Streamwise vortex generator for separation reduction on wind turbine profile

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Abstract. High angles of attack of the wind turbine blades induce severe flow conditions which lead to flow separation and, as the consequence, aerodynamic performance reduction. Implementation of a new type of passive streamwise vortex generator (Rod Vortex Generator - RVG), on a wind turbine profile in order to reduce the flow separation is presented. Numerical model validation is carried out for the S809 aerofoil and a wide range of angles of attack (AoA) employed as reference for flow control cases. Investigation of proposed passive control method involves attached as well as incipient and massive flow separation. A study of chordwise location of RVGs for different inflow conditions is performed. The numerical and experimental results are in good agreement. Obtained numerical results based on the RANS approach reveal a large potential of selected passive devices in reduction of flow separation and increase of aerodynamic performance.

1. Introduction
The interest in application of flow control devices on wind turbine blades has increased in last decades. One of the design objectives and turbine operation requirements is the reduction of blade vibration amplitude and improvement of turbine blade performance. Development is also driven by continuous increase of blade length. Compared with constant rotational speed and fixed/collective pitch-regulated rotors, current use of variable speed rotors combined with individual blade pitch control have proven capability to increase global energy extraction, but yet failed to handle the non-uniform inflow conditions along blade span, leading to presence of flow separation on the rotor blade. Separated boundary layer leads to increased aerodynamic losses, noise generation and fatigue loads. Different flow control devices have been developed and implemented on the blades during the last few decades in order to mitigate flow separation and/or blade loading. Different flow control devices and strategies have been proposed; e.g.: trailing/leading edge flaps [1], turbercled leading edge [2], plasma actuators [3] or vortex generators [4].

Vortex generators (VGs) are designed to create streamwise vorticity, which by convection mixes the flow, entraining high momentum fluid from the undisturbed air stream and enforcing transport toward the surface. It finally affects the higher shear stress and decreases separation size. The first experiments on VGs were reported by Taylor in the 1940s (vane vortex generators, VVGs) [5]. These first vortex generators consisted of thin solid plates mounted normal to the surface, of a height (h) of the order of the boundary layer, set at an angle with respect the local flow. Already in the 1958 Wallis demonstrated that a very similar wall shear stress could be obtained by the action of an inclined vortex jet blown from a designed orifice (air jet vortex generators, AJVGs) with a much lower drag penalty [6]. Dimensions and geometry of the hole, as well as, optimum orientation angles and air supply
strategy have been widely investigated [7, 8, 9]. Nevertheless, vane vortex generators are the most popular and a lot of results of experimental and numerical investigations are published. More recent studies on wall vortex generators were focused on the parasitic drag induced and its minimisation. In the early 1970s, Kuethe [10] studied non-conventional VGs with height to boundary layer thickness ratios inferior to 0.5. Research carried out by Rao in the 1980s [11] stated that low profile vortex generators (h/δ ≤ 0.65) have the potential of exceeding the performance of conventional VGs (h/δ ~1) due to much smaller parasitic drag. Nevertheless, low-profile VGs are more sensitive to positioning than classical VGs as consequence of less intense streamwise vortices generated. Since then many researchers have conducted investigations regarding shapes and dimensions of VGs. A comprehensive review on low profile VGs was presented by Lin [12].

The presented investigation is focused on the application of a new type of passive VGs, Rod Vortex Generator (RVG) [13], on a wind turbine profile, in order to study an aerodynamic enhancement possibility. The main advantage over air jet vortex generator is no need to supply air. Compared with classical vanes parasitic drag is much smaller. Besides, RVGs simple geometry allows the combination with MEMS technology and, as consequence, an option to deploy when needed. RVGs are defined by five parameters: skew angle (θ), pitch angle (α), diameter (D), height (h), and spacing (W). The θ and α orientation angles are set equal to their optimum values (maximum streamwise vorticity), θ = 45º and α = 30º, whereas rod diameter, height and spanwise spacing are proportional to the boundary layer thickness, δ (see Figure 1). Optimisation of the rod angles have been done as the preliminary investigations for the simplified configuration with the similar flow conditions and boundary layer at RVG location. Streamwise vorticity generated by a RVG with optimum skew and pitch angles is observed in Figure 1 (right). Displayed streamlines and contour map of streamwise vorticity reveal the creation of a strong primary vortex. Above the main vortex, a counter rotating secondary weak one is also created.

