# SEVERAL MEASUREMENT RESULTS ON THE WALL-BOUNDED TURBULENT BOUNDARY LAYER UTILIZING TOMOGRAPHIC TR-PIV TECHNOLOGY

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*Summary* The short paper reports on several measurement results concerning the wall-bounded turbulent boundary layer (TBL) based on the rapidly developing technology of the tomographic TR-PIV. They include the spatial typical characteristic scales, such as dissipation scale, shear scale, Taylor micro-scale and integral scale etc. in the TBL. Besides that, the spatial topology of coherent structure in the TBL is illustrated as well. Moreover, we focus discussion on an anisotropic eddy viscosity model of the coherent structure Reynolds stress.

## BACKGROUND INFORMATION

At the beginning of the year 2012, Zhou and Zhang [1] highlighted that researches on real turbulence should be the main focus of the further basic research of turbulence. They listed several points worth attention in the turbulence research, one of which was that classifiably building several universal simplified model for real turbulence. In addition, they confirmed the great practical significance of researches on the wall-bounded TBL. Last year, we were striving to study on the wall-bounded turbulence utilizing the tomographic TR-PIV signal database. In present paper, we present several measurement results on these following subjects:

### Spatial characteristic scale

Turbulence is a multi-scale, multi-level, multi-structure movement system. In such complicated system, structures at different scale play significant roles respectively. The Kolmogorov dissipation scale is the smallest scale of the multi-scale turbulent system, indicating that the fluctuating kinetic energy at the action of molecular viscosity into thermal energy; Taylor differential scale is the length scale of the smallest scale eddies identifiable produced in the turbulent flow. In addition, the shear scale is defined as the retroflex scale producing eddies owing to the role of the average velocity gradient in the shear turbulent flow field. When the largest scale is the order of magnitude of mean motions, we define integral scale as their characteristic scale. [2]

### Coherent structure

Coherent structures (CSs) are defined as such structures that possess the same flow characteristics or closely relate to each other within a space within which spatial magnitude is in the order of boundary layer thickness. These CSs have significant influences on the skin friction, mass and heat transfer of the TBLs as well as on the generation of turbulence kinetic energy. Hairpin vortex is generally accepted as the basic coherent vortex structure in a TBL.

### Anisotropic eddy-viscosity model

In terms of theoretical model of coherent structure dynamics system, the Reynolds stress components ($\tilde{r}_{ij} = -(< u_i' u_j' > - \overline{u_i' u_j'})$) contributes to the coherent part that are generally formulated by a complex eddy-viscosity model (CEVM): the eddy-viscosity coefficient ($\nu_T$) multiplied by the velocity strain rate of coherent structure, namely $\tilde{r}_{ij} = 2\nu_T \tilde{S}_{ij} + \delta_{ij}(\tilde{r}_{kk})/3$. In a more general sense, the CEVM for coherent structure Reynolds stress should be anisotropic. Different Reynolds stress components as well as the components of mean velocity strain rate correspond to different eddy-viscosity coefficients.

## 3D-3C VELOCITY VECTOR DATABASE AND DATA MINING METHOD

The three-dimensional three-component (3D-3C) velocity vector database of the wall-bounded TBL with zero-pressure-gradient to be processed in this paper have been obtained from a tomographic TR-PIV experiment in the water tunnel of the Aero and Hydrodynamics Laboratories of TU Delft. The TBL database consists of five groups; for each group contains 1023 instantaneous 3D-3C velocity vector volumes. It is over a grid of 92×99×22 (streamwise× spanwise×normal) measurement points located every 0.687mm, corresponding to a spatial resolution of 15 wall units (WU) in all three directions. The setup and several first interesting results have been described in Reference [3]. For completeness, we briefly recall some properties of the wall-bounded TBL in the Table 1.

**Table 1** Basic flow field properties of the TBL, as estimated by PIV

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|---|---|---|---|---|---|---|---|---|---|
| Free-stream flow velocity($U_e$) | 0.53 m/s | Reynolds number($Re_\theta / Re_\tau$) | 2460/800 | Friction velocity($u_\tau$) | 21.9 mm/s | Friction coefficient($C_f$) | $3.45\times10^{-3}$ | Boundary-layer thickness($\delta$) | 38.1 mm |

We calculated the characteristic scales of the wall-bounded TBL according to their definiens. [2] Moreover, We introduced an improved quadrant splitting method (IQSM) and a new conditional sampling phase average technique as the data-mining criterion to detect and extract coherent structures from such wall-bounded turbulent signal database. [4] We obtained four scales of coherent structure spatial topologies using the detecting criterion based on the spatial local-averaged velocity strains. However, considering the length of this paper, we just give several results of the fourth scale coherent structure spatial topology of which the Q2 (ejection) event is the detecting centre. More details are in Ref. [4].

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## RESULTS AND DISCUSSION

Typical spatial characteristic scales, such as dissipation scale, shear scale, Taylor micro-scale and integral scale etc. in the TBL at 3-5, 40-100, 20-50, and 4000 WU, respectively, were calculated by using the 3D-3C database of time series of spatial velocity field measured by tomographic TR-PIV. Results in Figure 1 show that dissipation scale slowly increases along the wall-normal position upwards; while the shear scale in the near wall region does not change significantly with the normal position; the integral scales do not change with the normal position.

