# Winner of the Leen van Wijngaarden Prize 2011

Gerrit E. Elsinga, TUD

## 3D insights into turbulence

Turbulence, particularly at the small scales, is associated with dissipative and swirling motions, which both involve velocity gradients rather than the velocity itself. Consequently, there has been a long-standing interest in fully three-dimensional velocity measurement techniques, as it allows determining all nine components of the velocity gradient tensor. Recently we introduced tomographic PIV [1] as a promising new method for measuring the instantaneous three-dimensional velocity field. In this approach the tracer particles are illuminated within a flow volume, and the light scattered by these particles is recorded from several viewing directions simultaneously, typically using 4-6 digital cameras. From the recordings the particle distribution is reconstructed as a 3D light intensity distribution discretized onto voxel elements, i.e. the volumetric equivalent to pixels. This reconstruction problem is solved iteratively using a tomographic algorithm. The particle displacement, hence flow velocity, is then obtained by a cross-correlation analysis of the two reconstructed volumes corresponding to subsequent particle illuminations.

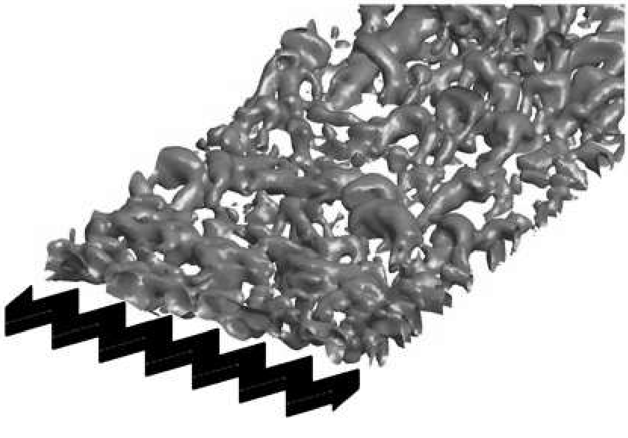

Figure 1 Vortical structures in a boundary layer disturbed by a zigzag trip

The tomographic-PIV approach is applicable to a broad range of flow cases, in which the characteristic fluid velocity may range from only a few mm per second in a water tank [2] all the way up to 510 m/s in a supersonic wind tunnel [3]. Furthermore, measurements can be performed in millimetre-sized volumes when employing a microscope objective with four ports for imaging [4], but meter-sized volumes can be accessed also, which has been demonstrated in a large-scale convection cell [5]. Complex internal flows, such as occurring in human artery bifurcations, can be measured when matching the refractive index of the fluid and the model [6]. Additionally, extensions to time-resolved three-dimensional measurements have been achieved in both air and water by employing high-speed lasers and imaging systems [7].

The variety of applications clearly demonstrates the versatility of tomographic-PIV, which makes that it is quickly gaining importance. So far, the resulting velocity volumes have mainly been used to provide quantitative visualizations of the coherent structures occurring in the various turbulent flows (figure 1). These studies help understanding the spatial organization of the turbulent motions at different scales. In that context, it is interesting to note that the statistical properties of the small scales appear to be universal when evaluated in a local eigenframe based on the velocity gradient tensor. The (qualitative) universality applies also to the extended local flow pattern, as we have recently demonstrated [8]. The average flow in such an eigenframe reveals a shear layer containing aligned vortical structures (figure 2), which is a flow pattern that is frequently observed in the instantaneous turbulent flow fields as well. Three-dimensional velocity data is now becoming generally available from experiments, and at the same time also from DNS at some reasonable Reynolds numbers. This development is very exciting, as it provides unique new opportunities to elucidate the nature of turbulence.

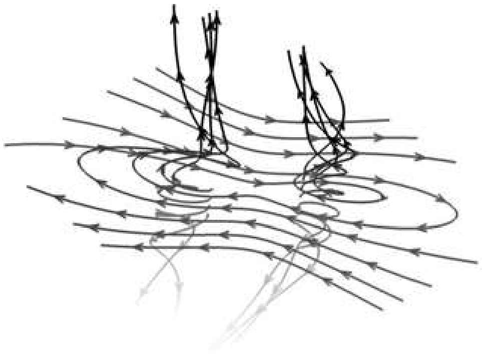

Figure 2 Streamlines showing the average flow pattern associated to the eigenframe of the local strain rate tensor. It consists of a shear layer containing two aligned vortical structures. The same pattern is observed universally across homogeneous isotropic and wall-bounded turbulence.

[1] Elsinga GE, Scarano F, Wieneke B, Van Oudheusden BW (2006) Tomographic particle image velocimetry. Exp Fluids 41: 933-947

[2] Worth NA, Nickels TB (2011) Time-resolved volumetric measurement of fine-scale coherent structures in turbulence. Phys Rev E 84, 025301

[3] Elsinga GE, Adrian RJ, Van Oudheusden BW, Scarano F (2010) Three-dimensional vortex organization in a high Reynolds number supersonic turbulent boundary layer. J Fluid Mech 644, 35-60

[4] Kim H, Grosse S, Elsinga GE, Westerweel J (2011) Full 3D-3C velocity measurement inside a liquid immersion droplet. Exp Fluids 51, 395-405

[5] Kühn M, Ehrenfried K, Bosbach J, Wagner C (2011) Large-scale tomographic particle image velocimetry using helium-filled soap bubbles. Exp Fluids 50, 929-948

[6] Buchmann NA, Atkinson C, Jeremy MC, Soria J (2011) Tomographic particle image velocimetry investigation of the flow in a modeled human carotid artery bifurcation. Exp Fluids 50, 1131-1151

[7] Schröder A, Geisler R, Staack K, Elsinga GE, Scarano F, Wieneke B, Henning A, Poelma C, Westerweel J (2011) Eulerian and Lagrangian views of a turbulent boundary layer flow using time-resolved tomographic PIV. Exp Fluids 50, 1071-1091

[8] Elsinga GE, Marusic I (2010) Universal aspects of small-scale motions in turbulence. J Fluid Mech 662, 514-539.