Effects of pulsed and continuous jet vortex generators in a turbulent boundary layer flow – an investigation by using two high-speed stereo PIV systems

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Abstract Two high-speed stereo PIV (HS-SPIV) systems have been used for the characterization of pulsed and continuous jet actuators in the turbulent boundary layer (TBL) wind tunnel at ONERA Lille, an Eiffel type wind tunnel in suction mode with a low turbulence level. The test aimed at generating an aerodynamic database useful for the characterisation of (unsteady) vortical structures responsible for the wall-normal fluid exchange which enable an increase of wall-shear stress in the wake of the jet actuator row. Jet vortex generators are well-established for controlling resp. inhibiting flow separation in flows with adverse pressure gradients. Comparing the efficiency of continuous and pulsed jet vortex generators is still of big interest for TBL flows in many aerodynamic and technical flow systems. The dataset is also useful for the validation of CFD tools or simplified models for such flow control devices. The work has been realized in close collaboration between ONERA and DLR.

1. Introduction and Motivation

Continuous and pulsed jet vortex generators are well known for their capability of inhibiting flow separation due to enhanced mixing in turbulent boundary layer (TBL) flows (Johnston and Nishi 1990). Jet vortex generators of adequate geometries produce streamwise vorticity which in interaction with the TBL increase the wall normal fluid transport. For a given ideal configuration this transport depends on the ratio between jet and bulk velocity, but with a moderate jet velocity - especially in a pulsed mode - the wall normal fluid exchange can be organized more efficiently. Especially the shifts of high momentum fluid towards the wall produce regions of higher wall-shear stress in comparison with the situation without jet interaction (Godard and Stanislas 2006, Ortmanns et al. 2008a, Costas et al. 2007). This is a favourable condition for TBL flows with adverse pressure gradients e.g. at wings or flaps of high-lift-configurations to remain attached to the wall (Magill and McManaus 2001). The efficiency of such stream-wise vorticity induced wall-shear stress has been found to be increased for small and average distances of the vortex core to the wall (Ortmanns et al. 2008b). Elaborated DNS of a strong jet vortex generator in a turbulent boundary layer flow at a moderate Reynolds number (Selent and Rist 2010) show the complex interaction between the stream-wise vorticity producing jet flow wake and the new formation of turbulent structures in the further development of the TBL. Nevertheless, for most relevant cases the role of the coherent structures for the temporal evolution of the wall normal momentum exchange for continuous and pulsed jet vortex generators in TBLs is still an open issue in the scientific community. Therefore the fluid dynamic principles and the spatial and temporal organisation of the induced flow topologies downstream of a jet actuator row in a relatively high Reynolds number TBL flow (Reₜ ~ 68000 for Uₜ = 30 m/s) have been investigated in the present work.

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wind tunnel in suction mode with a low turbulence level. The test aimed at generating an aerodynamic database useful for the characterisation of coherent structures responsible for the wall-normal fluid exchange in the wake of the jet actuator row working in continuous and pulsed modes. The transient nature of the flow organisation in the wake of pulsed jet vortex generators leading to enhanced mixing is still not well understood. The dataset is also useful for the validation of CFD tools or simplified models for jet vortex generators. The work has been realized in close collaboration between ONERA in Lille, France and DLR in Göttingen, Germany (Gilliot et al. 2011).

2. Experimental setup

A sketch and photo of the experimental set-up is shown in Fig. 1 and 2. The set-up consists of a combination of two synchronized stereoscopic HS-SPIV systems, one supported by ONERA and one by DLR. Both light-sheet planes are introduced perpendicular to the mean flow direction. The distances between the two light sheets have been varied during the test campaign, while the first measurement plane was introduced at a fixed position: 0.5*δ downstream of the spanwise row of jet vortex actuators. δ represents the fully developed turbulent boundary layer thickness at the actuator position (δ = 34 mm) without any artificial disturbances. The second measurement plane was successively placed at three different positions: 1*δ, 2*δ and 3.5*δ downstream of the actuator row.