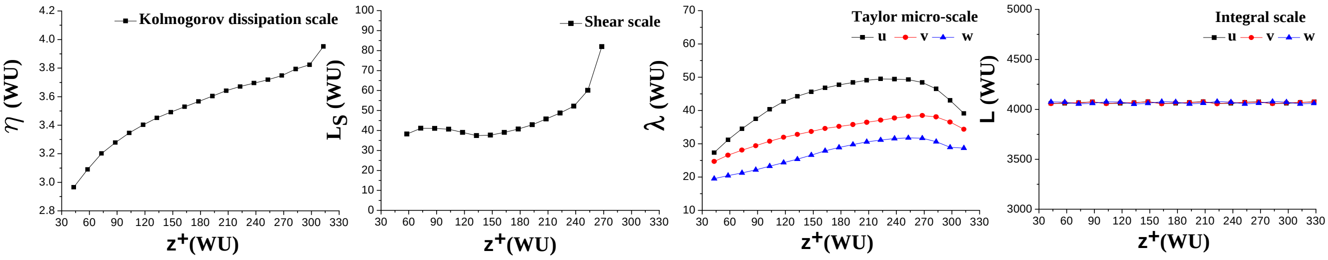


**Figure 1** Relations between dimensionless characteristic scales by viscous scale with wall-normal position $z^+$ in the TBL

As can be seen from Figure 2, there is a low-speed streak region (right-top) whose spanwise spatial scale is approximately from 300 WU to 360WU as the $z^+$ increasing, which agrees well with the average bursting period calculated in Ref. [2]. Besides, there is a couple of counter-rotating quasi-streamwise vortexes located on both sides of the Q2 event (right) which extend toward the wall, paralleling with the wall upstream but with an angle of around 45° between their necks and the wall bound downstream. We call it as "X chromosome" shape for short, which is a new kind of coherent structure. Moreover, the singularity in mathematics labelled "S" here plays a significant role in producing and maintaining turbulence.

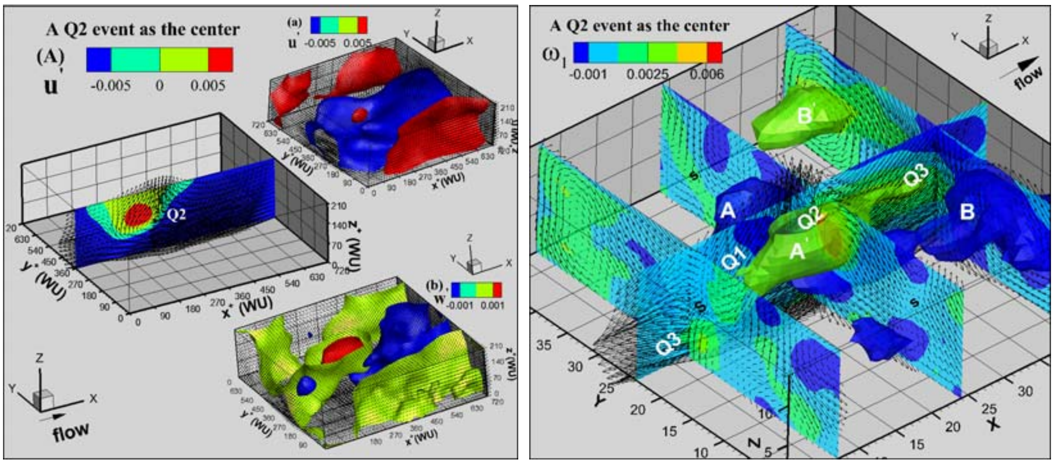


**Figure 2** The fluctuating velocity distribution (left) and the locally enlarged iso-surface contours of stream-wise fluctuating vorticity with tangent velocity vectors (right) of coherent structures containing a Q2 event as the center. Color coded by sign and strength.

We illustrate the Reynolds stress components and their corresponding mean velocity strain rate ones in Figure 3. Obviously there is spatial phase difference between $\tilde{r}_{ij}$ and $\tilde{S}_{ij}$. We will present further analysis at the XXIII ICTAM. The CEVM of CVs is suitable.

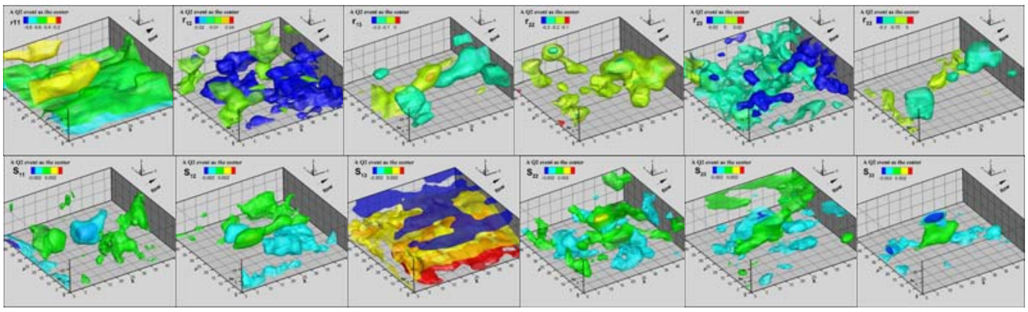

**Figure 3** The spatial phase-averaged distribution of Reynolds stress (top) and mean velocity stain rate (bottom) components.

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