Assessment of the CFD capabilities to predict aerodynamic flows in presence of VG arrays

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Abstract. Modelling of aerodynamic flows in the presence of vortex generators constitutes a big challenge for CFD due to the different scales involved. The present paper addresses this issue in terms of accuracy and cost. In the simple case of a VG pair placed on a flat plate with no streamwise pressure gradient, the option of fully resolving the VG and that of using the jBAY model are compared with measurements and other CFD simulations. Then the case of 3D separation control on a rectangular wing is considered and comparisons to measurements are performed. Although full resolution of the VGs improves accuracy, the vorticity production is still significantly underestimated, a fact linked with the incapacity of eddy viscosity models to predict vortex flows. It is found that the simulation of one VG pair with periodic side conditions gives fair predictions as long as the VGs keep the flow attached. At angles of attack where 3D separation occurs, this cost effective modelling approach is no longer valid and simulations should include the complete array of VGs. Stereo PIV data showed that close to the VGs (up to 37.2 VG heights downstream of the VGs) turbulent transport between the vortices is strong while further downstream (up to 47.2 heights) diffusion becomes dominant. The normal Reynolds stress distributions also indicate significant vortex wandering in both the normal and spanwise directions.

1. Introduction
Passive vortex generators (VGs) are commonly used as a means to enhance wind turbine power by delaying separation. The ability to predict the effectiveness of a VG configuration and to produce an optimal design is hence crucial. As VG size is at the order of the local boundary layer (BL) thickness or smaller, i.e. orders of magnitude smaller than the blade radius or the local blade chord, numerical prediction of the flow becomes quite challenging. In fact, fully resolving the viscous flow around a single VG pair on a wing requires a computational mesh of many million cells. As a result, the cost in the case of a blade having an array of VGs deployed over part of its length becomes prohibitively high. In order to overcome this cost issue, numerous approximate VG models have been developed which bypass the need of including the exact VG geometry in the simulations. They either approximate the presence of the VGs by adding body forces as in the case of the jBAY model [1] or add the effect of vortex shedding in model equations [2]. However, comparisons to measured data indicate that computations using such models tend to under-predict the effect of the VGs and so the design issue with respect to wind turbine blades remains open.

Based on the above, the present work aims at:

a) Assessing the prediction capability of the commonly used jBAY model as compared to fully resolved CFD computations and experimental data
b) Outlining a simulation strategy when considering an array of VGs

c) Examining the spatial development of the VG vortices on a wing experiencing 3D separation

The first point is examined for the case of a single VG located on a flat plate with zero-pressure gradient. Simulations with and without the jBAY model are performed and are compared to previously published numerical and experimental data [3]. The last two points concern the flow over a wing equipped with VGs. Two modeling strategies are investigated both using the jBAY model. The first option considers a strip containing a single VG with appropriate sidewall conditions corresponding to a spanwise periodic flow while the second option considers the full wing. They are denoted as "strip" and "full span" options. The simulation results are compared to original experimental data. The same set of experimental results is used to study the spatial evolution of the VG vortices.

2. Methods

2.1. Computational Approach

The (U)RANS MaPFlow solver [4] is used. MaPFlow is an unstructured, multi-block, MPI enabled finite volume compressible code, equipped with low Ma pre-conditioning and able to use two eddy viscosity turbulence models, the Spalart-Allmaras (SA) and the k-ω SST. For the zero - pressure gradient case the k-ω SST model is used so that results are directly comparable to those from [3]. For the flow past the wing model with VGs the SA model is used also for compatibility reasons with previous simulations [5]. This difference in turbulence modeling is not regarded critical since according to [6] both models give comparable results for flows with VGs.

For the flat plate case two grids are considered: the first grid concerns the jBAY model and is similar to that in [3] while the second fully resolves the VG geometry. For the wing case the question is whether it is correct to only consider one VG pair and solve the flow with periodic conditions or it is necessary to resolve the complete VG array. In all simulations the boundary layer mesh ensured the y+ value was lower than 1 throughout the wing surface. Details on the grids are given in Table 1, while a grid dependence study can be found in [7].

Table 1: Total number of cells for the different grids used in the present study.

| Case                  | VG on flat plate                  | VG on wing  |
|-----------------------|-----------------------------------|-------------|
|                       | jBAY model                        | Fully Resolved | "Strip" (AR = 0.058) | Full span (AR = 2.0) |
| Number of Cells       | 1.5x10^6                          | 3.0x10^6     | 1.0x10^6             | 7.5x10^6              |

2.2. Experimental data

The experimental data concerning the flat plate case are taken from [8], where a complete description of the experimental set-up can be found. A single rectangular vane VG was mounted on a long flat plate at an angle of attack of 16° with respect to the free stream. The local turbulent BL thickness (δ) at the VG location was δ ≈ 35 mm and the free stream velocity was U = 35 m/s. The VG height was h = 7 mm (h/δ = 0.2) and its chord length was 49 mm (l/h = 7).

