Evaluating vortex generator jet experiments for turbulent flow separation control

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Abstract.

Separating turbulent boundary-layers can be energized by streamwise vortices from vortex generators (VG) that increase the near wall momentum as well as the overall mixing of the flow so that flow separation can be delayed or even prevented. In general, two different types of VGs exist: passive vane VGs (VVG) and active VG jets (VGJ). Even though VGs are already successfully used in engineering applications, it is still time-consuming and computationally expensive to include them in a numerical analysis. Fully resolved VGs in a computational mesh lead to a very high number of grid points and thus, computational costs. In addition, computational parameter studies for such flow control devices take much time to set-up. Therefore, much of the research work is still carried out experimentally. KTH Stockholm develops a novel VGJ model that makes it possible to only include the physical influence in terms of the additional stresses that originate from the VGJs without the need to locally refine the computational mesh. Such a modelling strategy enables fast VGJ parameter variations and optimization studies are easily made possible. For that, VGJ experiments are evaluated in this contribution and results are used for developing a statistical VGJ model.

1. Introduction

Flow control by means of active VGJs has gained increasing interest in the flow control community during the last two decades. In opposition to passive VVGs that are fixed and unmodifiably, therefore leading to parasitic drag when not needed, active VGJs have the advantage to be switched off when not needed. Moreover, VGJs provide operation modes with different mass flow rates, as well as steady and periodic activation without the need for geometrical setup changes. As a consequence, unwanted parasitic drag does not develop for VGJs. Nevertheless, a complete study of VGJs is more extensive than for VVGs, since various setup parameter combinations may be studied. Still, efficient combinations of the operation parameters have been found in earlier studies. For that, many different experiments have been carried out by various research groups. This contribution concentrates on the theory behind the evaluation of VGJ experiments that were previously carried out by Ortmanns (2008) at Technische Universität (TU) Braunschweig, Germany. Focus is put on the derivation of the additional second-order statistics, i.e. the additional stress distributions that originate from the VGJ vortices. The statistics are required in order to develop a model for VGJs which is solely based on the VGJ setup parameters and that makes it possible to easily include VGJ devices in a computational grid without the need for local mesh refinement.
2. Vortex generator jet experiments

The VGJ experiments that are used for the evaluation study were originally carried out by Ortmanns (2008) at TU Braunschweig, Germany. In particular, only single VGJ setups in a zero-pressure gradient (ZPG) flat plate boundary-layer flow were examined. Ortmanns carried out the experiments in the 1.3 x 1.3 m^2 and 5.7 m long test section of the closed return atmospheric low speed wind tunnel that can achieve a free stream velocity of \( U_\infty = 60 \text{ m/s} \). Furthermore, the wind tunnel has a heat exchanger that ensures the air temperature to be constant at maximum 10.0±0.5 °C above ambient temperature. The turbulence level of the wind tunnel is 0.2% at a wind speed \( U_\infty = 53 \text{ m/s} \) and the average wind speed is uniform within ±0.2%. Particle image velocimetry (PIV) was used for the determination of the instantaneous cross-plane velocity fields. For a description of the PIV method, the interested reader is referred to Raffel et al. (2007).

Vortices originated from a round fluidic VGJ that was located 4.7 m downstream of the leading edge of the flat plate. The VGJ investigated had a diameter \( d = 6.4 \text{ mm} \), a varying pitching angle \( \alpha = 15^\circ - 105^\circ \), and a varying skew angle \( \beta = 30^\circ - 45^\circ \). The free stream velocity \( U_\infty \) was set to 25 m/s or 50 m/s for different investigations. Moreover, the VGJ velocity ratio \( \lambda = U_{VGJ}/U_\infty \) was set to 2.5 and to 5.0, leading to four different VGJ cases in terms of \( U_{VGJ} \).

Figure 1 illustrates the general design parameters for the VGJ.

![Figure 1. The single VGJ actuator geometry and its parameters, taken from Ortmanns (2008).](image)

The spanwise measurements were taken at different cross-planes downstream of the VGJ position at \( x = 50, 100, \) and 200 mm. They represent farfield planes where vortices already are fully-developed. The time-averaged PIV results containing the vortex flow are used, and an analysis of the resulting vortex velocity field is carried out in this paper. The analytical methods are presented in Ch. 3.

