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VELOCITY CORRELATIONS IN TURBULENT BOUNDARY LAYER ON SMOOTH AND ROUGH SURFACES

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The spatial velocity correlations within a turbulent boundary layer are evaluated from PIV experiments for two cases, boundary layer on smooth and rough walls respectively. Basic features of the two cases are shown. Typical length-scales and shapes of coherent structures could be estimated form the evaluated correlations.

Keywords: turbulent boundary layer, velocity fluctuations, spatial correlation, rough wall

Introduction

Turbulent flow in general is characterized by fluctuating velocity and pressure fields. For its analysis two approaches are used basically. Statistical-kinetic approach involves a single point correlations represented by Reynolds stress tensor which is based on time correlations omitting spatial scales. The second statistical-probabilistic approach describes spatial structures using space correlations.

Basic information could be find in classical literature [2,6]. Theory of velocity fluctuation correlations in turbulent shear flows and especially in turbulent boundary layers is well developed the detailed study [1]. Correlation is connected with appearance of coherent structures in flow (see e.g. [3,4]).

In the presented study, the measurements have been carried out in the plane perpendicular to the wall (*y*-direction) and parallel to the mean flow (*x*-direction) above the turbulent boundary layer. Only in-plane velocity components have been evaluated using PIV method.

2. Correlation of velocity

The double point correlation is generally defined as covariance between velocity fluctuation components at two separated points acquired simultaneously

$$R_{ab}(\mathbf{x},\mathbf{r}) = \overline{a(\mathbf{x},t)\,b(\mathbf{x}+\mathbf{r},t)}\,. \tag{1}$$

Here suffices a,b denote fluctuations of in-plane velocity components u,v or out-of-plane vorticity component ω, $\mathbf{x}$ is position vector of reference point and is fixed, $\mathbf{r}$ is relative position vector of variable point (space shift), bar $\overline{....}$ denotes ensemble average.

In most cases the double-point correlations are used in the normalized form using the signals standard deviations as correlation coefficient C_{ab} – see e.g. [1]

$$C_{ab}(\mathbf{x},\mathbf{r}) = \frac{R_{ab}(\mathbf{x},\mathbf{r})}{R_{ab}(\mathbf{x},0)} = \frac{\overline{a(\mathbf{x},t)\,b(\mathbf{x}+\mathbf{r},t)}}{\sqrt{\overline{a^2(\mathbf{x},t)}\;\overline{b^2(\mathbf{x}+\mathbf{r},t)}}}\,. \tag{2}$$

This definition implies that for vanishing space shift we get $C_{ab}(\mathbf{x},0)=1$. For any nonzero shift this value is less than 1, in general $C_{ab}(\mathbf{x},\mathbf{r}) \in \langle -1,1 \rangle$. In principle, the absolute value of correlation falls with growing both space and time shifts, however possible local peaks correspond to periodical structures appearance and for big shifts we get correlations fluctuating around zero.

Correlation coefficient could be interpreted as measure of statistical dependency: its absolute value approaching 1 is sufficient condition for statistical dependency. However, the correlation coefficient does not carry any information concerning statistical independency.

3. Experimental Setup

The experiments have been carried out in the blow-down facility of cross section 250 x 100 mm^2, the longer side was used to develop the boundary layer in distance 2 *m* from the channel input. The boundary layer was developed on the 250 *mm* wall.

Two experiments have been carried out, the first on smooth wall, the second on rough wall. For the wall roughness the 60-grit sandpaper has been used, mean height of grains was 0.435 *mm*, this corresponds to $y^+ = 6$. The velocity of outer stream was $U_e = 4.6$ *m/s*, low turbulence (less than 0.1 %). Corresponding Reynolds number based on distance from the channel inlet was about 6.10^5, while the Reynolds number based on impulse thickness was about 800.

Standard configuration of time resolved PIV was used for measurements, particles were generated using fog SAFEX generator, introduced to the inlet of the blow-down facility. Two velocity components were evaluated in the *xy* plane perpendicular to the wall. The velocity has been evaluated in the grid 63 x 79 interrogation area 32 x 32 pixels, overlap 50 %. The 1500 subsequent complete vector fields are evaluated with frequency 500 *Hz* representing 3 *s* in physical time. Please note that the thickness of the laser sheet is about 1 *mm*.

More details on experimental setup could be found in [9].