**Figure 1**: Sketch of the set-up of two HS-SPIV systems at the test section of the turbulent boundary layer wind tunnel at ONERA, Lille including the jet actuator row
For the recording of PIV images, high resolution CMOS cameras (1024 x 1024 pixels) were used. Each camera has been equipped with Nikon lenses (f = 105 mm) adapted to Scheimpflug mounts operating at an aperture number of $f_\theta = 8$ in order to achieve in-focus particle image diameter of ~3 pixels for diminishing the peak-locking effect at 17 µm pixel width of the used CMOS cameras. All cameras have been reduced in the spatial resolution to 1024 x 768 pixels in z- and y-direction for reaching 4 kHz framing rate. Each camera has been connected to its own dedicated computer on which the recorded frames from the camera RAM have been stored after each measurement case.

Calibration of both stereo camera systems has been achieved by using a 2 mm thick transparent glass target with regular grid lines printed on one side placed in the respective light-sheet plane and...
attached to the wall. After mapping of the particle images a disparity correction procedure has been applied in order to correct for the errors in positioning the calibration target and induced by the refractive index changes of the oblique viewing through the glass target from one camera side. The magnification factor was fixed at $M = 18 \text{ px/mm}$ at a mapped field-of-view of 1380 x 770 pixels.

**Figure 2:** Two synchronized HS-SPIV systems at the SCL wind tunnel at ONERA, Lille. Support and valves of the (pulsed) jet actuator row are marked by red ellipse. Flow from right to left.

Due to a favourable coupling of the image acquisition with the pulse frequency of the jet actuator row (at 50 Hz or 100 Hz) and in order to avoid light pulse interferences of one HS-SPIV system on the respective images of the other system a camera framing rate of 4 kHz was chosen in order to reach an alternating PIV acquisition frequency of 1 kHz for each system: i.e. both systems acquired double-images at 1 kHz with a phase shift of 500 µsec in between the acquisition of the two HS-SPIV systems (see figure 4). The valves control electronics of the jet actuator row gets its trigger signals from the master clock in order to enable phase locked HS-SPIV measurements for both systems. In figure 3 a sketch of the triggering scheme is given: At 50 Hz jet frequency each HS-SPIV system measures the instantaneous velocity vector fields at 20 fixed phase positions in a time depended series of each pulsed cycle, while at 100 Hz jet frequency 10 phase positions per cycle were recorded respectively (see timing diagram in figure 4). Following the timing diagram the DLR HS-SPIV system at $x = 34, 68$ or $119$ mm corresponding to $1.0\delta, 2.0\delta$ and $3.5\delta$ downstream of the actuator row is imaging first and the ONERA HS-SPIV system located at a fixed position of $x = 17$ mm corresponding to $0.5\delta$ (see Table 1) downstream of the actuator is imaging always with $500 \mu$s delay, while both systems acquire double images in an alternating mode. The synchronization of the whole measurement system has been realized by the programmable sequencer V5.1 from Hardsoft with 16 independent TTL channels. In total 8192 single images have been captured at 4 kHz for each HS-SPIV system and each measurement case according to Table 1.
The jet vortex generator row consists of five electro pneumatic valves which have been mounted below a flat plate and used to generate five continuous or pulsed jets. The distance between each actuator in spanwise directions is \( z = 20 \text{ mm} \) in order to limit the interaction between the induced vortices. The geometric characteristics of the actuator are the following: the diameter of each hole is \( d = 3 \text{ mm} \) and the jet direction is oriented with two angles, in incidence \((\alpha = 30^\circ)\) and in yaw \((\beta = 60^\circ)\) as depicted in figure 5. In previous studies it was shown that yaw angles between \(45^\circ\) and \(75^\circ\) (Zhang 2000) generate stronger vortices than others. The spanwise row of actuators (feeding system, valves and drilled flat plate) has been calibrated on a specific bench before the wind tunnel test (see figure 6 left). For the qualification of the jet velocities and response times at opening and closing of the valves the hot wire technique has been used. A specific calibration procedure of the hot wire developed at ONERA for micro-jets, dealing with the small size of the jet with respect to the sensor size, has been employed. The hot wire signals at \(1 \text{ mm} \) distance above the orifice and at \(U_j = 60 \text{ m/s}\) jet velocity for \(f = 75 \text{ Hz}\) and \(f = 150 \text{ Hz}\) are shown in figure 6 right.
Figure 5: Plate with row of five inclined jet vortex generators (flush mounted during operation, d = 3 mm, incidence angle = 30°, yaw angle = 60°)

At both frequencies the flow reaches the required $U_j = 60$ m/s jet velocity at about one millisecond after opening of the valves starts, while the top hat signal form shows values with low variations during opening. During the HS-SPIV measurements jets have been activated in a continuous or pulsed mode (see table 1). When using normalised amplitudes and time scales for the different values of the jet frequencies and velocities all signals are superimposed.

