Investigation of a tripped turbulent boundary layer flow using time-resolved tomographic PIV

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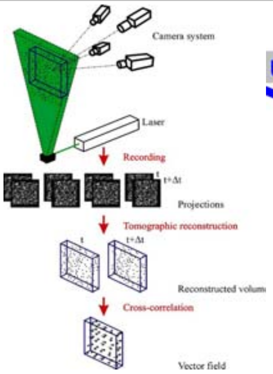
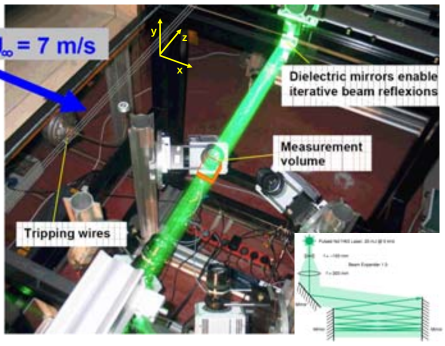
Principle of Time-Resolved Tomographic Particle Image Velocimetry (3D-3C(t)-PIV)



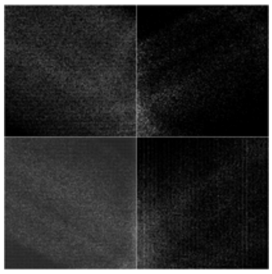


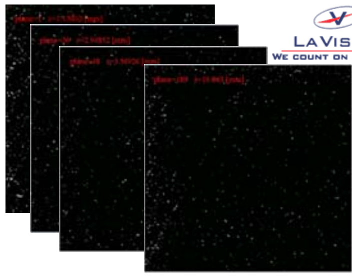
Experimental apparatus and procedure

A flat plate boundary layer flow was generated at the open test section of the circuit type 1m- wind tunnel of the DLR, Göttingen, at a free stream velocity of U_∞ = 7 m/s with zero pressure gradients. A transparent and smooth surface glass plate is utilized to provide optical access from its bottom and a good flow quality. The plate has an elliptic leading edge to prevent flow separation. Four tripping wires, one with 1.5 mm diameter and three with 1 mm diameter were positioned with 1 mm x-distance close to the surface at $(Re_x)^{1/2} \approx 290$ along the whole span-wise elongation of the plate. This bypass transition of the flow results in the development of a turbulent boundary layer flow. In a box of about 34 x 18 x 35 mm³ in x-y and z-directions around $(Re_x)^{1/2} \approx 450$ tracer particles has been illuminated by laser light pulses at 4 kHz with 21 mJ each in order to achieve PIV recordings without using the frame straddling method. The light source was a Nd:YAG laser from *Lee Laser inc.* Two highly reflective dielectric mirrors aligned in the x-y-direction are installed nearly parallel and close to the surface of the flat plate on opposite sides of the measurement region. The collimated laser beam undergoes multiple reflections between the two mirrors passing through the measurement volume approximately 15 times before exiting (see sketch left). This arrangement resulted in a light amplification with a factor ~5 with respect to a single pass system. The specific illumination arrangement has the advantage that all viewing directions collect scattered light both in forward and backward directions, which provided the level of light needed for imaging particles in the whole volume.

Tomographic reconstruction of particle images in a volume and 3D- PIV evaluation

Four *Photron APX-RS* CMOS cameras (896 x 860 pixels² at 4 kHz) are equipped with Nikon lenses with a focal length *f* = 100 mm and an aperture of *f#* = 8. Finally up to 18 mm in y-direction could be resolved for the tomographic particle image reconstruction for the measurement volume. By using inverted signals of 4 kHz TTL-signals from a signal generator for the camera triggering the laser pulses were located exactly in the middle of each exposure and 1000 images were captured for each run. The data recording, volume calibration and calculation of the 3D-3C vector fields are performed using DaVis 7.3 software from LaVision. The three-dimensional particle light intensity distribution is reconstructed by means of the tomographic algorithm MART (multiplicative algebraic reconstruction technique) specialized for PIV signals returning a 3-D array of voxels representing the measurement volume where the intensity is digitally stored (Elsinga et al. 2005, 2006). For volume calibration each camera records images of a 3D-calibration target at several positions in depth through the volume. A linear translation stage with stepper motor has been used in order to ensure high accuracy of the several target positions in y-direction. The calibration procedure returns the viewing directions and field of view by using a polynomial fitting procedure. The tomographic reconstruction relies on accurate triangulation of the views from the different cameras. Before reconstruction of the tomogram, the particle image recordings require pre-processing in order to eliminate background illumination, reduce local inhomogeneities of light intensities. Sliding minimum subtraction and a Gaussian smoothing of the particle images are the applied operations.