4. Results

The boundary layer is well developed turbulent one on the flat wall with smooth and rough surface. The half-percent boundary layer thickness δ was in the case of smooth wall 22.5 *mm*, while in the case of rough wall 24.6 *mm*. The Cartesian coordinates are to be non-dimensioned using the respective boundary thickness: $\left(x/\delta, y/\delta\right)$.

The correlations have been evaluated for a fixed reference point located in the distance $y = \delta/2$ from the surface.

Measuring plane (*xy*) is perpendicular to the wall and parallel to the mean flow direction. The results are to be presented in two forms. Distributions in the measuring plane are shown as contour plots. Then two sections are presented, the first $y/\delta = 0.5$ and the second $x/\delta = 0$. Note that both sections pass through the reference point.

Results evaluated for smooth wall are presented by full-line, while results related to rough wall are shown using dashed-line. Labels are added to some contours.

Correlations of u and v velocity and vorticity components ω are to be presented in all combinations.

First, correlation of longitudinal velocity u and transversal velocity components v are to be shown in Figs. 1, 2 and 3.

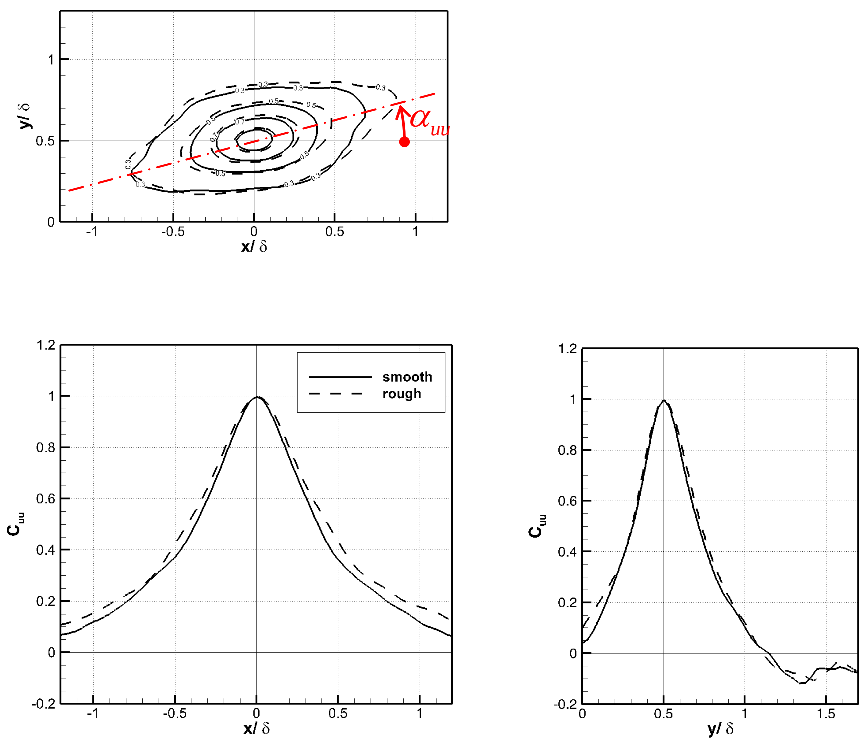

Fig. 1: Correlation of longitudinal velocity components C_{uu} .

