamic hysteresis. In this regard, double-row VGs were also found to result in a higher effectiveness than single-row VGs. Previous works are only about the influence of VGs on light dynamic stall. However, the flow separation in deep dynamic stall will become severer due to the strong disturbance of vortex motion.

The main objective of this work is to understand the influence of single-row and double-row VGs on deep dynamic stall. The fully-resolved URANS method is used to identify the controlled and uncontrolled airfoil flow characteristics. The aerodynamic responses and flow field development are carefully analyzed to reveal the influence of VGs on deep dynamic stall.

2. Numerical modelling of dynamic stall with vortex generators

Figure 2 gives the geometry of VGs implemented on the NREL S809 airfoil. According to the design methodology of VGs [4, 5], the main VG parameters are $h=5$ mm, $d/h=3.5$, $D/h=7$, $L/h=3$, and $\beta=18^\circ$. Two chordwise installations are considered: $x_{VG}/c=15\%$ (single-row); $x_{VG}/c=15\%$ and $40\%$ (double-row).

Present numerical modelling is entirely consistent with that in the previous work [12]. Table 1 provides the main features of the computational mesh. The mesh includes only one pair of VGs (Figure 3), and the translational periodic boundary condition is used on spanwise boundaries. Mesh dependency study has been conducted with the General Richardson Extrapolation method [12]. The mesh has 1000 cells on each VG vane. The Reynolds number is $1\times10^6$ ($c=0.457$ m and $U_0=33.68$ m/s).
Figure 2. Schematic of the rectangular vane-type vortex generators in a counter-rotating configuration. (a) isometric view; (b) planar view.

Figure 3. Boundary-layer and surface mesh of the airfoil with single-row VGs.

Dynamic stall is generated by oscillating airfoil about the quarter-chord axis. This dynamic motion is simulated by the sliding mesh method [14] to ensure the AOA satisfies the following variation:

$$\alpha = \alpha_m + A \sin (2\pi ft)$$

The definition of reduced frequency is given by \( k = \frac{\pi f c}{U_0} \). The deep stall condition of \( \alpha_m = 18.75^\circ \), \( A = 10.3^\circ \), and \( k = 0.078 \) is used in this study, according to the wind-tunnel experiments [15].

URANS equations are solved by the commercial software of ANSYS/FLUENT 16.0 [14]. Table 2 gives the main settings of URANS simulations. The SST \( k-\omega \) eddy viscosity model [16] and the \( \gamma-Re_\theta \) transition model [17] have well succeeded in simulating the unsteady airfoil flow [8, 18].

Table 1. Main features of the mesh

| Mesh configuration | Structured O-type | y+ |
|--------------------|-------------------|----|
| Normal growth ratio | 1.08               |    |
| Far-field Distance  | 20 c               |    |
| Mesh size (million) | 2.9 (single-row VGs) | 3.5 (double-row VGs) |

Table 2. Main settings of the URANS simulations

| Spatial discretization | Third-order MUSCL convection scheme |
| Temporal discretization | Bounded second-order implicit scheme |
| Pressure-velocity coupling | Coupled algorithm |
| Time steps per cycle | 540 |
| Inner iterations | 20 |
| Turbulence model | SST \( k-\omega \) model |
| Transition model | \( \gamma-Re_\theta \) model |

Due to the lack of measured data of dynamic stall with VGs (unsteady-controlled), the numerical modelling has been validated against two sets of available measured data: steady-controlled and unsteady-uncontrolled. For steady-controlled data, the numerical modelling can accurately predict the pressure distributions of the DU97-W-300 airfoil with and without triangular VGs [5, 12]. For unsteady-uncontrolled data, the calculated results also agree well with the measured data of the NREL S809 airfoil undergoing light dynamic stall [12].

Furthermore, Figure 4 indicates that the predicted \( C_l-\alpha \) and \( C_d-\alpha \) hysteresis loops generally agree with the experimental data [15] and Johansen’s CFD results [18] under the deep dynamic stall condition. The hysteresis loops also show noticeable fluctuations at the high AOAs due to the vortex shedding and passage over the suction surface. The aerodynamic responses are correctly predicted during the flow separation and reattachment processes. The numerical modelling of dynamic stall with VGs should therefore be adequately accurate.
he downstroke process can be further aerodynamic responses to delay the onset of dynamic stall.