Figure 6: Hot wire probe during calibration of each jet (left) and hot wire signals at 75 Hz (right, top) and 150 Hz (right, bottom) for 60m/s jet velocity

For the evaluation of the time dependent series of particle images acquired in frame straddling mode a local iterative multi-grid cross-correlation algorithm with image deformation scheme has been applied to the image numbers 1 and 2, 5 and 6, 9 and 10 and so on for the DLR PIV system and the respective intermediate image numbers for the ONERA PIV system avoiding background light in all double-frames from light reflection interferences. By this method 2048 instantaneous velocity vector fields per case and HS-SPIV system have been calculated. A final window size of 20 x 20 pixels at 6 pixels step width in y- and z- directions corresponding to a spatial resolution of 1.11 mm at 0.33 mm grid spacing between two neighbouring velocity vectors has been reached. The evaluation procedure results in an array of 237 x 127 instantaneous 3-component velocity vectors (including masked areas at the wall) per measurement field. With respect to the above mentioned problematic of the strong velocity gradients and inhomogeneous seeding distribution immediately downstream of the jet actuator row average outlier ratios between less than 1 % at $x = 119$ mm, where mixing of particles and reduction of gradients dampened the problems, and up to ~
4 % at x = 17 mm downstream the actuator have been registered by a normalised median filter with a value of 1.9 and an absolute velocity histogram filter. Values have been interpolated by neighbouring vectors, which induced a convergence problem and bias shift towards smaller values in the areas of the immediate jet wake. In a convergence study the difference of the average over 1000 instantaneous velocity vector fields divided by the overall average over 2048 velocity fields still leaves local differences up to 5 % within the above mentioned regions.

Due to the local convection velocity (assuming ~ 0.7U∞ for the jet wake area) two subsequently measured velocity vector fields in a plane perpendicular to the mean flow with 1 ms increments in time enables to capture only relatively large coherent flow structures > 0.6δ for U∞ = 30 m/s and > 0.3δ for U∞ = 15 m/s at least twice. The induced spatial and temporal behaviour of the jet wake streamwise vorticity of both jet actuator modes have been the main focus of the present investigation. The corresponding length of the evolving coherent vortical structures is penetrating all measurement planes at certain phase positions of the cycle even for the case with a jet frequency of f = 100 Hz and U∞ = 30 m/s free stream velocity. The effects of the (pulsed) jet wake vortices within the TBL flow will therefore be analysed in the next chapter.

3. Results

For U∞ = 30 m/s, a jet pulse frequency of f = 100 Hz and a VR= Uj/U∞ = 2 (z = 0 at middle of five actuator positions) the instantaneous 3-component velocity vector fields at all measured planes at the same phase position of the jet pulse cycle are presented in figure 7. A turbulent boundary layer profile is visible with large coherent areas of u-velocity fluctuations typical for the outer part of the boundary layer above the logarithmic region. The wakes of the pulsed jets are affecting the region below y = 10 mm and are still quite significant at this phase position for the two downstream planes although the velocity fluctuations from the TBL flow is almost of the same amplitude. At the first two planes the re-organised TBL flow is represented with no direct jet wake interaction.

![Figure 7: Instantaneous velocity vector fields out of a 1 kHz time series at all investigated planes at U∞ = 30 m/s and 100 Hz jet pulse frequency (measured at the same phase position).](Image)
Averaging over all velocity measurements of the dataset without regarding the different cycle-phases and calculating the respective RMS values was the first step in the further analysis of the time series of velocity fields. The second step was phase-averaging the different fixed positions per cycle so that a quasi-time-resolved reconstruction of the average induced vortical wake flow could be realized. For the averaging of the velocity vector fields of the pulsed jet case at f = 50 Hz 102 samples for each of 20 different phase-locked positions have been used, while for the f = 100 Hz case 204 samples for 10 different phase-locked positions were present. From this point a triple decomposition could enable the calculation of periodic and non-periodic parts e.g. of the Reynolds stresses, but due to the small number of samples we focus our analysis in the present work onto the time dependent phase-locked averages.