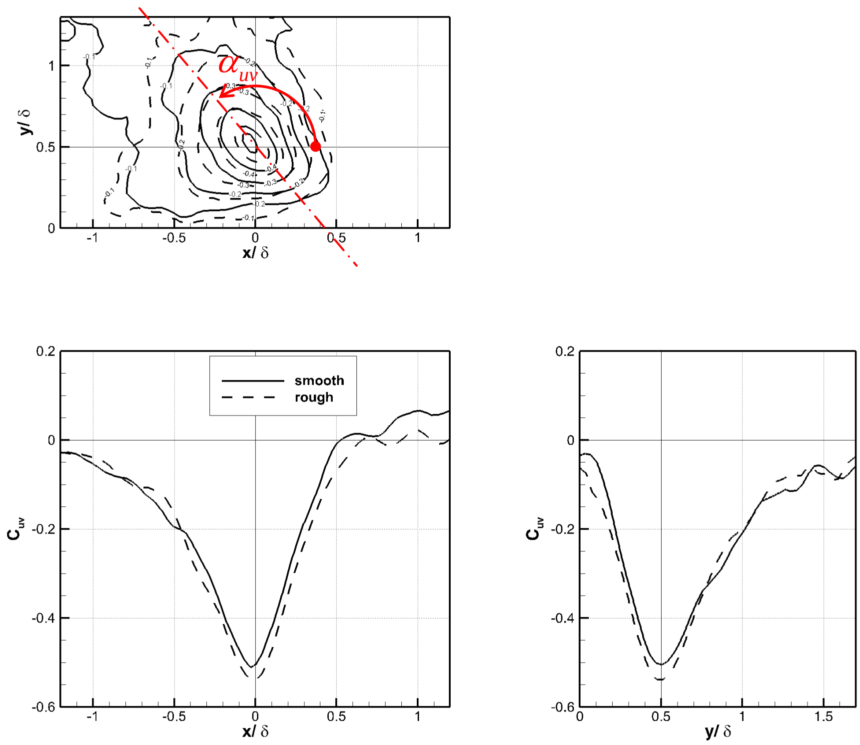

Fig. 2: Correlation of longitudinal and transversal velocity components C_{uv} .

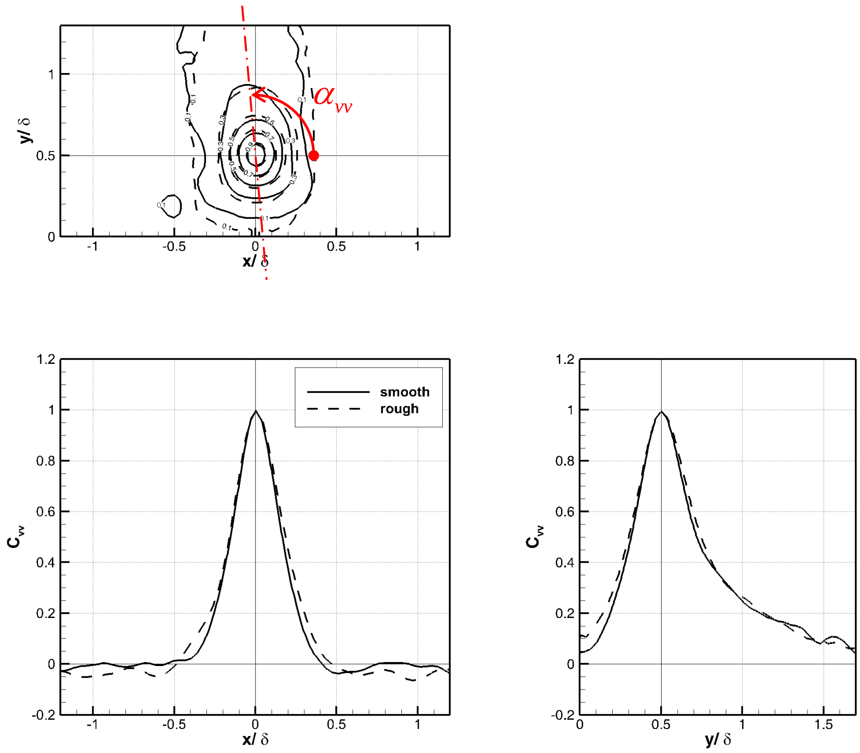

Fig. 3: Correlation of transversal velocity components C_{vv}.

In correlations distributions the axis of quasi-symmetry has been added (in red), position angle α indicates its inclination. For the C_{uu} and C_{vv} we get the value 1 in the reference point by definition, while C_{uv} yields about -0.5. Negative mixed correlation indicates production of turbulence process. The reference point represents global extreme of the correlation absolute value, with growing reference and variable points distance the values of all correlations approach zero. (No matter if from negative or positive side). Note that correlation of transversal components C_{vv} exhibits much compact structure then that of longitudinal components C_{uu}. However broader profile of the C_{uu} is visible only in longitudinal direction x, in transversal direction y are both correlations equivalent.

The contours represent shape of coherent structure connected with velocity fluctuations in given directions. Contours form elliptical structures with center in the reference point and the longer axis oriented in a specific direction. For the C_{uu} the longer axis direction angle is $\alpha_{uu} = 15\deg$, while for the C_{uv} the angle is $\alpha_{uv} = 130\deg$ and for the C_{vv}, $\alpha_{vv} = 95\deg$.

Vortices in flow-field could be quantified using vorticity component perpendicular to the measuring plane. However the vorticity is calculated from the in-plane velocity components, so adding the vorticity to the analysis no extra information appears, in fact.

Note that shear regions are characterized by non-zero vorticity as well.