For the wing case, experiments were performed at the NTUA wind tunnel. The tests concerned an 18% thick airfoil optimized for use on multi MW wind turbine rotors [9]. Pressure and Stereo - PIV measurements were performed and the detailed description of the experimental set-up can be found in [7]. The airfoil profile and measurement planes can be seen in Figure 1 (Left) and a schematic representation of the test set up is given in Figure 2. The rectangular wing experiences 3D separation of the stall cell (SC) type as detailed in [5, 10, 11]. The inherently unstable SC was successfully stabilized by means of a localized spanwise disturbance in the form of a zigzag tape [11], which was used for both the controlled and the uncontrolled cases. The wing model had a c = 0.6 m chord and all experiments were conducted at Re = 0.87x10^6. The VG lay out for the wing case was selected after a numerical parametric study was performed using the "strip" option [7]. The examined parameters are given in Figure 1 (Right) and their final values in Table 2. The VG height of the best performing configuration was equal to the local BL thickness.
Figure 1: Left: Airfoil profile and Stereo - PIV measurement planes at $\alpha = 10^\circ$; Right: Vortex Generator configuration parameters

Figure 2: Schematic planform view of the test set up showing the wing, the fences, the pressure taps at the centre of the wing span, the stabilizing disturbance and the Stereo PIV cameras along with the measurement planes at $x/c = 0.6$ (plane A), $x/c = 0.7$ (plane B) and $x/c = 0.8$ (plane C).

Table 2: VG configuration parameters for the best performing VG configuration. All parameters are defined in Figure 1.

| Parameter | Value |
|-----------|-------|
| $x/c$     | 0.3 or 0.4 |
| $V_G$     | $20^\circ$ |
| $H$       | $\delta = 6$ mm |
| $L$       | $3h$ |
| $d$       | $11.7h$ |
| $D$       | $3.7h$ |

3. Results

3.1. Single Vortex Generator on a flat plate in a zero pressure gradient flow

A comparison of the present flat plate computation results with those from [3, 8] is performed with the intention of (a) validating the implementation of the jBAY model in the MaPFlow code and (b) examining whether a better solution could be obtained with a finer grid and thus assess the prediction.
capability of the commonly used jBAY model. Results show (Figure 3, below) that when a similar grid is used the presently presented jBAY model results compare very well with the WindUS data [3]. This confirms that the jBAY model implementation in MaPFlow is correct. When the VG geometry was fully resolved (FR) with a fine grid, the obtained results were an improvement over the computational results in [3] (66% increase in peak vorticity), as Figure 3 shows. However, there are still considerable differences compared to the experimental data of [8]. Further increase in the number of cells (from ~3 million to ~6 million) gave only a marginal increase in initial peak vorticity (+3%). This indicates that the difference in initial peak vorticity is due to turbulence modeling and not to grid resolution, in agreement with [3, 8, 12].

Figure 4 shows velocity and vorticity contours on planes downstream of the VG. The presently reported fully resolved simulation is compared to the also fully resolved simulation from [3] and the experiments from [8]. The velocity deficit in the upwash region of the experimental data is higher than in any of the simulations. In terms of vorticity, MaPFlow results are closer to the measured data, but peak values are still significantly lower.

It is clear that even for this relatively simple case, fully resolving the VG geometry can only provide quantitatively correct results. This means that the additional cost of this approach is not justified in terms of accuracy. Based on this observation it was decided to use the significantly cheaper jBAY approximation for the next, more complex case (array of VGs on a wing experiencing 3D separation).

![Figure 3: Peak vorticity variation with distance from the VG. Comparison between the present computational results (MaPFlow) and the experimental [8] and numerical data [3] (WindUS).](image)