A validation of employed numerical model for wind turbine profile investigations is done as the first step. The NREL S809 aerofoil is chosen for research purposes, not only due to be representative of wind turbine profiles, but preferably because it constitutes a basic cross-section of the well experimentally documented NREL Phase VI wind turbine rotor [14]. The S809 aerofoil was extensively tested at the Ohio State University (OSU) [15], Colorado State University (CSU) [16], Delft University of Technology (DUT) [17] and more recently at the Glasgow University (GU) facilities [18]. From the amount of available data only the fixed pitch, free transition configurations with Reynolds number of 1 million, from the Somers’ [17] and Ramsay’s [15] experiments are harnessed for validation purposes.

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**Figure 1.** Rod vortex generator configuration with retraction possibility (left) and induced streamwise vorticity with streamlines (right)
2. Numerical model description

Numerical RANS (Reynolds Averaged Navier-Stokes) simulations are carried out by means of the 3D block structured Euranus flow solver from the FINE™/Turbo package (Numeca Int.). The compressible, mass-weighted equations are solved adopting a Hakimi preconditioning scheme to increase the convergence rate and accuracy of the solution. The two equation nonlinear eddy viscosity turbulence model of the low-Reynolds Explicit Algebraic Reynolds Stress Model (EARSM) is applied. The solver uses a finite volume approach for a spatial discretization of the RANS equations (central, 2nd order with scalar artificial dissipation) and Runge-Kutta type integration in time. A 2 step multigrid approach with 2 grid levels is applied in order to accelerate the convergence. The CFL number is set to 2. A perfect gas model is employed for closure of the system of differential equations. The dynamic viscosity is calculated using the Sutherland’s law.

The aerofoil surface and rod vortex generators are modelled as adiabatic walls. The profile chord length is taken as the unit, c = 1 m. Farfield boundary conditions are located at 40 chords from the profile to avoid influence of the boundary conditions on the flow around the profile. At the farfield, inflow velocity \( V_\infty \) and static pressure \( P_\infty \) and temperature \( T_\infty \) conditions are imposed. Two sets of C type grids are employed and normal distance to the first grid points layer above the surface is set to \( 3 \times 10^{-5} \) m \( (y^+ < 1) \). The mesh is also refined close to the leading and trailing edges, as well as, in the proximities of implemented rod vortex generators for the case with RVGs and in the suction side mid-chord (initial rod location) for clean configuration. The S809 aerofoil surface is defined by 737 x 145 nodes in the wrap around and normal directions, respectively.

For the clean case a 2D grid is generated with 0.3 million computational cells distributed into 13 blocks. In order to limit needed computational time and required resources, the 3D computational domain for the RVG case is reduced to a slice of the original experimental model, inside which a single rod is placed and periodic boundary conditions applied at lateral surfaces. Further reduction of number of cells is possible by the application of non-matching boundary conditions (NMB) at a distance of 0.13c normal to the wall, so the final mesh size is \( 3.3 \times 10^6 \), distributed among 29 blocks. The mesh for clean and RVGs cases is the same in the streamwise and normal directions, apart from the blocks affected by RVG presence. Proximities of the RVG are resolved by means of a butterfly mesh topology with 33 nodes in the spanwise direction (Figure 2).