Now, the correlations of velocity components u and v with vorticity ω are to be shown in Figs. 4, 5 and in Fig. 6 the vorticity correlation.

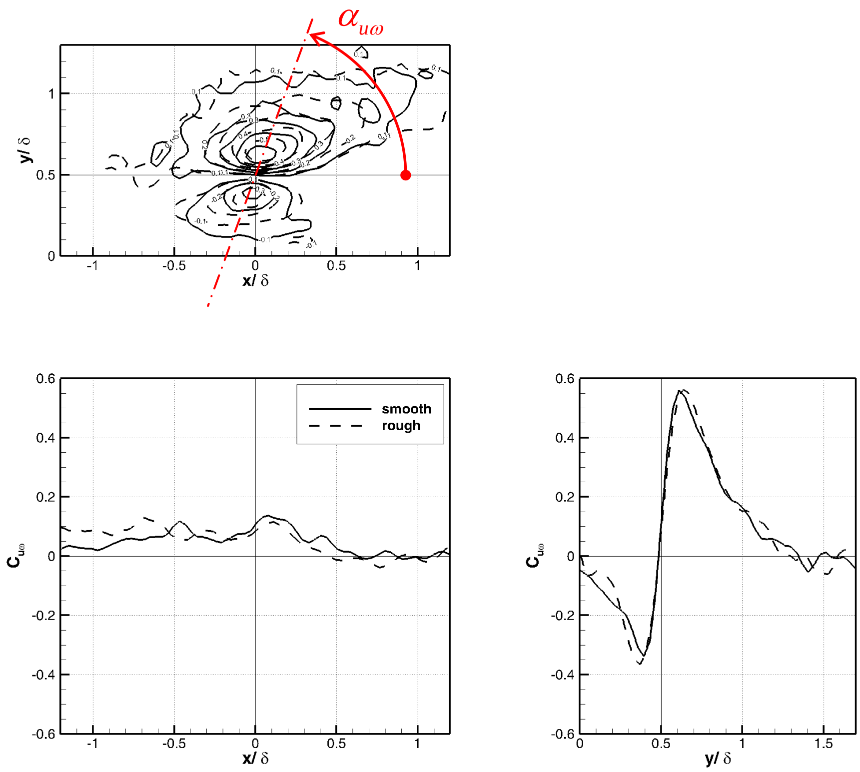

Fig. 4: Correlation of longitudinal velocity component and vorticity $C_{u\omega}$.

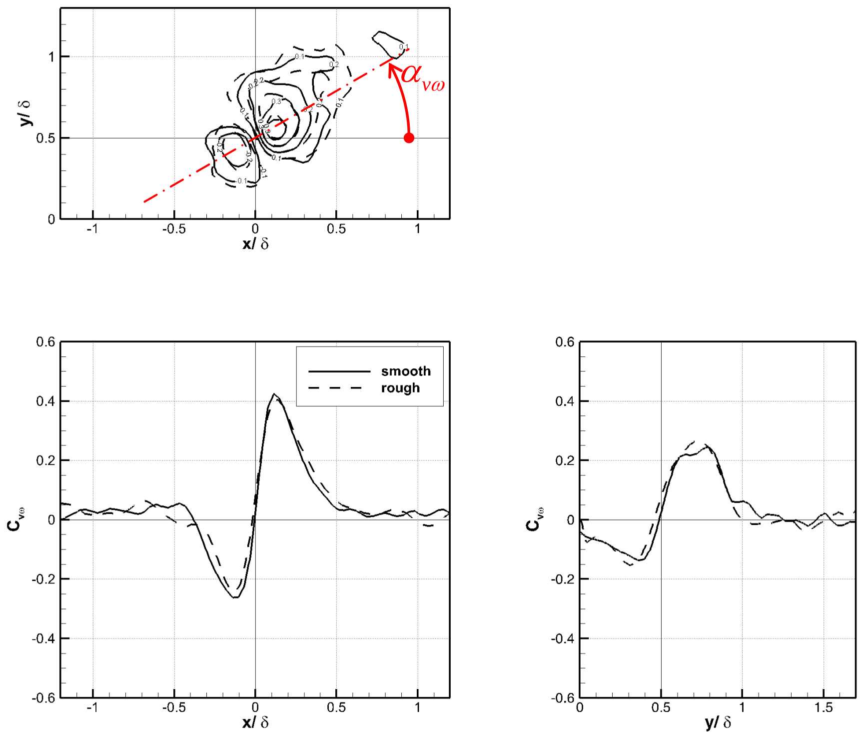

Fig. 5: Correlation of transversal velocity component and vorticity $C_{v\omega}$.

