Stereo-PIV as a tool for optimization of flow control devices

P. Scholz, J. Ortmanns, M. Casper
TU Braunschweig, Institut für Strömungsmekanik
Bierroder Weg 3; 38108 Braunschweig
contact: P.Scholz@tu-bs.de

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Abstract

Active flow control earns growing interest for manufacturers of large transport aircraft because of the constant need to improve these aircraft in terms of less fuel consumption, higher efficiency, steep approaches and departures and less weight. Flow control devices that are based on fluidic actuators, e.g. vortex generator jets (VGJs), have shown a promising potential to influence separating boundary layers and keep them attached, see e.g. Ortmanns et al. (2006); Ortmanns (2009); Scholz et al. (2006); Casper et al. (2009). Such devices create a longitudinal vortex that shifts momentum inside the boundary layer. For an efficient operation such devices need to be optimized regarding their ability to influence the flow. However, optimization turns out to be very challenging because of the vast parameter space and the lack of an adequate “figure of merit”.

Stereo-3C2D-PIV turned out to be a very valuable tool for the optimization. The velocity fields measured in flat plate boundary layers with and without VGJs comprehend all information that is needed to assess these devices. This contribution will outline the measurements and analysis, associated problems and solutions with respect to the above described goals. The core of the analysis is the subtraction of two datafields. Subtractions always lead to very large relative errors, therefore each step must be optimized carefully to obtain the maximum accuracy.

Experimental Setup

For the experiments different low-speed tunnels located in Braunschweig were used. The velocity fields were acquired using a 3C3D-PIV system (Two cameras LaVision imager Pro X 71M; Quantam Brillant Twins 150mj Nd-YAG-laser; LaVision DaViS 7 Software) with the light sheet orthogonal to the bulk flow direction and orthogonal to the plate. The raw data was preprocessed in different steps:

- Stereo-PIV self-calibration
- Calculation of the average image separately for each camera
- Subtraction of the average images from the individual ones to increase signal-to-noise ratio (esp. close to the reflection line)
- Generation of analytical mask based on average image: mask pixel, if average intensity is greater than 75% of the typical intensity of a particle image

Correlation is based on standard algorithms, 2nd-order multi-pass evaluation with decreasing window size, 50% overlap, window-shifting and deformation and Whittaker reconstruction. To obtain a large statistical basis each dataset is based on up to 1000 individual images.

Data Analysis

Figure 2 highlights a typical dataset resulting from the measurements. The longitudinal vortex affects a downward motion on one side and thus a locally thinner boundary layer. Figure 3 highlights a typical dataset resulting from the measurements. The longitudinal vortex affects a downward motion on one side and thus a locally thinner boundary layer.

Accuracy Challenge

The value of \( R_V \) results from a subtraction and is thus very sensitive to experimental errors. Therefore the PIV raw-data needs special treatment. Small shifts in z-direction (normal to the wall) due to vibrations of the camera and/or the flat plate need to be erased. This was done by determining small displacements of the reflection line (relative to the first picture of a dataset) by a cross-correlation technique and then shifting each image by that amount so that the reflection line is exactly at the same position in each image in the dataset.

Secondly it must be ensured that for correlation of the reference dataset (flowfield without actuation) and the dataset for evaluation (with actuation) the position of the interrogation windows relative to the reflection line is equivalent. This means that a reference interrogation window position is defined (e.g. bottom of the first interrogation window shall equal the top of the reflection line). This seems trivial, however typically the position of the first interrogation window is chosen very arbitrarily, e.g. top left corner of the final image. As a result the z-positions of the final velocity vectors differ slightly, which is crucial because curvature of the velocity profiles and inhomogeneous seeding close to the wall creates a systematic uncertainty that must be held constant for all datasets.

On the one hand the first interrogation window should be close to the wall, on the other hand it must strictly be avoided that it reaches into the masked reflection line: Correlating into masked areas typically leads to spatial errors, because the vector is placed in the center of the interrogation window, but is based on the pixel displacement in only in one part of the window.

Fig. 5 highlights an exemplary result of an analysis. The data characterizes a vortex generator jet pulsing at f=50 Hz with \( \Delta=20\% \) duty-cycle, extracted from phase-locked 3C3D-PIV measurements. The square wave in the upper subfigure highlights the driving signal. It is worthwhile to note that the maximum effect in terms of \( \Delta R_V \) is reached during the inactive part of the cycle, although the maximum circulation \( \Gamma \) exists around the end of one cycle. The reason for that is the varying wall normal distance of the vortex core \( z_{vc} \). During the active part the jet displaces the longitudinal vortex so that it resolves far away from the wall. As soon as the jet is switched the vortex core descents while the circulation decreases. However, the closer distance to the wall then increases \( \Delta R_V \).

Exemplary Result

These results offer a lot of insight into the mechanisms of pulsed vortex generator jets which would have not been able to acquire with discrete measurements (e.g. wall shear stress).

Summary

The core of 3C3D-data obtained by stereoscopic PIV measurements for the assessment of fluidic flow control generator jets is described. By comparing the velocity fields relative to a base case (without actuation) the effectiveness and the efficiency of such devices to control flow control scenarios can be ascertained. The method can be used for datasets generated in flat plate boundary layers and is still able to assess the ability of the device to control separation. This is done by means of a momentum balance.

The inclusion of the contribution of different factors which is typically a source for large experimental errors. Therefore considerable effort must be spent to prepare the raw images for correlation and to eliminate or equalize errors resulting from the experimental setup and the curvature of the flowfield. By doing so the PIV study can deliver any information that is needed to optimize them for active flow control applications.

References