Non-conventional vortex generators calculated with CFD

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Abstract.

Wind turbine blades size has increased during last years due to wind turbine platform growth especially for offshore applications. The interest of wind turbine manufacturers in blade add-ons have raised to mitigate flow separation and blade loading. One type of add-ons are the vortex generators (VGs).

VGs are passive flow control devices that are usually triangular or rectangular vanes inclined to the flow and are dimensioned with regard to the local boundary layer thickness. VGs are known for their capability of delaying separation and increasing lift force on the blade. Their main drawback is the drag penalty added to the blades. In this work, novel shaped VGs are computed with OpenFoam using a fully resolved approach to test if they are efficient with regard to the drag penalty. The use of non-conventional VGs reduce the separated flow zone in the leading-edge of the vane resulting in a lower residual drag and in an increase on the overall efficiency. This fact would reduce the loads associated with the vane.

Three VG shapes are simulated. Two of them have a cross section based on thin airfoils and the other one is a conventional rectangular VG used as reference. The VGs are mounted on a flat plate and they are calculated for the same flow characteristics and size than the ones used in the experiments performed under the scope of the AVATAR project [1]. Relevant quantities, such as the peak vorticity, the vortex vertical and lateral paths, wall shear stress, velocity contours and drag coefficient, will be compared in order to evaluate the VGs performance.

1. Introduction

VGs are designed to create vorticity on the blade surface mixing high momentum zones of the upper part of the boundary layer with low momentum zones near the surface resulting in a velocity profile less prone to separation. The use of VGs will lead to a drag increase but with some benefits in noise reduction (results measured in TÜBerlin in collaboration with the company SmartBlade [2]) and also with a mitigation effect on blade erosion.

These devices are usually rectangular or triangular (conventional VGs) vanes inclined at an angle to the incoming flow. They are usually dimensioned in relation to the local boundary layer thickness to allow for the best interaction between the generated vortex wake and boundary layer, and are usually placed in pairs upstream of the flow separation area.

In terms of power production, Fernandez et al [3] study in their paper the energy production increase of NREL 5 MW wind turbine using the blade element momentum theory and concluding that an overall increase on the average wind turbine power output can be found when using VGs ranging form 3% to 10% depending on the average wind. An increase in the rotor thrust is also
reported. Other researchers as Oye[4] and Sullivan [5] conducted experiments in 1MW and 2.5MW wind turbines with VGs reporting increments of energy production of 24% and 11% respectively.

The increased drag associated with the VG due to the change in pressure distribution and in friction, is the main handicap. In spite of this fact, the increment in structural loads have been studied by [6] and the results show that the additional loading due to the use of VGs has very low impact on the blade structure, significantly lower than its design load levels. A good VG design would be the one more efficient in delaying flow separation but with a minimum associated drag.

Some works found in the literature study non conventional VGs with the objective of finding geometries that present less resistance to the flow. In a rectangular VG shape the flow separates at the leading edge of the VG, with the use of aerodynamically shaped VGs the objective is to maintain the flow attached to the VG the as far as possible. In the study presented in [7] six VG geometries have been studied, four of them are based on rectangular and triangular VGs, and the rest are based on cross-sectional airfoil shapes (based on the NACA0012 airfoil). These VGs are conceived for aeronautical designs.

In the study of Hansen [8] a VG based on a ClarkY airfoil is evaluated in the wind tunnel, the VG chord varies with height while the one studied in this paper has an extruded geometry shape. Their main conclusion is that by simply adding aerodynamically shaped VGs efficiency can be increased by %4. Suarez [9] recently studied other types of VGs called rod VGs designed with the aim of reduce the parasitic drag added to the blades.

The outline of this paper is the following: first, the different VG geometries studied are described as well as the meshes and the computational domains. Then, the results obtained and the comparison between the performance of the VGs is done plotting several quantities of interest. Finally, the conclusions will be summarised.