For the reference case the dimensionless parameters Re and M∞ are kept constant compared to the Ramsay’s experimental model [15] and the ambient temperature \( T_\infty \) is set to 288 K. Thus the free stream density \( \rho_\infty \) and pressure \( P_\infty \) are rescaled (\( \rho_\infty = \frac{\text{Re} \mu}{V_\infty}, P_\infty = \frac{\rho_\infty}{\text{Re}_\infty} T_\infty \)). The free stream speed \( V_\infty \) and dynamic viscosity \( \mu \) do not need to be rescaled, \( V_\infty = M_\infty \left[ (\gamma-1) C_p T_\infty \right]^{1/2} \) and \( \mu = \mu(T) \) (Sutherland’s law). Turbulence intensity at the farfield applied is such that level of turbulence is lower than 0.1% upstream of the aerofoil.

![Figure 2. Grid and boundary conditions for RVG and S809 aerofoil](image-url)
3. Reference configuration

Lift $C_l$ and drag $C_d$ coefficients as a function of angle of attack $\alpha$ are depicted in Figure 3. The EARSM model provides an accurate prediction of lift for moderate angles of attack, but overestimates its value for larger ones. A more detailed insight into the flow behaviour may be obtained by comparing the predicted pressure coefficient $C_p$ distributions with the experimental data. In Figure 4, $C_p$ distributions for two selected angles of attack, $\alpha = 4.1^\circ$ and $13.3^\circ$, are compared with available experimental data and a reasonably good agreement is obtained.

![Figure 3](image1)

**Figure 3.** Force coefficients versus angle of attack for S809 aerofoil at Re = $1 \cdot 10^6$

![Figure 4](image2)

**Figure 4.** Pressure coefficient $C_p$ distributions for S809 aerofoil at Re = $1 \cdot 10^6$

4. Flow control case – Rod Vortex Generator application

Angles of attack ranging from 4° to 14° are considered for flow control study and the highest inflow angle, with separation onset located at $x/c \approx 0.53$, taken as reference. Rods are initially located at mid-chord and dimensioned according to parameters established in Table 1, where $\delta_{base}$ is set equal to mid-chord boundary layer thickness at reference inflow angle ($\delta_{base} \approx 0.022 \cdot c$).

Figure 5 compares lift $C_l$, drag $C_d$ and pitching moment $C_m$ coefficients for clean and RVGs cases with respect to the angle of attack. At low inflow angles the pressure redistribution induced by presence of rod vortex generators causes a slight lift increase, while aerodynamic performance, given by $C_l/C_d$, is decreased as a consequence of induced parasitic drag. As the angle of attack increases to 10° separation emerges. With the application of RVGs separation present at angles of attack above 10° is reduced and lift is increased. Thus, despite the parasitic drag introduced by RVGs, implementation of these flow control devices lead to increase of lift to drag ratio as consequence of separation reduction. Due to the pressure redistribution induced by presence of RVGs, a modification in $C_m$ with respect to the clean configuration is observed for the studied range of inflow angles.
Aerodynamic enhancement is obtained by means of the implementation of RVGs for inflow angles ranging from 10º to 14º and the maximum improvement is observed for an angle of attack of 12.2º. At such inflow angle, the lift is increased by 5.2% with respect to the clean case and drag reduced by 1.2%, leading to an increase of lift to drag ratio above 11%. Additionally, as shown in Figure 6, the volume of reversed flow is reduced to less than a 3% of the original. Numerical simulations are carried out for one rod only, but for visualization purposes a set of three RVGs are depicted in Figure 6 (total span of $6 \cdot \delta_{\text{base}}$). In the background of isosurfaces indicating detached flow zone (dark green), contour maps of chordwise velocity $V_x$ above a surface $z = \delta_{\text{base}}$ (mid-span of first slice) for clean and flow control cases are presented.

An increase of inflow angle above 10º enforces more upstream separation location. Consequently, it can be expected that flow control devices location moved upstream from the initial mid-chord position will lead to a higher improvement of aerofoil performance for higher inflow angles. If RVGs moved more downstream, it may happen that they are located in the separation zone and they are not effective. Thus, notwithstanding the aerodynamic performance improvement obtained by implementing the RVGs at certain location, it is needed to investigate the chordwise location effect on
the device effectiveness. Flow control device should be neither positioned too close to the separation (not enough space to develop vortical structures), nor too far away (vorticity diffusion).

