Parametric study of vane-type vortex generators under adverse pressure gradient by source term modelling in OpenFOAM

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Abstract. The aim of the study is to analyse and characterize the primary vortices produced by single low profile vane-type vortex generators (VGs) of different heights positioned on a flat plate with a backward-facing ramp and adverse gradient pressure for an incident angle of 15º. The effect of the vortex generator is implemented by using a source term in the Navier-Stokes equations according to the so-called jBAY source term model. In order to carry out the parametric study of the primary vortex, Computational Fluid Dynamics (CFD) simulations have been performed for different VG heights using the Navier-Stokes equations at a Reynolds number of $Re \theta = 9100$ based on the local boundary layer momentum thickness $\theta$ in open-source code OpenFOAM. As a preliminary result, the jBAY model reproduces relatively well the streamwise pressure coefficient distributions on the flat plate floor. Finally, the advantage of using this model over a fully mesh-resolved vortex generator model for certain cases must be remarked because a lower number of cells is needed in the model domain with a saving of computational time and resources.

1. Introduction

Flow separation control and the energy losses associated with the boundary layer (BL) have emerged as a key point in certain industrial fluid dynamics applications. The flow separation from a continuous surface is governed by the adverse pressure gradient and the viscosity. If the flow must remain attached to the wall, the stream should have enough energy to overcome the adverse pressure gradient, the viscous dissipation along the flow path and the energy loss caused by the modification in momentum. If the loss is such that further advancement of the fluid is no longer possible, then the flow separates from the surface.

Vortex generators (VGs) are passive devices to control flow which are able to change the motion performance of the fluid in the BL region. VGs are small vanes not aligned with the oncoming flow and they act by exchanging momentum from the distant flow region to the wall-closed inner region. Triangular and rectangular conventional VGs have been implemented onto wings of airplanes (Figure...
1) for flow control to efficiently improve mixing of the BL and transfer momentum nearby the wall by delaying or suppressing the flow separation. In the experimental work performed by Velte [1] and the associated simulations carried out by Fernandez-Gamiz et al. [2] and Urkiola et al [3] demonstrated that the primary vortex produced by a rectangular VG mounted on a flat plate showed self-similarity for axial and azimuthal velocities. In most applications, VGs are designed with their height $h$ similar to the local BL thickness $\delta$ and mounted normal to the surface with an incident angle to the flow to produce streamwise vortices. However, the residual drag related to these $\delta$-scale conventional VGs might be relatively large in some flow-control application.

The generation of streamwise vortices by means of the implementation of vane-type devices with reduced height is a simple method to enhance their efficiency. Lin et al. [4] proved that when decreasing the height of standard VGs to a value lower than the local BL thickness, the momentum transfer keeps being large enough to avoid or delay flow separation downstream of the VGs. These so-called low-profile VGs were mounted on multi-element high-lift airfoils with the aim of controlling the flow separation on the flap. Ashill et al. [5] in a conceptual and experimental study showed a successful delay of the shock-induced separation on a transonic profile by mounting Sub Boundary Layer Vortex Generators (SBLVG). According to Lin [6], the implementation of these low-profile VG devices could be considered as a feasible option to be implemented when the flow-separation positions are relatively fixed and the vanes can be implemented upstream relatively nearly the flow separation. The European FP7 AVATAR project [7] and [8] has compiled a large amount of experimental and numerical work on VGs on flat plates, airfoils for 2D and 3D flows and their corresponding advances.

![Image](image.png)

**Figure 1.** Sketch of an airfoil with a set of pairs of triangular vortex generators (VGs) placed on its upper surface.

In order to design and optimize the position of the vortex generator on a wind turbine blade, CFD tools can be used as for instance Fernández-Gamiz et al. [9] do. However, modelling the fully-meshed VGs on a full rotor computation becomes expensive. A different option of modelling VGs in CFD is to model its influence on flow using body forces. Bender et al. [10] developed a source term model called the BAY model. The underlying main of this model is based on replacing the vane-type VG by a local source term. The results when applying this model are quite satisfactory as shown for instance by Florentie et al. [11].

