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Hairpin Vortices in Turbulent Boundary Layer

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Abstract: *The experiments on dynamics of turbulent boundary layer on the plane rough wall without pressure gradient are to be presented. Sand roughness of the wall is considered. Measurements are carried out using Time-Resolved PIV technique in plains parallel and perpendicular to the wall. The results on rough wall are compared with the base case of boundary layer on smooth wall. Hairpin vortices and theirs packets have been detected. Topology and typical size of those structures substantially differ in the cases in question.*

1. Introduction

The PIV method applied to the plains parallel to the wall has been used for study of the turbulent boundary layer (TBL) structure was suggested for the first time in [1]. They demonstrated the method in which the flow structure is described by planar fields of three-dimensional velocity vectors can be visualized effectively in a single plot. In combination those could be used to identify and characterize packets of hairpin vortices as shown e.g. in [3]. A recent extension of the hairpin vortex paradigm has been reported by [2], who performed PIV experiments in streamwise-wall-normal planes and found heads of hairpins organized coherently into packets. They concluded that these spatially organized packets of hairpins explained the long tails in previous correlation measurements, as well as the existence of long low speed streaks, sweeps and ejections.

2. Hairpin vortex identification

The packets of hairpin vortices are identified using the strategy presented in [2]. Supposing mean flow from left to right, a hairpin vortex is characterized by negative vorticity on the top of the region, positive on the bottom and negative longitudinal velocity area in between forming well known low-velocity streaks, as shown schematically in Fig. 1.

The slice in Fig. 1b represents vorticity and velocity distribution in the slice plane xy (see Fig. 1a) cutting the hairpin vortex necks.

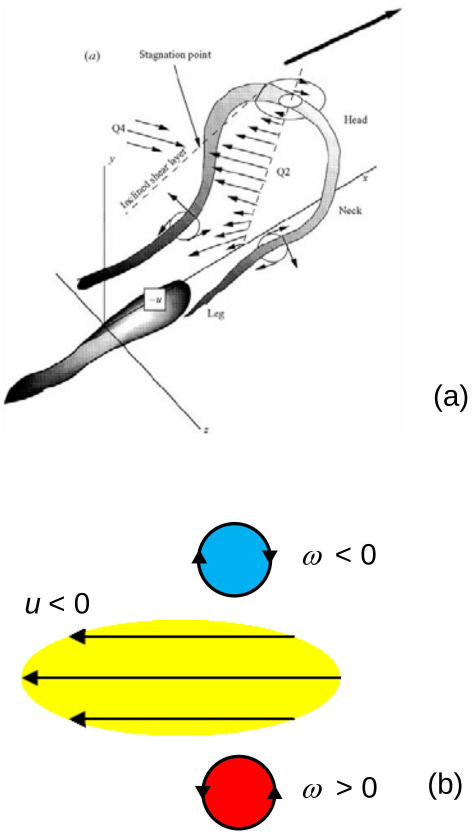


Figure 1: Model of a hairpin vortex from [2], 3D schematic view (a) and slice (b)

The Fig. 1a represents a typical pattern which should be identified in a TBL to prove presence of hairpin vortices or their packets.

The identification of hairpin vortices using the xy slices is possible as well as shown in [4].

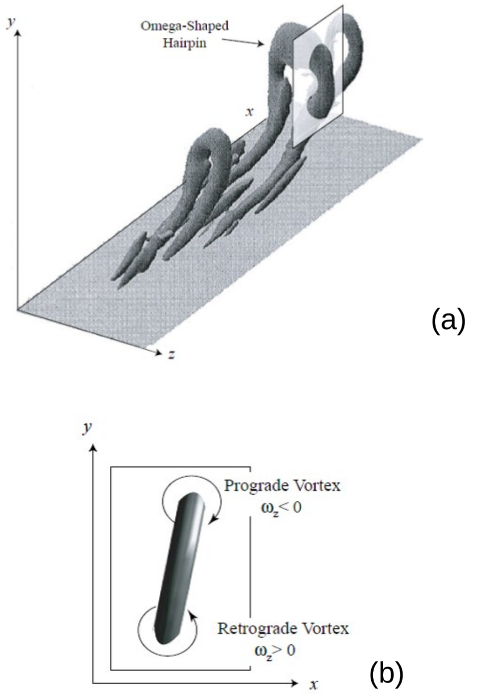


Figure 2: Omega shaped hairpin vortex (a) slice (b) (from [4])

In Figs. 2ab there is three-dimensional visualization of a hairpin vortex packet illustrating the existence of omega-shaped hairpin structures (from [4]). Spatial signature (b) reveals if the omega-shaped structure in (a) were sliced through one of its shoulders in the streamwise-wall-normal plane.

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.

Rough wall, 60-grit sandpaper, mean height of grains is 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. 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.

The standard Cartesian coordinate system xyz has been introduced with x streamwise direction and y direction perpendicular to the wall. Two velocity components were evaluated in the xy plane perpendicular to the wall and at the xz plane parallel to the wall. The horizontal measuring plane xz was in the distance from wall $y = 4.3$ mm corresponding to $y^+ = 60$. Please note that the thickness of the laser sheet is about 1 mm.