3. Analytical methods

The vortex velocity evaluation technique uses the statistical effects of the VGs (valid both for VVGs and for VGJs) on the flow, see also Törnbloom & Johansson (2007). Generally, VGs induce a vortex velocity field \( V_i \) in the flow and for an analysis, the instantaneous flow field \( u_i \) can be decomposed into three different velocity contributions:

(i) the time-averaged flow field \( U_i \),
(ii) the time-dependent turbulent fluctuations \( u'_i \), and
(iii) the additional vortex velocity field \( V_i \) introduced by the VGs,

resulting in a velocity triple decomposition

\[
  u_i = U_i + u'_i + V_i.
\]
Such a triple decomposition of the instantaneous flow field can be used for an analysis of the Reynolds averaged Navier-Stokes (RANS) equations of the mean flow, reading

$$\frac{D U_j}{Dt} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial U_i}{\partial x_j} - u'_i u'_j \right).$$  \hspace{1cm} (2)

In the statistical modelling approach, the Reynolds stress tensor $u'_i u'_j$ from Eq. (2) is substituted by an extended Reynolds stress tensor given by $\overline{u'_i u'_j} \equiv u'_i u'_j + \Delta V_i V_j$, that contains the spanwise averaged additional vortex stress contributions $\Delta V_i V_j$ reading

$$\Delta V_i V_j(y) = \frac{1}{D} \int_{-D/2}^{D/2} V_i(y, z) V_j(y, z) dz,$$  \hspace{1cm} (3)

with $V_i$ originating from the velocity triple decomposition in Eq. (1). A Reynolds stress based turbulence model is then needed for capturing the extended Reynolds stress tensor and for describing the distribution and the development of the total stress components $\overline{u'_i u'_j}$ in a computational fluid dynamics (CFD) analysis.

This modelling approach was successfully applied for the modelling of passive VVGs, see also von Stillfried et al. (2011a) and Törnblom & Johansson (2007). As an example, Fig. 2 shows the two different flow states in an asymmetric diffuser without flow control (2 a) and with applied VVG model (2 b), respectively. Here, it can be seen how the application of the VVG model successfully prevents the flow from separating from the upper wall. Moreover, it could be shown that the VVG model is capable of predicting correct trends and tendencies for a parameter variation of passive VVGs in adverse-pressure gradient flat plate boundary-layer flow, see von Stillfried et al. (2011b)

**Figure 2.** Turbulence kinetic energy contours and streamlines from von Stillfried et al. (2011b): a) separated flow without VG, b) attached flow with applied VVG model.

Within this project, the effective method for VVGs of decomposing the total velocity field and modelling the additional vortex stress tensor $\Delta V_i V_j$ is going to be extended to VGJs. For that purpose, basic knowledge of the vortex stress tensor $\Delta V_i V_j$ and its downstream development behind the VGJs is studied.

4. Results

A CFD analysis including the fully-resolved vortex structures by a single VGJ in a ZPG flat plate boundary-layer flow was recently carried out by Kékesi (2010). The spanwise averaged vortex stresses $\Delta V_i V_j$ of that flow case are given in Fig. 3 a) (not showing the $\Delta U W$ and the $\Delta V W$ vortex stresses). A drawback of the single VGJ analysis is that it is difficult to correctly spanwise average $V_i V_j$ since spanwise periodicity of the vortex velocity field is not given. Moreover, the $\Delta U W$ and the $\Delta V W$ vortex stresses do not vanish for a single VGJ, whereas they eventually
vanish for VGJ arrays due to spanwise periodicity. The long-term aim is to create a novel model for VGJ arrays, giving a periodic spanwise vortex velocity field before spanwise averaging and by that, describing the additional vortex stresses correctly within the RANS approach. This follows the same modelling approach as of the VVG modelling and is justified since the VGJ stress distributions from Fig. 3 a) are principally similar to previous vortex stress results from passive VVGs, cf. Fig. 3 b).