Four additional chordwise locations, $x_{RVG}/c = 0.35, 0.40, 0.45$ and $0.55$, and four different flow cases are considered for RVGs investigation. All cases are selected for high inflow angles: $11.2^\circ, 12.2^\circ, 13.3^\circ$ and $13.9^\circ$, with separation onset located at $x/c = 0.88, 0.65, 0.55$ and $0.53$, respectively. Boundary layer thickness at reference inflow angle ($AoA = 13.9^\circ$) grows rapidly along the suction side of the aerofoil, $\delta/c \approx 0.013$ at $x_{RVG}/c = 0.35$ and $\delta/c \approx 0.035$ at $x_{RVG}/c = 0.55$. Consequently, for the RVG chordwise location investigation, two scenarios are considered: RVGs with dimensions proportional to local reference boundary layer (case 1) and RVGs with height ($h$) and diameter ($D$) kept constant (case 2). In the former case local boundary layer thickness $\delta^*$ at $AoA = 13.9^\circ$ is taken as reference. RVGs parameters values are summarized in Table 2.

![Figure 6. Isosurface of detached flow (dark green) and contour maps of chordwise velocity for clean and flow control cases with $x_{RVG}/c = 0.50$ at $AoA = 12.2^\circ$.](image)

Table 2. RVGs parameters value for cases 1 and 2

| Parameter     | Case 1 | Case 2 |
|---------------|--------|--------|
| Height, h [mm]| 0.36$\delta^*$ | 7.78   |
| Diameter, D [mm]| 0.20$\delta^*$ | 4.32   |
| Spacing, W [mm]| 43.2 (W/D $\approx$ 6.3-16.5) | 43.2 (W/D = 10) |
| Location, $x_{RVG}/c$ [-] | 0.35 - 0.55 | 0.35 - 0.55 |
| Inflow angle, AoA [º] | 11.2 - 13.9 | 11.2 - 13.9 |

In the Figure 7 contour maps of skin friction coefficient on the S809 aerofoil suction side at the angle of attack $12.2^\circ$ for case 1 are shown. At the top, the uncontrolled case is shown, below, the cases for increasing chordwise location of RVGs are displayed. The skin friction provides information of the shear stresses distribution and indicates the location of flow separation. Additionally, streamlines plotted allow the assessment of the flow patterns development on the aerofoil and visualisation of the reattachment line.

It is shown in the Figure 7 that skin friction along the chord increases downstream of the RVGs location and it is higher than the one obtained for the clean case. Zones of lower friction are present between rods. This structure is originated by the streamwise vortices and its effect on locally increased and decreased shear stresses in spanwise direction. Additionally, a spanwise velocity component has been generated by the RVGs, rooted in the spanwise migration of the created vortices. As the RVGs location is moved downstream, the penetration of streamwise vorticity generated is increased and the separation further decreased.
For case 1 lift $C_l$ and drag $C_d$ with respect to the case without flow control are shown in Figure 8. The variation for the considered RVG locations and inflow angles indicate better or worse cases, which means the positive or negative effect obtained if RVG is applied. It is observed that the lift increases for all locations and inflow angles, but for the angle of attack $13.9^\circ$ and $x_{RVG/c} = 0.55$, where RVG is located inside the separation bubble. The reduction of drag is obtained for certain rods locations and angles of attack. However, the configuration of maximum lift increase corresponds with the area of drag reduction, pointing the configurations as the aerodynamically improved. In case of angle of attack $11.2^\circ$ the maximum lift is obtained for RVGs located at $x_{RVG/c} = 0.55$. The lift is decreasing as they are placed closer to the leading edge. Simultaneously, when the RVG location is moved upstream the drag

![Skin friction coefficient $C_{f_x}$ and surface streamlines for different RVGs chordwise locations at AoA = 12.2° for case 1](image)