2. Vortex generators geometry
The studied VGs have a cross section based on a rectangle, a ClarkY airfoil and RonCZ airfoil. The airfoils ClarkY and RonCZ used can be found in the literature. They are non-symmetrical thin airfoils, with a relative thickness of 11.7% and 12.1% respectively. The cross sections of the VGs based on thin airfoils are shown in Figure 1.

![Figure 1. Studied VGs cross-sections.](image)

It is important to note that the RonCZ is an airfoil with a special aerodynamic behaviour with the appearance of laminar bubbles for low Reynolds numbers that produce an unstable behaviour and a sharp efficiency curve. The prediction of the laminar bubbles that could appear in the RONCZ airfoil is out of the scope of this paper since a RANS fully turbulent approach is used. The global quantities predicted numerically should not change considerably due to these
laminar bubbles, it should be in a real VG design in which these laminar bubbles could lead to flow instabilities.

All the VGs main geometric characteristics are the same as the one tested in the AVATAR project [1] and they are mounted on a flat plate. The VG height is 5 mm, their chord is 12.5 mm and the angle of attack to the incoming flow is 18 degrees. The separation between the VGs trailing edge is 12.5 mm. These quantities are summarised in Table 1.

| Symbol               | Value      |
|----------------------|------------|
| VG height            | h          |
| VG chord             | l          |
| Angle of attack      | α          |
| VG pair TE separation| TE         |

Table 1. Vortex generators geometry

3. Computations description

The employed CFD tool is the open source code OpenFoam version 4.0. All the computations were performed with the same characteristics as the AVATAR experiments [1]: Reynolds number based on the boundary layer momentum thickness of 2600 and free stream velocity of 15 m/s. These experiments were used to validate the OpenFoam results for the rectangular VG and the results were satisfactory.

The computational domain height is 35 mm, length 1.55 m and width 80 mm. The boundary conditions used are summarised in Table 2 and the turbulence model used is the $k$-$\omega$ SST model.

| Quantity | Inlet          | Outlet         | VG             | Bottom         | Top            | Sides        | Dimension      |
|----------|----------------|----------------|----------------|----------------|----------------|--------------|----------------|
| $U$      | freestream     | zeroGradient   | fixedValue     | fixedValue     | zeroGradient   | symmetry     | [m/s]          |
| $p$      | zeroGradient   | fixedValue     | zeroGradient   | zeroGradient   | zeroGradient   | symmetry     | [N/m$^2$]      |
| $\nu$   | calculated     | calculated     | zeroGradient   | zeroGradient   | zeroGradient   | symmetry     | [m$^2$/s]      |
| $\kappa$| inletOutlet    | zeroGradient   | $kq$RWallFunction | $kq$RWallFunction | zeroGradient   | symmetry     | [m$^2$/s$^2$] |
| $\omega$| fixedValue     | zeroGradient   | omegaWallFunction | omegaWallFunction | zeroGradient   | symmetry     | [1/s]          |

Table 2. Boundary conditions for VG in flat plate (model $k$-$\omega$ SST).

The meshes were done with ICEMCFD from ANSYS. An O-type mesh is used to discretize the solution domain around the VG geometry with the point closer to the surface at a distance of $10^{-5}$ to ensure $y^+ \leq 1$, according to $k$-$\omega$ SST model. In total, the 3D mesh has 12 millions cells to discretize the solution domain when modelling the VG pair.

The most important part of the mesh is the downstream zone of the VG trailing edge, since it needs to collect all the vorticity to study the development of the boundary layer after the vortex. An area of five times the VG height is refined in order to define in detail the vortex characteristics. Therefore, the highest concentration of cells is found in this zone, about 65% of them.

The meshes used are shown in Figure 2.

4. Results for the VGs studied

CFD computations over a pair of VGs mounted on a flat plate based on the geometries described in the previous sections are shown next (rectangular, RonCZ and ClarkY).