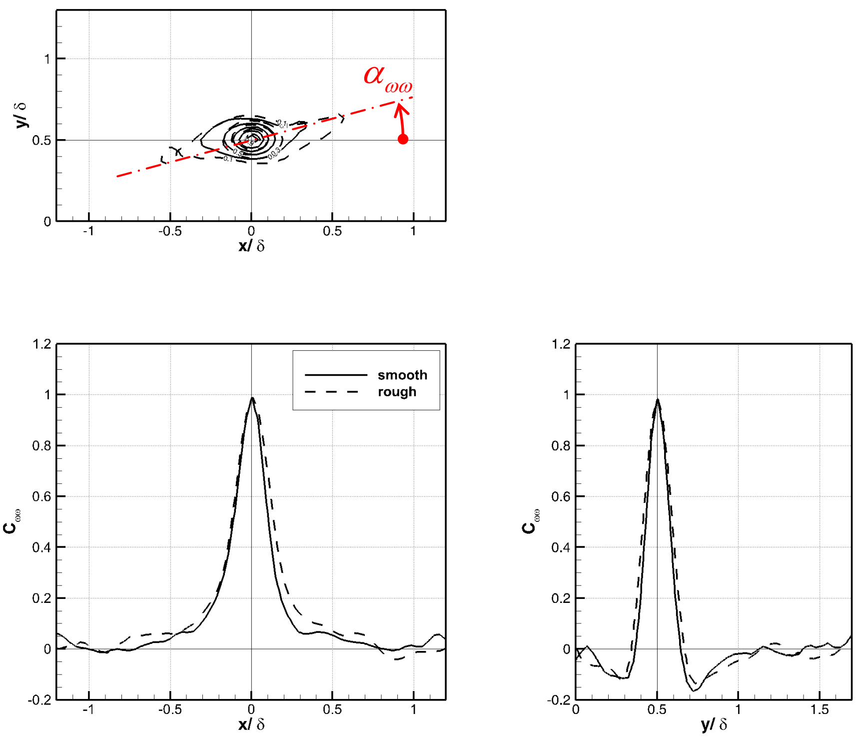

Fig. 6: Correlation of vorticity $C_{\omega\omega}$.

Correlation of longitudinal velocity component and vorticity $C_{u\omega}$ shows positive values with maximum located above the reference point (farther from the wall), while bellow this point the correlation is negative. This result indicates that low-velocity streaks ($v < 0$) in the reference point position would be accompanied by vortices with negative vorticity (clockwise direction) above and positive below the reference point most probably. The quasi-symmetry axis is inclined by $\alpha_{u\omega} = 70\,\text{deg}$, however line of change of sign is parallel to wall passing through the reference point.

The $C_{v\omega}$ correlation distribution pattern is similar to $C_{u\omega}$, but the angle of the axis is $\alpha_{v\omega} = 30\,\text{deg}$ meaning diagonal configuration.

The vorticity correlation $C_{\omega\omega}$ in Fig. 6 shows very narrow peak with circular cross-section, however for lower values the character becomes elliptical with inclination angle $\alpha_{\omega\omega} = 15\,\text{deg}$. This result indicates weak interaction among the vortices in the turbulent boundary layer.

Influence of the surface roughness is clearly visible from all diagrams. Generally, the character of the correlations distribution is not affected, however the values of correlations in places of relatively high signal statistical dependency, indicated by big correlation absolute value. This means that in the case of rough wall bigger and better pronounced coherent structures are present in the flow than in the case of turbulent boundary layer on smooth wall. Wall roughness acts as a source of initial disturbances which are amplified selectively resulting in well-developed turbulent coherent structures.

Note: permutated correlations (e.g. C_{uv} and C_{vu}) show qualitatively similar character of distributions, however the patterns are nearly symmetrical with center of symmetry in the reference point. Physical meaning of permutated correlations is different as well. (Not presented here.)

Conclusion

Correlations of velocity components and vorticity in the plane perpendicular to the wall are evaluated in boundary layers on smooth and rough walls. Typical distributions of velocity components and/or vorticity correlations are shown.

The shape of most probable topology of coherent structures could be estimated from non-zero correlation areas.

Influence of the wall roughness on turbulent boundary layer is demonstrated. It affects size of the correlated areas and correlation local values. Rough wall exhibits stronger correlations.

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