**Figure 7.** Skin friction coefficient $C_{f_x}$ and surface streamlines for different RVGs chordwise locations at AoA = 12.2° for case 1
is increased. It means that even if a higher vorticity is created by a RVG located more upstream, the streamwise vortices dissipate along the distance to the separation. Similar effect to the analysed above is obtained for the inflow angle 12.2°. The maximum improvement in aerodynamic performance by the implementation of flow control devices is obtained for $x_{RVG}/c = 0.50$. As the angle of attack increases to 13.3° the separation line moves to $x/c = 0.55$ and the optimum RVG location is at the mid-chord. More upstream locations provide smaller increases in lift (vortices are more dissipated) and higher drag. For $x_{RVG}/c = 0.55$ the lack of distance to the separation onset impedes the development of the vortex structure and a high drag penalty appears. Further increasing of the angle of attack up to 13.9° a more modest profit is obtained with the RVG inclusion. The RVGs located at $x_{RVG}/c = 0.55$ show a negative effect on the aerodynamic performance as expected since the devices are located inside the region of detached flow (separation onset at $x/c = 0.53$). At this inflow angle only RVGs located at mid-chord provide a drag reduction. Based on the contour map analysis one can conclude that for the present case the optimum RVG location is at mid-chord, $x_{RVG}/c = 0.50$.

In Figure 9, contour maps for variations of lift $C_l$ and drag $C_d$ coefficient for the considered RVG locations and inflow angles, with respect to the case without flow control, are depicted for case 2. Similarly to the case 1, the lift increase is obtained for all locations and inflow angles, but for the angle of attack 13.9° and $x_{RVG}/c = 0.55$, where RVG is located inside the separation bubble. Compared with the case 1, reduction of drag and further increase of lift are shown for RVGs locations upstream of the mid-chord. If RVGs are moved downstream to $x_{RVG}/c = 0.55$ the opposite effect is obtained. Variation of lift and drag values is based on the alteration of RVGs height to local boundary layer thickness ratio $h/\delta$, keeping rod height and diameter unchanged.

**Figure 8.** Effect of RVGs chordwise location on $C_l$ and $C_d$ for case 1

**Figure 9.** Effect of RVGs chordwise location on lift and drag coefficients for case 2
If RVG designed for initial location at mid-chord are moved upstream, then the rods are located at thinner boundary layer what increases the $h/\delta$ ratio, leading to stronger streamwise vortices in comparison with the same rod location for case 1. Notwithstanding this fact, when initial location $x_{RVG}/c = 0.5$ is taken as the reference, penetration of the streamwise vorticity is shortened and interaction with detached flow is weaker for upstream locations. It leads to smaller values of lift and higher drag. This effect can be observed in Figure 10 where streamwise values of $C_{fx}$ together with streamlines are depicted on the suction side of the S809 aerofoil for an angle of attack AoA = 12.2º and the range of RVGs locations studied, $x_{RVG}/c = 0.35-0.55$. When compared with Figure 7 for case 1 vorticity penetration is extended for rods locations upstream of initial configuration and shortened at $x_{RVG}/c = 0.55$, as mentioned above.

Figure 10. Skin friction coefficient $C_{fx}$ and surface streamlines for different RVGs chordwise locations at AoA = 12.2º for case 2
5. Conclusions
Numerical model was satisfactorily validated and employed for the investigation of aerodynamic improvement by means of rod vortex generators. Numerical results obtained for a clean S809 aerofoil were considered as reference for the flow control analysis. RVGs were initially located at mid-chord and dimensioned in relation to the local boundary layer thickness. A location study was performed and effect on aerodynamic forces analysed. Introduction of RVGs have proven to lead to improvement of aerodynamic performance and decrease of flow separation. Optimum configuration was provided by a mid-chord location. At mid-chord location the maximum improvement is observed for an angle of attack of 12.2º, with an increase of lift to drag ratio above 11% and separation is nearly totally eliminated. The successful implementation of rod vortex generators to the wind turbine profile points RVGs as possible flow control devices for the wind energy industry.

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