The following figures (Figures 3 to 6) show the vertical and lateral paths of the vortices, the peak vorticity and the viscous forces on the wall comparing the three different geometries studied. These magnitudes are obtained from cutting planes normal to the flow direction at
different locations after the VG pair and postprocessing the vortex evolution on them. The primary vortex center at each plane is the point with the maximum value of vorticity which drives to an analysis of its value (peak-vorticity) and the vertical and lateral path of this point.

According to Figures 3 and 4, the rectangular VG produces vortices that move further from the wall than the other two geometries, having an intermediate trajectory the ClarkY VG. These differences can be observed in both directions which means that the rectangular VG produces bigger vortices than the other geometries studied. From planes 30h to 50h (h is the device height), aerodynamically shaped VGs produce a lower oscillation in the vertical trajectory than the one produced by the rectangular VG, so that a more stable vortex is obtained.

The peak vorticity, shown in Figure 5, is also higher for the rectangular VGs and the ClarkY is again in the second place. A correlation between the vortex trajectory is found which remarks the influence of the peak-vorticity in the vortex size and the diffusion downstream the vane. Hence, the vortices produced by the rectangular vane are stronger.

The streamwise component of the wall shear stress has been measured at the middle of the vane. The value of this stress in the flat plate tends to be converged to the same value further away from the VG pair. Then, aerodynamically shaped VGs are in a good agreement with the rectangular vane in terms of delaying the stall due to the same increase in wall shear stress far from the VGs location.

Figure 2. Meshes used in the computation (rectangular, ClarkY, RonCZ).

Figure 3. Vertical path of the VGs.

Figure 4. Lateral path of the VGs.
The drag coefficient produced by the existence of the VGs has been obtained for the three different geometries studied. It is the sum of pressure and friction forces and has been obtained integrating both magnitudes in the VG pair wet surface. This surface is the blue area shown in Figure 7. The values are summarised in the table included in the same Figure 7.

| VG          | Drag coefficient |
|-------------|------------------|
| rectangular | 0.1405           |
| ClarkY      | 0.0986           |
| RonCZ       | 0.0808           |

As the drag coefficient of the rectangular vane is bigger than the produced by the rest geometries, the flow around the vane has been analyzed. Figure 8 shows a top view of the velocity fields produced by the rectangular VG and the ClarkY VG. As it can be observed, in the rectangular VG the flow separates in the leading edge of the vane while in the airfoil shaped one a non-separated region appears that explains the reduction in the induced drag.
Figure 8. Flow comparison between the rectangular VG and the ClarkY VG. Top view of the velocity field.

Velocity contours for the VGs based on the RonCZ, ClarkY and rectangular VGs are plotted in Figure 9. Three locations downstream of the VG pair are shown. As it can be observed, the vortex size increases when moving far from the VG pair corroborating the vertical and lateral paths tendency shown in Figures 3 and 4. On the other hand, the vortex strength decreases for the more downstream locations. In these figures the different types of vortices produced by the different shaped VGs at the same location after the VG pair can be clearly observed.
5. Conclusions and future work

In this paper, non-conventional geometry VGs have been computed with a fully resolved approach. The choice of VGs based on airfoil shapes is inspired by the idea of reducing the drag force added by the use of VGs in the blades.

The main conclusion is that rectangular VGs produce stronger and bigger vortices with higher vorticity. In addition, the vortices produced by the VGs analysed are different in size and shape and develop in a different way along the domain.

When analysing the drag force, the rectangular VGs produce the highest drag so VGs with airfoil shape cross section are more beneficial in terms of drag penalty. When observing the flow fields, the flow separates in the leading edge of the rectangular VG while in the airfoil shaped VGs remain attached in a certain area leading to a drag reduction. With this regard, the VG based on the RonCZ airfoil is the one that presents less resistance to the flow but in
real operation it could lead to instabilities produced by laminar bubbles. This conclusion could change depending on the VGs angle of attack and the separation between pairs and will be checked in future works.

Currently, aerodynamically shaped VGs are studied mounted on airfoils to demonstrate that the drag reduction achieved when they are mounted on a flat plate appears also when working in airfoils. These results will be presented in future works.

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