3. Results and discussion

3.1. Hysteresis loops

Figure 5 shows the effect of VGs on aerodynamic hysteresis loops. During the upstroke process, the aerodynamic coefficients with single-row and double-row VGs are fairly close together. VGs are found to delay the onset of dynamic stall effectively. The $C_l$ without VGs rapidly diverges from the linear regime at $\alpha=16^\circ$, manifesting an early start of the flow separation (Figure 5a). The $C_l$ with VGs, however, follows the linear theory until $\alpha=22^\circ$. At the high AOAs, the uncontrolled airfoil produces dramatic fluctuations in the aerodynamic forces due to the dynamic stall vortex. The degree of these fluctuations seems to be reduced by VGs (Figure 5).

During the downstroke process, single-row and double-row VGs make a great difference in aerodynamic responses of the airfoil. To analyze the results in detail, the downstroke process can be further separated into the following three parts:

- From $\alpha_{\text{min}}$ to $\alpha=25^\circ$, double-row VGs make the decreases in $C_l$ and $C_d$ quickly restored in comparison with single-row VGs. This implies that the second row of VGs has a great impact on the massively separated flow when the downstroke starts.
- From $\alpha=25^\circ$ to $\alpha=13^\circ$, single-row VGs keep a high $C_l$ of the airfoil, but at the cost of high hysteresis intensities of $C_l$ and $C_m$. However, double-row VGs gradually decrease the $C_l$ at first, and then slowly increase it during the flow reattachment process.
- From $\alpha=13^\circ$ to $\alpha_{\text{min}}$, single-row VGs lead to significant increases in the aerodynamic hysteresis intensities in comparison with double-row VGs. This suggests that the second-row VGs can help the aerodynamic coefficients readjust to the linear regime at low AOAs.

![Figure 5](image-url) **Figure 5.** $C_r-\alpha$ and $C_d-\alpha$ hysteresis loops of the NREL S809 airfoil with and without VGs. Solid lines denote increasing AOA, and dashed lines decreasing AOA. (a) $C_l$; (b) $C_d$; (c) $C_m$.
To quantify the impact of VGs on deep dynamic stall, the dynamic-stall parameters in Table 3 can be extracted from the hysteresis loops in Figure 5. The aerodynamic pitch damping $\zeta_{cm}$ is defined as:

$$\zeta_{cm} = -\int C_m d\alpha / 4A^2$$  \hspace{1cm} (2)

The high value of $\zeta_{cm}$ also means a high degree of torsional aeroelastic stability. If the $\zeta_{cm}$ becomes negative, the amplitude of pitch oscillation will tend to increase gradually [19]. Therefore, airfoil flutter will appear unless restrained.

| Case name          | $C_{l,max}$ | $\alpha_{C_{l,max}}$ | $C_{l,dec}$ | $C_{m,inc}$ | $C_{m,dec}$ | $C_{m,min}$ | $\zeta_{cm}$ |
|-------------------|------------|----------------------|-------------|-------------|-------------|-------------|--------------|
| clean             | 1.78       | 28.62                | 0.67        | -0.34       | -0.120      | -0.605      | 0.153        |
| single-row VGs    | 2.49       | 23.37                | 1.26        | -0.23       | -0.280      | -1.086      | 0.055        |
| double-row VGs    | 2.65       | 26.24                | 1.95        | -0.60       | -0.399      | -1.028      | 0.124        |

Compared to the clean case, single-row and double-row VGs increase the $C_{l,max}$ by 40% and 49%, respectively. This indicates that double-row VGs can further delay the onset of dynamic stall and elevate the $C_{l,max}$. VGs are also found to greatly decrease the $C_{m,min}$ by almost 70%, mainly because VGs can postpone the forward movement of the center of pressure with the separated flow suppressed.

Table 3 shows that single-row VGs greatly reduce the $\zeta_{cm}$ by 64%. This implies that single-row VGs can undermine the torsional aeroelastic stability, and have the potential risk of making the airfoil flutter. In this regard, double-row VGs perform better than single-row VGs and only decrease the $\zeta_{cm}$ from 0.153 to 0.124.

3.2. Flow structures

Figure 6 shows the effect of VGs on unsteady streamlines and pressure fields. Three typical AOAs of 9.83°, 18.75° and 27.67° are selected according to the three extents of flow separation: fully attached flow, trailing-edge (TE) separated flow and massively separated flow, respectively. The flow development around the clean airfoil also indicates a severer flow separation during the downstroke process than during the upstroke process. This implies that the flow reattachment during the downstroke process is retarded, thereby resulting in the aerodynamic hysteresis.

During the upstroke process, VGs can effectively eliminate the TE separated flow at $\alpha=18.75^\circ$. The $C_l$ with VGs is therefore greatly increased (Figure 5a). At $\alpha=27.67^\circ$ ($\uparrow$), three separation vortices appear on the suction side of the airfoil without VGs, including two relatively small vortices on the first half of airfoil and one major TE vortex on the second half. Notice that single-row and double-row VGs generate the forth TE separation vortex. This small vortex edges the major separation vortex out, and then brings about a remarkable suction peak near the trailing edge (Figure 7a). Surprisingly, the second-row VGs seem to produce a negative effect and decrease the value of TE suction peak.

