Moving Tomographic PIV for investigation of coherent structure evolution in turbulent boundary layers

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In recent years, volumetric particle image velocimetry (PIV) techniques have been exploited to study turbulent boundary layers within which three-dimensional characteristics of coherent structures can be quantified (Elsinga et al. 2010). Beyond the identification of individual eddies and eddy packets within the boundary layers, their generation, evolution, and interaction can be investigated experimentally. In the present work, a moving Tomographic PIV (TPIV) method was designed and applied to measure the velocity field in three-dimensional volumes and to track coherent vortices and packet structures in a turbulent boundary layer with $Re_c \approx 2500$. The aim of the work was to investigate the real-time evolution of hairpin structures and eddy packets over long distances. A vortex identification method proposed by Gao et al. (2011), based on three-dimensional swirl strength and direction, was used to identify and examine vortical structures in the logarithmic region.

Experimental Setup and Methods

The moving TPIV experiments were carried out in a water channel with test section of 8 m length, 1.2 m span, and 390 mm water depth and 0.5 m/s free stream velocity. The turbulent boundary layer was stimulated by a trip wire at the entrance of the channel test section. At about 6m downstream, the boundary layer thickness was $\delta=125$ mm with corresponding Reynolds numbers of $Re_c=6000$ and $Re_c=2500$. The TPIV setup included four 2K by 2K cameras with magnification of 0.07mm/pixel. The TPIV platform was mounted on a traverse system on the top of the water channel. The entire measurement system moved at the convection speed of the measurement volume in the turbulent boundary layer and travelled about 2.3 m (4.3m to 6.6m downstream from the trip wire) to track the flow. The measurement volume was illuminated using a dual head Nd:YAG laser with 370 mJ/pulse and a twin-pulse frequency of 5 Hz with a 3ms time interval between pulses. The laser beam was expanded into a sheet with thickness ~10mm. The resulting illuminated measurement volume was $\approx 80 \times 80 \times 10$ mm$^3$ (1650 $\times$ 1650 $\times$ 200 viscous units). Two wall-normal locations in the logarithmic region were investigated: $z^*=100-300$ and $z^*=300-500$. Silver-coated glass spheres with diameter of 10 $\mu$m were used as tracers. Volumetric velocity fields were obtained by processing the raw image sets via Davis 7.4 (Lavision).

Results and Conclusions

Moving TPIV was applied successfully to study evolution of hairpin structures and eddy packets. Meandering, merging and breaking of slow regions were observed, as well as interactions among individual neighboring vortices. The meandering of long slow regions at both wall-normal locations was tracked using cross-correlation between neighboring time steps. It was found that long slow regions could persist within the logarithmic region over 156 corresponding with a time period $\tau' > 2300$, and the packet regions could travel stably forward in the streamwise direction while maintaining fixed spanwise inclinations in the range 0-10 degrees. Well-aligned eddy pairs were observed surrounding a long slow region with convection velocity of 92% of the local mean (Fig. 1). The streamwise spacing between these eddy pairs is $\approx 300$ viscous units (0.125) at the lower location, while it is about 400-500 viscous units (0.16-0.28) at the higher location, similar to the observation of Elsinga et al. (2012). The surrounding eddy pairs of the example cases have strong circulation averaging 500 and 350 at the lower and higher locations, respectively.

Fig. 1 Eddy packet at $z^*=200$. Blue: slow region with $U' < 0.92 \bar{U}$; Red/green contours mark eddies with $|U'| > 200$ and positive/negative sign. Field of view is 0.658$\times$0.658.

References