The main goal of this study is firstly the implementation of the so-called jBAY Source Term Model proposed by Jirasek [12] into OpenFOAM code [13] and secondly to investigate how well the open source CFD simulations are able to mimic the physics of the flow behind two modelled rectangular conventional and sub-boundary layer vortex generators (VGs) mounted on a three-dimensional flat plate with a backward-facing ramp under adverse pressure gradient conditions for an incident angle of 15°. This study is based on Errasti et al [14].

2. Theoretical background

The model consists of a single rectangular VG positioned on a flat plate with a backward-facing ramp. The three-dimensional computational domain modelled in OpenFOAM represents the extended test
section of the wind tunnel experiment performed by Lin [15] and is shown in the illustration of Figure 2. Note that the single VG is placed upstream the backward-facing ramp. The domain has been designed following a previous simulation study by Konig et al [16].

The geometry dimensions of the vane-type VG determined by a length $L$ two times the VG height $H$ are depicted in Figure 2 for two different heights $H_1=0.8\delta$ and $H_2=0.2\delta$ where $\delta$ is the local boundary layer thickness just upstream edge of the ramp. The vortex generators respectively are positioned at distances of $5\delta$ and $2.5\delta$ from the upstream edge of the ramp.

![Figure 2](image.png)

**Figure 2.** Description of the computational domain. The domain dimensions are expressed in meters.

In the current work, the jBAY source term model by Jirasek [12] based on the BAY model developed by Bender et al. [10] is implemented. The BAY model was designed for simulating vane-type vortex generators into finite volume CFD codes and allows substituting the VG geometry by a subdomain of similar size at the original VG location where a specific body force distribution is then applied. In the Figure 3, the selected cells where the body force will be applied are indicated. According to Bender et al. [10] a new term the final lift force on a single cell $L_{cell}$ is given by the following expression:

$$L_{cell} = C_{VG}\rho (\vec{u} \times \vec{b})(\vec{u} \cdot \vec{n}) \frac{\vec{u} \cdot \vec{t}}{\vec{u}} S_{VG} \frac{V_{cell}}{V_s}$$

where $\rho$ is the local density, $\vec{u}$ the local velocity, $\vec{b}$ the unit vector defined as $\vec{b} = \vec{n} \times \vec{t}$ with $\vec{n}$ and $\vec{t}$ the unit vectors normal and tangential to the VG respectively, $S_{VG}$ the vortex generator area, $C_{VG}$ a relaxation constant parameter of value $C_{VG}=10$ (see Jirasek [12]), $V_{cell}$ the volume corresponding to a single cell and $V_s$ the total volume of the grid cells where the model is applied. The model is incorporated into the CFD code as a source term in the Navier-Stokes momentum and energy equations.
3. Experimental data

Experimental data for this study has been taken from the experiments carried out by Lin et al. [15]. The current computational domain partially based on a previous simulation study performed by König et al. [16] consists of a flat plate with a backward-facing ramp and adverse pressure gradient where selected cells corresponding to a single rectangular vortex generator according to the jBAY model and positioned at a point where the VG height is 20% and 80% the local boundary layer thickness $\delta$ at the upstream edge of the ramp for the cases H1 and H2 respectively. The angle of incidence of the vane with respect to the oncoming flow is $\beta=15^\circ$ for the two VG cases.