![Graph a) and b)](image)

**Figure 3.** Spanwise averaged vortex stresses $\Delta V_i V_j$ for: a) a single fully-resolved VGJ from Kâkesi (2010) at $x/\delta = 0.60$, $U_\infty = 25$ m/s, $\lambda = 2.5$, and b) modelled VVGs with $h_V G = 18$ mm from von Stillfried et al. (2011a) at $x/\delta = 0.60$, $U_\infty = 26.5$ m/s, $\delta = 86.6$ mm

Experimental research of single VGJs was previously carried out at TU Braunschweig, Germany, by Ortmanns (2008) and a research cooperation was initiated by the authors. A complete evaluation study of the VGJ experiments will be published in a prominent journal paper soon. The aim of this analysis is to evaluate the experimental data in terms of the vortex velocities $V_i$ and the spanwise averaged additional vortex stresses $\Delta V_i V_j$ as well as their downstream development in order to build a VGJ model similar to the VVG model. For that purpose, the two-dimensional results from the stereoscopic PIV measurements at the streamwise positions $x = 50$, 100, and 200 mm downstream of the VGJs was used. The velocity triple decomposition was applied on the time-averaged PIV velocity field containing the vortices and the additional vortex stresses $\Delta V_i V_j$ by the VGJs were extracted. Figure 4 shows the distribution of the $\Delta V_i V_j$ vortex stresses from the experiments (the $\Delta U W$ and $\Delta V W$ stresses are again not shown here) for the single VGJ with a setup $U_\infty = 25$ m/s, $\lambda = 2.5$, $\alpha = 45^\circ$, and $\beta = 90^\circ$.

It is observable in Figs. 3 a) and 4 that both the spanwise averaged VGJ vortex stresses from the fully-resolved computations and from the experiments are qualitatively very similar compared with the VVG modelling results from Fig. 3 b). Nevertheless, it can be observed that the fully-resolved VGJ results differ somewhat quantitatively from the VGJ results from experiments. Especially the $\Delta V V$ and the $\Delta W W$ stresses show deviations in terms of the stress distribution for $\Delta W W$ as well as for the peak value for the $\Delta V V$ stresses. Moreover, the vortex core (approximately located at the peak position for $\Delta U$) in Fig. 3 a) is located closer to the wall at $z/\delta \approx 0.15$ compared to the vortex core from the VVG model at $z/\delta \approx 0.2$. Moreover, it can be seen from Figs. 4 a) - c) that the VGJ vortex from the experiments has a very stable wall-normal position which does not vary much along the streamwise vortex path. It can also be concluded from Figs. 3 and 4 a) that the specific VVG setup creates stronger vortex stresses than the VGJ setup shown here and that, initially, the vortex stress peaks can be as high as three times the peak values for the VGJs.
Figure 4. Spanwise averaged vortex stresses $\Delta V_i V_j$ for single VGJs at streamwise positions $x/\delta = 0.6, 1.2,$ and 2.3 (a), b), and c), respectively) for $U_\infty = 25$ m/s, $\lambda = 2.5$, $\alpha = 45^\circ$, and $\beta = 90^\circ$. $\delta = 86.6$ mm.

5. Conclusions

An evaluation study of the time-averaged PIV results from single VGJ experiments was carried out by means of a velocity triple decomposition and corresponding spanwise averaged vortex stress $\Delta V_i V_j$ were determined. At the streamwise position $x/\delta = 0.6$, it was shown that the resulting VGJ vortex stresses from the computations are very similar to the VGJ vortex stress distribution from the experiments. Moreover, the results proved to be very similar to previous investigations by the authors concerning the modeling of passive VVGs, see also von Stillfried et al. (2011a,b). Yet, the specific setup presented here shows that the resulting vortex stresses from the VVG model differ quantitatively from the VGJ results. Therefore, it is concluded that vortices originating from a passive VVG are by trend stronger and more distinct. Therefore, it can be concluded that the modelling strategy for passive VVGs is also applicable to modelling active VGJs. The existing VVG model uses the VVG setup parameters in combination with the lifting-line theory in order to determine the modelled vortex velocities. Due to the different and various VGJ parameters, a novel VGJ model must therefore be based on another approach that takes into account the various VGJ setup parameters. Based on the evaluation of the experiments here, a VGJ model approach is currently developed at KTH Stockholm.

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