3.2. Array of Vortex Generators on a wing experiencing 3D separation

3.2.1. Vortex Generators at x/c = 0.3. Figure 5 shows the force coefficient polars for the cases without VGs and with VGs at x/c = 0.3. SC formation is delayed by 5° and Cl is found to increase up to 15° angle of attack. At lower angles of attack a drag penalty of 0.002 also appears. In the same figure results from the "strip" simulations are also given. It is clear that lift is overestimated with or without VGs. This is attributed to two inherent shortcomings of the simulations. Firstly, in all computations only half a VG pair was modelled and symmetry side conditions were applied. This means that the numerical wing aspect ratio is AR = 0.058, while SCs scale with the wing chord and do not develop when AR < 1 [7, 13]. This explains the difference between the numerical and experimental results for the uncontrolled case [5]. In addition, the stabilizing zigzag tape used in the experiments located at the centre of the wing suction surface (see Figure 6 and [11] for details) could not be modelled in the "strip" simulations. The ZZ tape brought the separation line upstream locally, even when a SC was not created, see Figure 6. This phenomenon was more pronounced at higher angles of attack, which partially explains the deviation between the computational and experimental results in the case with the VGs. The increase in maximum Cl of 0.457 compares well with the
experimentally obtained increase of 0.495. The additional drag at the lower angles of attack is found to be 0.001 in the simulations (as compared to 0.002 in the experiments).

| Δx/h | Experiment | MaPFlow | WindUS |
|------|------------|---------|--------|
| 3    | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| 5    | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| 10   | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |
| 17   | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| 50   | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) |
| 109  | ![Image](image16.png) | ![Image](image17.png) | ![Image](image18.png) |

Figure 4: Velocity and vorticity contours at six stations downstream of the VG. Comparison between the fully resolved simulations (MaPFlow) and the experimental [8] fully resolved numerical data[3] (WindUS). The velocity scale is common for all plots while the vorticity scales change with Δx/h.

| α [deg] | Experimental - no VGs | Experimental - VGs | slice CFD - no VGs | slice CFD - VGs |
|---------|------------------------|--------------------|--------------------|-----------------|
| 0       | 1.0                    | 1.5                | 1.2                | 1.7             |
| 2       | 1.5                    | 1.8                | 1.6                | 1.9             |
| 4       | 1.8                    | 2.1                | 1.9                | 2.2             |
| 6       | 2.0                    | 2.2                | 2.1                | 2.3             |
| 8       | 2.2                    | 2.4                | 2.2                | 2.5             |
| 10      | 2.3                    | 2.5                | 2.4                | 2.6             |
| 12      | 2.4                    | 2.6                | 2.5                | 2.7             |
| 14      | 2.5                    | 2.7                | 2.6                | 2.8             |
| 16      | 2.6                    | 2.8                | 2.7                | 2.9             |

Figure 5: Lift (left) and drag (right) polars for the case without VGs and with VGs at x/c=0.3. Experimental (Re = 0.87x10^6) and computational (Re = 1.0x10^6) results.
Figure 7 shows the comparison between Stereo PIV results and "strip" CFD results on planes A, B and C at x/c = 0.6, 0.7 and 0.8, respectively, or at Δx/h = 27.2, 37.2 and 47.2. On all planes a vorticity isoline for ω = ω_{max}/2 is drawn, indicating the vortex core. In the numerical data the VG vortex is significantly diffused and peak vorticity is smaller, as expected. In both the experiments and simulations the BL obtains a distinct "Ω" shape under the influence of the VG vortices.

![Figure 6: Flow visualization for the case with VGs at x/c = 0.3, Re = 0.87x10^6, α = 10°. The separation line moves fwd at the centre of the wing span, downstream of the centrally located stabilizing zigzag strip. Blue tape (0.2mm thick) was used to cover the VG strip and the pressure taps during the TiCO2 flow visualization experiments. Flow is from top to bottom and gravity from left to right. The red line indicates the approximate separation location.](image)

3.2.2 Vortex Generators at x/c = 0.4. It is generally preferable to locate VGs as close to separation as possible in order to minimize the additional drag and to increase the VGs effectiveness. Figure 8 (left) shows the lift polar for the uncontrolled case and for the controlled case with the VGs at x/c = 0.4. There is a hysteresis of the flow around α = 13° for the controlled case and the VGs fail to prevent SC formation beyond 14°. At that point a SC is created that engulfs the VGs and thereby cancels their ability to suppress separation. For α < 13° the pressure distribution along the wing chord is very similar for the two controlled cases (VGs at x/c = 0.3 or 0.4), as the pressure distribution at α = 10° shows in Figure 9 (top left).

With regard to simulations, up to 10° the predictions with either the "strip" or the “full span” option are in good agreement with the measurements. Up to this angle of attack, no SC is formed in the experiments and the mainly attached flow is predicted well in the simulations (Figure 9, top right). At 11° (Figure 9, bottom left) a SC is formed in the full span simulation, which does not exist in the experiments. It is conceivable that this happens because the jBAY model predicts weaker VG vortices than they actually are and thus underestimates their ability to prevent SC formation. At this angle, the agreement between the predictions from the "strip" option and the experiments remains good. However, once a SC is created in the experiments at higher angles, e.g. α = 16° (Figure 9, bottom right), the agreement between the measured pressure data and the results of the full span option improves. On the contrary the "strip" simulation over-predicts the effect of the VGs as SC formation does not occur, due to the limited span of the computational domain.