4. Computational configuration

Open source code OpenFOAM [13] is used for reproducing the primary vortex. This open source CFD code is an object-oriented library written in C++ to solve computational continuum mechanics problems. In the OpenFOAM CFD code, the user has only to specify the following three parameters for a specific VG: the grid cells where the source term model will be applied, the VG area and the angle of incidence $\beta$ of the main flow direction with respect to the VG orientation. Steady-state, incompressible and turbulent flow is assumed and Reynolds Average Navier-Stokes (RANS) turbulence modelling according to the Shear Stress Transport (SST) turbulence model proposed by Menter [17] is applied in the simulations. The computational domain was discretized with a structured-type mesh and hexahedral faces of around $5 \times 10^5$ cells for the H1 = 0.8$\delta$ vane-type VG case and $2 \times 10^6$ cells for the H2 = 0.2$\delta$ vane-type VG case. Full second order linear-upwind schemes for the discretization were implemented for all the simulations. Two quality mesh parameters such as mesh orthogonality and mesh skewness for the two VG cases were studied in order to analyse the mesh quality. According to Richardson and Gaunt [18] Extrapolation Method, a grid dependency study was performed for three different mesh resolutions: coarse, medium and fine. The iterative solution process was carried out in the simulations of the two VG cases until the residual errors dropped below $10^{-4}$ for the pressure $p$ and $10^{-5}$ for the velocities $U_x$, $U_y$ and $U_z$ and the turbulence quantities used, e.g., the turbulent kinetic energy $k$ and the specific dissipation rate $\omega$. In the two meshes corresponding to the two VG cases analysed, the value for the dimensionless distance of the first wall cell $y^+$ is lower than 1 as required by the turbulence model adopted.

5. Results
Figure 4 shows the vortex visualization based on the velocity field distribution at four planes normal to the streamwise direction and located at normalized distances $x/\delta$ respect to the boundary layer thickness $\delta$ from the backward-facing ramp where the domain origin is placed. This visualization allows just checking in a non numerical approach the vortex formation past the modelled VG.

As a preliminary result, the effect generated by the modelled VG of height $H_1=0.8\delta$ placed at $x=-5\delta$ upstream the ramp on the streamwise pressure coefficient distribution $c_p$ along a measurement line on the flat plate floor past the passive device is shown in Figure 5.
Figure 5. Streamwise pressure coefficient distribution $c_p$ along a measurement line on the flat plate floor past the VG. The red rectangles represent the simulated data (jBAY model), the blue circles the distribution data (Baseline) obtained from the baseline simulation and the green triangles the experimental (EXP) distribution data. Plots corresponding to the VG of height $H_1=0.8\delta$.

The path or trajectory of the vortex in the vertical ($y$) and lateral ($z$) directions can be determined by computing the location of the vortex center generated by the VG all along the downstream axis $x$. The modelled vertical and lateral paths are shown in Figure 6 are in concordance with the experimental vortex lateral and vertical paths.

Figure 6. Normalized vertical (a) and lateral (b) paths function of the normalized distance $x/\delta$ from the backward-facing ramp for the $H_1=0.8\delta$ (blue rectangles) and $H_2=0.2\delta$ (red circles) vane-type VG cases. VGs, flat plate and ramp are also shown (not at scale).

A way to study the vortex size is by means of the half-life radius $R_{0.5}$ defined as the radial distance from the vortex center to the point where the vorticity is half the peak vorticity $w_{\text{max}}$ captured in a cross-stream plane. Figure 7 shows the vortex size evolution expressed in terms of the normalized half-life radius $R_{0.5}$ for the $H_1=0.8\delta$ and $H_2=0.2\delta$ vane-type VG cases at different locations $x/\delta$ past the VG.
Figure 7. Vortex size evolution expressed in terms of the normalized half-life radius $R_{0.5}$ at difference normalized distances $x/\delta$ for the H1=0.8 $\delta$ (blue rectangles) and H2=0.2 $\delta$ (red circles) vane-type VG cases.

6. Conclusions

The generation of vortices and their effects by single low profile vane-type vortex generators of different heights positioned on a flat plate with a backward-facing ramp and adverse gradient pressure has been successfully carried out by CFD simulations using the OpenFOAM code in a preliminary approach. The influence of these vortex generators (VGs) on the computational domain flow is implemented by using a source term in the corresponding Navier-Stokes equations according to the so-called jBAY source term model.

The preliminary results obtained for the two vane-type vortex generators for the JBAY modelled pressure distributions are in concordance with the experiments where the influence of these VG devices is observed. However, the streamwise pressure distribution has been slightly underestimated in certain regions far from the ramp and overestimated in other regions by the jBAY model.

The implementation of the jBAY model represents an advantage over a fully mesh-resolved Vortex generator model for certain cases due to a meaningful decrease in the cell number of the computational domain in the CFD simulations. This implies saving of computational time and resources.

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