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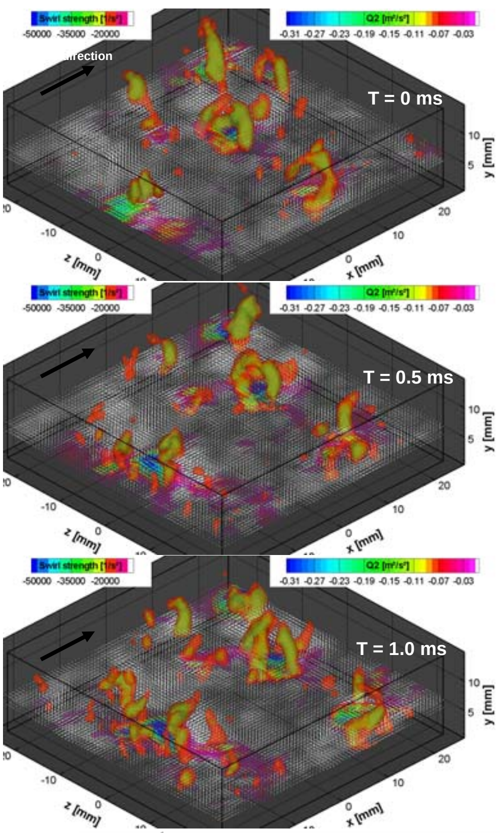
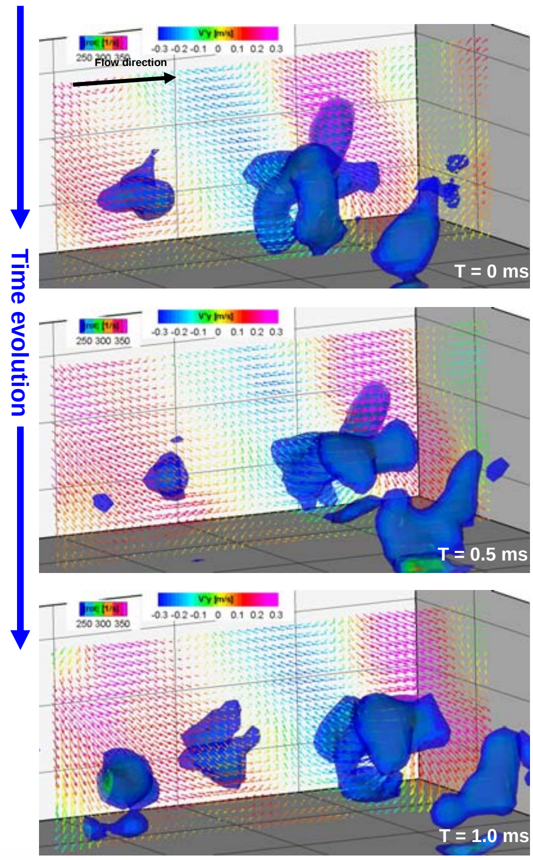
The reconstructed particle image distribution in the volume has been analyzed with an iterative multi-grid volume deformation scheme reaching a final 48³ voxels (2 x 2 x 2 mm³) interrogation box size with 75 % overlap yielding the instantaneous three-dimensional velocity volume over a grid of approximately 48 x 24 x 52 measurement points (~59000 3C-vectors at 4 kHz).

Results: 4 kHz- time series of 3-D-3C instantaneous velocity vector volumes

Time series of 3D -3C velocity vector volumes with swirling strength magnitude



Coherent vortical structures governing turbulent flow exchange e.g. Q2 / Q4 events



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The structures found in a wire tripped flat plate turbulent BL flow are presented in the shown figures. The cross-correlation of the reconstructed particle image volumes has been calculated without using frame straddling that means instantaneous velocity vector volumes representing time steps of 250 µs each. The average flow velocity of 500 velocity vector volumes has been determined and subtracted from each single realization. Three instantaneous velocity fluctuation vector volumes, with respect to this non-converged average profile, with a time separation of 500 µs each are represented in the figures by 3D- swirling strength (left column) and 3D- iso-vorticity contour surfaces (right column). Additionally two 3C-velocity vector fields in x-z-planes with Q2 colour coding (left) and in x-y-planes with *V'y* colour coding (right) with 2 mm distance are plotted each. We can find the representative arch structure with negative *V'x* velocities included between their legs. A strong Q2 event region is located directly upstream of this vortex structure, while a Q4 event region is located directly downstream. This behaviour might indicate that the arch topologies are more or less self-sustaining structures as singular realizations: they induce a transport of high-momentum fluid downwards to the wall at downstream locations and "use" this energy to re-feed the Q2-event in upstream direction and thus their vortical topology. As visible in the swirl strength visualisation in the left column stream-wise swirl does not play a major role as often proposed for coherent structure- and hairpin vortex-models in TBL flows. On the other hand asymmetric swirl arches or even single vortex columns are visible, which confirms previous research.

With the present or future data measured in turbulent flows by 3D-3C(t)-PIV a combined topological and Lagrangian view of the detailed flow and momentum exchange mechanisms could be obtained by applying hybrid PIV-PTV algorithms, which would combine different branches of the turbulence research community. This promising technique enables valuable quantitative insight for the understanding of the structural self-organization and the energy and momentum budgets of such turbulent flows.

Elsinga G.E., Wieneke B., Scarano F. and van Oudheusden B.W. (2005), Assessment of Tomo-PIV for three-dimensional flows; Proceedings of *6th International Symposium on Particle Image Velocimetry Pasadena, California, USA, September 21-23, 2005*

Elsinga G.E., Scarano F., Wieneke B., and van Oudheusden B.W. (2006), Tomographic particle image velocimetry, *Experiments of Fluids*, **41**, Number 6, December 2006, pp. 933-947(15)

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