Large-scale measurements in turbulent pipe flow using 3D Lagrangian Particle Tracking

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Understanding the evolution and dynamics of very large-scale motions (VLSMs) and/or turbulent superstructures (TSS) in turbulent pipe flows and within turbulent boundary layers (TBL), respectively, at high Reynolds numbers is of vital importance in fluid mechanics and aerodynamics investigations. Jiménez (1998) showed that eddies with streamwise lengths of 10–20 boundary layer thicknesses ($\delta$) are present in the logarithmic region of wall-bounded flows. Kim and Adrian (1999) found streamwise energetic modes with wavelengths up to 14 pipe radii ($R$) in fully developed turbulent pipe flow. This finding has recently been confirmed with full spatial resolution by DNS over a large domain of 30 $R$ at moderate Reynolds numbers [Ahn et al. 2015]. As shown by experimental data, these superstructures seem to directly interact with small-scale structures near the wall, leaving a ‘footprint’. This impact on the conditions near the wall is of particular interest for the wall-shear stress induced drag production, as the large-scale structures underlie outer scaling (their extent is dependent on $\delta$ and the Reynolds number), while it was assumed that near-wall structures do not.

A direct comparison of high Reynolds number turbulent pipe and ZPG-TBL flows according to their mean and Reynolds stress profiles, to their scaling properties, spectral contents and the entangled role of coherent structures (superstructures) in the near wall, logarithmic and core/wake region is of eminent interest [Jiménez 2018]. Following this thought, we present a large-scale Lagrangian Particle Tracking (LPT, Schröder & Schanz 2023) investigation of pipe flow, complementing an existing dataset on TBL flow (Schanz et al. 2019).

The measurements were conducted in the Cottbus Large-Pipe facility (CoLa-Pipe). The aim was to measure the flow within the full cross-section along a glass-pipe section, of ~1 m length ($\approx 10 R$), allowing to fully visualize the VLSM structures and their spatio-temporal development. The glass-pipe segment was used for better optical access and was integrated with an acrylic self-adhesive black foil to reduce background illumination and reflections.

Fig. 1: a) Overview of the test section (I), the camera setup (II), the bypass to allow illumination (III) and the LED arrays (IV, light path in green). b) top view on the camera system with installed beam splitters. c) detail view on one camera with beam splitter. d) examplary camera image, showing the double view on the test section. e) seeding box, with hoses to insert HFSBs into the pipe. f) the illuminated test section; HFSB visible as streaks.
The glass-pipe was located at 120 pipe diameters, where flow was assured to be fully developed turbulent. The flow was seeded using Helium-filled soap bubbles, which were created in a container and inserted into the settling chamber of the pipe (Fig. 1e). The bubbles were illuminated by two arrays of white high-power LEDs, whose light was introduced into the pipe via a plane glass window in a U-shaped bypass close to the end of the main lane pipe (see Fig. 1a). The reflected light was captured by a system of four Phantom V2640 cameras, installed below the test section (Fig. 1b). The elongated shape of the measurement volume ratio (~5:1) allowed for two improvements: Firstly, we were able to capture the flow twice per camera, by installing a beam splitter in front of each camera (Fig. 1c), effectively doubling the number of available views. Secondly, the images filled less than half of the sensor (Fig. 1d), allowing to crop the sensor to maximize the number of recorded images fitting (51,916 consecutive images per run). A wide range of Reynolds number was covered, ranging from \( Re_\tau = 1530 \) to \( Re_\tau = 14,000 \). The corresponding recording frequencies range from 1.5 to 13 kHz. 20 runs were performed for \( Re_\tau = 1530, 3140 \) and 11,900, respectively, capturing approx. 4.000 m of flow for each case.

Fig. 2: STB results for cases with \( Re_\tau = 1530 \) (top row) and \( Re_\tau = 11,900 \) (bottom row), showing instantaneous particle distribution in the full volume (left), a central slice (60 mm thick, middle) and a streamwise view (right).

The images were evaluated using the DLR-implementation of the Shake-The-Box algorithm (Schanz et al. 2016). For low velocities, high seeding concentrations of up to 0.1 particles per pixel were achieved, allowing to instantaneously reconstruct the motion of around 90,000 bubbles (see Fig. 2, top row). With increasing velocities, the number of bubbles per volume decreases - as does the LED light, which still proved sufficient for reliable tracking. At \( Re_\tau = 11,900 \) (free stream velocities up to 58 m/s) approx. 13,000 bubbles can be tracked instantaneously (see Fig. 2, bottom row). Fig. 3 shows results of regularized interpolation (FlowFit, Gesemann et al. 2016) of the dense particle field at \( Re_\tau = 1530 \), revealing the complex vortical system transported in and created by the turbulent flow. The evaluations are still ongoing. This work was supported by the DFG through grants SCHR1165/5-1/2 and EG100/24-2 as part of the Priority Program on Turbulent Superstructures (SPP 1881).

Fig. 3: FlowFit interpolation of particle tracks at \( Re_\tau = 1530 \): Isosurfaces of Q-Criterion (Q = 2000/s²) in 50 mm deep slices in the x-y (left) and the y-z-plane (right).

References
Schanz D et al. (2019) Large-scale volumetric characterization of a turbulent boundary layer flow. 13th Int. Symposium on PIV, Munich