It is therefore concluded that as long as VGs are effective in preventing SC formation, simulating one VG with the jBAY model gives acceptable results. Once a SC is created, however, only full span
simulations can correctly predict the flow. The angle at which the SC is first created is not predicted well by the full span computations with the jBAY model, conceivably due to the model’s tendency to under predict the VG vortices peak vorticity and hence their ability to re-energize the boundary layer.

3.2.3. Vortex evolution in space. Stereo PIV measurements were taken at x/c = 0.6 and 0.8 for both controlled cases (VGs at x/c = 0.3 and 0.4). Since the pressure (and hence the velocity) distribution along the airfoil is similar in the two cases (see Figure 9, top left) the vortex evolution downstream of the VGs can be examined by combining the two sets of measurements, as shown in Figure 10.

Figure 7: Comparison between Stereo PIV (positive z/h) and numerical data (negative z/h). Left: Normalized streamwise velocity contours. Right: Normalized vorticity contours. Vorticity isolines for $\omega = \omega_{\text{max}}/2$ for each vortex are also plotted. Top, middle and bottom row correspond to plane A ($x/c=0.6$, $\Delta x=27.2h$), B ($x/c=0.7$, $\Delta x=37.2h$) and C ($x/c=0.8$, $\Delta x=47.2h$), respectively. The wing surface is always at y/h=0 and z/h=0 is the centreline between the two VGs.
The two vortices grow in size as they proceed downstream and move upwards, away from the wing surface under mutual induction. The change in vortex shape from $\Delta x/h = 17.2$ to $\Delta x/h = 37.2$ (see vorticity isolines on each plane) suggests that there is strong interaction between the two vortices in this part of the flow. From $\Delta x/h = 37.2$ to $\Delta x/h = 47.2$ the vortices grow, but maintain their elongated...
shape, suggesting that diffusion dominates the flow. The distribution of $\overline{w'w'}/U_{\text{inf}}^2$ also changes in the first three planes while it appears diffused from the third to the fourth plane, in support of the previous statement.

The high concentration of $\overline{u'v'}/U_{\text{inf}}^2$ between the two vortices is attributed to vortex wandering. As the measurement snapshots suggest, when the two vortices approach each other the combined upwash between them becomes strong, whereas it is weakened when they move away from each other. Vortex wandering (in the vertical direction) is also suggested by the high concentration of $\overline{w'w'}/U_{\text{inf}}^2$ on the first two planes (closer to the VGs).

![Figure 10: Stereo PIV measurements on planes x/c = 0.6 and x/c = 0.8. The 1st and 3rd plane in each image have the VGs at x/c = 0.4 while the 2nd and 4th plane have the VGs at x/c = 0.3. "delta_x/h" is the distance from the VGs' trailing edge. Vorticity isolines for $\omega = \omega_{\text{max}}/2$ for each vortex are also plotted. First row: Left: Normalized streamwise velocity; Right: Normalized streamwise vorticity. Second row: Left: $\overline{u'v'}/U_{\text{inf}}^2$ ; Right: $\overline{w'w'}/U_{\text{inf}}^2$ normal Reynolds stress.]

4. Conclusions

The present work indicates that in the context of eddy viscosity turbulence modelling, the jBAY model is a decent compromise. The option of fully resolving the VG geometry is not accurate enough to justify the significantly higher cost involved. Irrespective of whether or not the VG is fully resolved, the VG vortex intensity is underestimated and further increase in grid resolution fails to improve predictions; a conclusion that reconfirms previous reports on the inadequacy of eddy viscosity models to predict VG flows.
"Strip" simulations with the jBAY model were found acceptable for predicting the polars of airfoils with VGs, as long as SC formation is suppressed. Beyond that point, Cl will wrongly keep on increasing and therefore the resulting improvement of the blade performance will be fictitious. Modelling the complete wing span improves prediction at higher $\alpha$, where a SC is formed. However, full span simulations underestimate VG effectiveness at lower angles of attack. This is conceivably because the strength of the generated VG vortices is under-predicted.

Experimental data for the flow past VGs on an airfoil reveal that up to 37.2h downstream of the VGs, turbulent transport between the VG vortices and the underlying flow is strong while further downstream (up to 47.2h) diffusion becomes the main mechanism that governs the flow. The normal Re stress distributions also indicate significant vortex wandering.

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