During the downstroke process, the leading-edge (LE) and TE separation vortices alternately shed into the wake. At $\alpha=27.67^\circ$ ($\downarrow$), single-row VGs hardly keep the LE separation vortex attached to the surface, and then produce a greatly distorted pressure field. The suction value is therefore considerably reduced, even lower than the data of uncontrolled flow (Figure 7b). However, double-row VGs effectively suppress the LE flow separation and lead to a high suction before the mid-chord point. Notice that both single-row and double-row VGs eliminate the secondary TE separation vortex.

At $\alpha=18.75^\circ$ ($\downarrow$), the uncontrolled airfoil flow undergoes a major LE separation vortex. The height of vortex also begins to decrease, and the center of the vortex core gradually moves downstream. This implies that the airfoil flow begins to reattach slowly. VGs, however, cause a tertiary vortex. The second-row VGs even make this separation vortex detached from the surface, and vastly decrease the suction and $C_l$ (Figure 7c). Interestingly, double-row VGs on the suction side also have a significant impact on the $C_{p,max}$ distribution on the pressure side. This impact considerably reduces the pressure difference between the pressure and suction sides. At $\alpha=9.83^\circ$ ($\downarrow$), Figure 6 indicates that the second-row VGs can effectively accelerate the flow reattachment and produce a high LE suction peak.
4. Conclusions

This paper presents a detailed flow analysis of the deep dynamic stall of the NREL S809 airfoil with single-row and double-row VGs. Based on this study, three main findings can be summarized as follows.

- VGs can delay the onset of deep dynamic stall and increase the $C_l_{\text{max}}$ as they do in the light dynamic stall. VGs are also found to attenuate the fluctuations in aerodynamic forces near the $\alpha_{\text{min}}$, although they can generate an additional TE separation vortex.

- For single-row VGs, the $C_l$ is kept at a high value when the airfoil pitches down from $\alpha=25^\circ$ to $\alpha=13^\circ$, but at the cost of high hysteresis intensities of $C_d$ and $C_m$. The flow reattachment is also significantly retarded near the $\alpha_{\text{min}}$. Consequently, single-row VGs undermine the torsional aeroelastic stability and have the potential risk of making the airfoil flutter.

- For double-row VGs, the decreases in $C_l$ and $C_d$ are quickly restored when the airfoil begins to pitch down. Compared to single-row VGs, double-row VGs can effectively accelerate the flow reattachment and help the aerodynamic coefficients readjust to the linear regime rapidly.
These findings also indicate that deep dynamic stall with VGs becomes highly complicated during the downstroke process, because VGs are fully submerged in separation vortices. This study contributes to the understanding of deep dynamic stall with single-row and double-row VGs, and provides a performance assessment of VGs in controlling highly unsteady aerodynamic loads on wind turbines.

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Nomenclature

- \( \uparrow \) upstroke process
- \( \downarrow \) downstroke process
- \( \alpha \) angle of attack (AOA)
- \( \alpha_{\text{Cmax}} \) AOA of \( C_l_{\text{max}} \)
- \( \alpha_{\text{m}} \) mean AOA
- \( \alpha_{\text{max}} \) maximum AOA
- \( \alpha_{\text{min}} \) minimum AOA
- \( \beta \) geometric vane inflow angle
- \( \zeta_{\text{cm}} \) aerodynamic pitch damping
- \( A \) AOA amplitude
- \( c \) chord length
- \( C_d \) drag coefficient
- \( C_l \) lift coefficient
- \( C_{l,\text{dec}} \) \( C_l \) at \( \alpha_{\text{Cmax}} (\downarrow) \)
- \( C_{l,\text{max}} \) maximum \( C_l \)
- \( C_m \) pitching moment coefficient
- \( C_{m,\text{dec}} \) \( C_m \) at \( \alpha_{\text{Cmax}} (\downarrow) \)
- \( C_{m,\text{inc}} \) \( C_m \) at \( \alpha_{\text{Cmax}} (\uparrow) \)
- \( C_{m,\text{min}} \) minimum (maximum nose-down) \( C_m \)
- \( C_p \) pressure coefficient
- \( D \) inter-vane spacing
- \( d \) intra-vane spacing
- \( f \) frequency of oscillation
- \( h \) vane height
- \( k \) reduced frequency
- \( L \) vane length
- \( U_0 \) freestream velocity
- \( x \) chordwise location
- \( x_{\text{VG}} \) chordwise location measured between the airfoil and VG leading edges

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