By using this data a comparison can be presented between the influences of continuous and pulsed jets on the TBL flow. The average velocity contour fields and corresponding RMS fields presented in figure 8 are calculated with 2048 instantaneous SPIV images each without using the phase information. The two average velocity contour fields show for both cases the decay of the aerodynamically relevant wall-normal (v-component) velocity of opposite sign with downstream positions. The positive v-velocity side (red colour coding) of the induced average vortices is slightly larger (up to 12 m/s and for the w-component up -16 m/s at x = 17 mm) in the first three planes than the negative part (blue) as the jets are blowing mass away from the wall in the first instance. With respect to the fact that the v-velocity magnitude shown in the overall average contour fields of the pulsed jet actuator in figure 8 (right) is based on ~50 % of the mass flow of the continuous jet actuator shown (left) there seem to be no hint for higher efficiencies of the wall-normal fluid exchange for pulsed actuators. The presented positive and negative values for the v-velocity at the pulsed case are not significantly more than half of those at the continuous case.
The RMS contour fields in the figure 8 (bottom) show special features of both flow types. While for the continuous case the maximum fluctuation is located close to the vicinity of the wake of the blowing jets at relative large distances from the wall the maximum fluctuations for the pulsed jet are located with large values close to the wall in the direct vicinity and immediate wake of the blowing jet orifices. This might not be very surprising as the jet is pulsating. But with respect to the goal of these flow control devices large turbulent kinetic energy distributions close to wall are also favourable for inhibiting flow separation. The transient nature of the pulsed jet wakes explaining the large RMS values close to the wall will be analysed later in this work.

A judgement on the efficiency of the two jet actuator methods at the measured velocities and jet frequencies can be determined on the basis of the relation between flow velocity deficits in the wake to the ratio of transported high momentum fluid towards the wall or velocity increase [4]. In figure 9 the distribution of the overall average u-velocity differences to the undisturbed turbulent boundary layer flow is shown for the continuous (left) and pulsating jet at f = 50 Hz (right) actuator flow. It is clearly visible for both cases that high momentum fluid is guided around the single vortices closer to the wall (purple/red areas) leading to higher wall-shear stress. While with the opposite process low momentum fluid with a velocity deficit is transported away from the wall (blue regions) which remain visible as slightly elevated wakes of the original jet cross flow. While for the continuous jets the regions of velocity increase and deficit are located with pronounced maxima and minima in all measurement planes the u-velocity differences for the pulsed jet are slightly wider distributed in spanwise directions especially for the planes further downstream. Besides the amplification of slight artifacts of the velocity distribution due to the calculation of differences the integral momentum increase close to the wall is of the same size for both actuator modes when taking into account the differences of induced momentum of ~ 2:1 for the continuous
to the pulsed jet with 50% duty cycle.

Figure 9: Average difference velocity contour plots between jet actuator and undisturbed turbulent boundary layer at all four measurement planes with delta_u-component of velocity colour coded. Left: delta_u of continuous jet field and right delta_u of the pulsed jet actuator row at 50 Hz, both at \( U_\infty = 30 \text{ m/s} \).

In order to quantify the overall average effects of the continuous and pulsed jet vortex generators onto the wall-normal fluid transport in their wake flows an integral calculation of the squared v-velocity component within the iso-vorticity contour area \( S \) consisting of values below \( \omega_x = -400 \text{ s}^{-1} \) has been performed for all measurement planes according to equation (1), where \( S \) corresponds to the mentioned vorticity area and \( v^2 \) the squared wall normal velocity component with and without jets (while \( v^2 \) without jet is very close to zero for a converged average).

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Delta_{\text{v}_\text{w}}^2 = \frac{1}{S} \int_S (v^2_{\text{with jets}} - v^2_{\text{without jet}}) \text{ds} \quad (1)
\]

In figure 10 the integral values of the average \( v^2 \)-velocity components within the areas of vorticity \( S \) with values below \( \omega_x = -400 \text{ s}^{-1} \) have been displayed for all three jet actuator modes and measurement planes at \( U_\infty = 30 \text{ m/s} \). The \( v^2 \)-velocities are normalized by the size of the area \( S \) and divided by 2 for pulsed jets (50% duty cycle). Using such a normalization of the values all decay-curves are very close to each other, which means that within the same amount of induced average x-vorticity the same amount of wall normal fluid transport can be organized. For overall averages this result seems reasonable, but this way of calculation does not consider the transient phases of the pulsed jet wakes!
The transient nature of the development of wall-normal velocity exchange for four phase-locked averages at different time instants after the valve trigger at $f = 100$ Hz and $U_\infty = 30$ m/s is shown in figure 11. Due to the imaging frequency the time increment is $\Delta t = 1$ ms for each plane with a 0.5 ms delay for the upstream plane at $x = 17$ mm. Three subsequent v-velocity distributions of the pulsed jet wakes show the transient organisation of the flow in all planes. At $x = 119$ mm or $3.5 \delta$ the wake of the pulsed jet already produces slight wall normal velocities at an elevated position $\sim y = 15$ mm only 6 ms after opening trigger of the valves. In the subsequent images an increase of the v-velocity magnitude is visible while the corresponding vorticity structure moves at the same time closer to the wall and in negative z-direction, which is the blowing direction of the jets with $\beta=60^\circ$ yaw angle. This behavior explains the wider distribution of the u-velocity differences in figure 9 and might be advantageous for inducing wall-shear stress due to its moving character.

In the top-left image of figure 11 the v-velocity phase average at $t = 2$ ms resp. 2.5 ms after the valve trigger for initiating the opening is shown. At that time instant a first effect in the induced v-velocity can be noticed here at plane $x = 17$ mm, while a small amount of v-velocity induced by the forerunning pulse is still present at $x = 119$ mm. In the left-bottom image at 7 ms after valve trigger a considerable amount of streamwise vorticity reaches the downstream plane at $x = 119$ mm. Assuming that the jet vortex actuator effect was present at $x = 17$ mm already at $t = 2$ ms due to the pronounced structures at $t = 2.5$ ms an average convection velocity for the induced streamwise vortices of $\sim 20.4$ m/s can be calculated, which corresponds to $\sim 0.68 U$. 

**Figure 10:** Integral values of average $v^2$-velocity components within the areas of vorticity with values below $\omega_x = -400$ s$^{-1}$. Values are normalized by the size of S and divided by 2 for pulsed jets for all three jet actuator modes and measurement planes at $U_\infty = 30$ m/s
Figure 11: Transient development of wall-normal velocity exchange for four phase-locked averages (top-left to bottom-right; v-velocity colour coded). The last three v-velocity distributions are subsequent with Δt = 1 ms increments of the pulsed jet wake at f = 100 Hz and $U_\infty = 30$ m/s.

For a few phase-averaged time instants where the wake flow has been fully established the v-velocity magnitude is even slightly larger for the pulsed jets in comparison to the continuous ones in the two intermediate planes at $x = 34$ and 68 mm. But especially at times when the jet wake vortices first reach the different planes in the pulsed mode the continuous jets produce a larger v-velocity magnitude in comparison. As stated before the overall wall normal momentum exchange is of the same order for both flow types considering the jet momentum differences. Only the transient character of the pulsed jet might have an advantageous effect to the wall shear stress enhancement due to its unsteady character as visible in the larger RMS values close to the wall in figure 8 and the spanwise shifting of large vortical structures in time as shown in figure 11.

4. Summary

The wake effect of a row of flush mounted continuous and pulsed air jet actuators onto a turbulent boundary layer flow has been investigated by means of two HS-SPIV systems. Time series of 3-C velocity vector fields in two planes simultaneously at different distances to the actuator row and perpendicular to the mean flow have been measured at 1 kHz. The changes in $u$- and $v$-velocity in relation to the undisturbed TBL flow and in comparison of the continuous and pulsed jet modes have been investigated. Continuous and pulsed jets induce streamwise vortices which increase the $u$-velocities close to wall by wall-normal momentum exchange. A comparison of the overall averages and differences in the $u$- and $v$-velocity distributions of both jet blowing modes shows no
significant benefits for one of the working modes. Nevertheless, a look on the transient character of the pulsed mode support the idea of a more efficient production of wall-shear stress due to temporal spanwise shifts of the vortical structures and the overall unsteady flow behavior.

References

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