4. Results

The basic characteristics of the boundary layers are evaluated from measurements in xy planes in streamwise direction perpendicular to the wall.

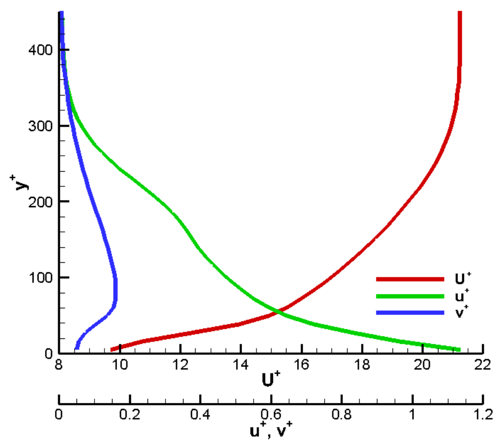


Figure 3: Profiles of mean velocity and standard deviations

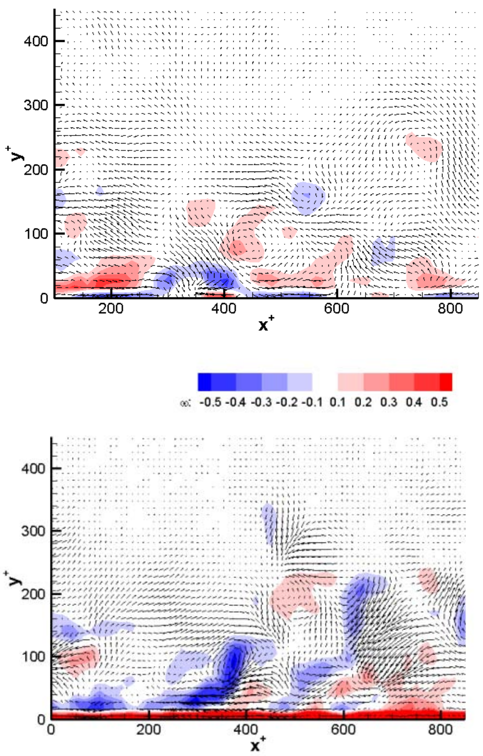
In Fig. 3 the mean velocity profile and longitudinal and transversal velocity fluctuation components standard deviations are shown for the smooth wall. The case of rough wall exhibits the same features, departures are of the order evaluation error. The distance coordinate y and velocity components are given in nondimensional form as usual for the TBL. The characteristic velocity and length scales are the friction velocity u_τ and the viscous length scale δ_ν respectively:

$$u_\tau \equiv \sqrt{\tau_w/\rho}, \quad \delta_\nu \equiv \nu/u_\tau . \tag{1}$$

Here τ_w is wall shear stress, ρ is density and ν is kinematic viscosity. From these we can form non-dimensional velocity and height in wall units:

$$U^+ \equiv \frac{U}{u_\tau}, \quad y^+ \equiv \frac{y}{\delta_\nu} = \frac{u_\tau y}{\nu}. \tag{2}$$

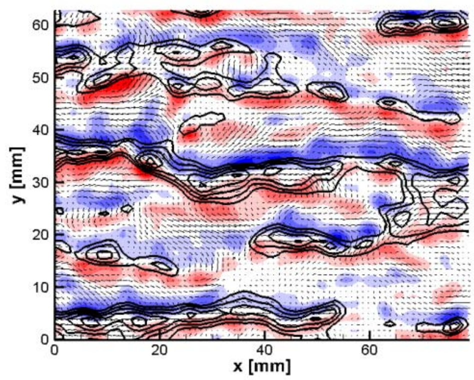
The TBL thicknesses have been evaluated for both cases. The conventional thickness $\delta_{0.995}$ was 22.5 mm and 24.6 mm respectively, while impulse thickness δ_2 was 2.32 mm and 2.64 mm respectively for smooth and rough surfaces. Then the shape factors H_{12} have been evaluated being 1.53 and 1.57 respectively. Obviously, the boundary layers could not be considered a fully developed turbulent boundary layer as the shape factor is still too high (for a fully developed turbulent boundary layer it should be about 1.4).
The mean velocity profile shows well developed logarithmic part. Please note that the points close to the wall are of informative meaning, because the size of the interrogation area (i.e. measuring point) was about 1 mm corresponding to Δy^+ of about 13, so viscose sublayer could not be well resolved.



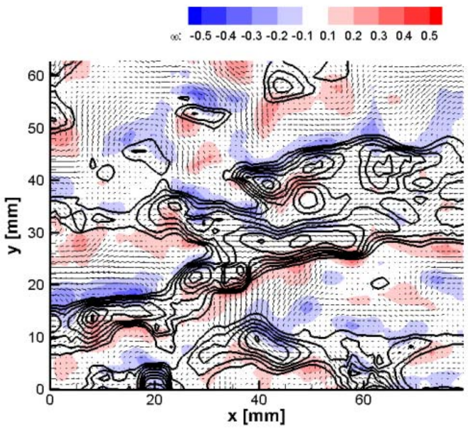
(a) (b)

Figure 4: Instantaneous velocity (vectors) and vorticity (color) distribution in turbulent boundary layer on smooth (a) and rough (b) walls

The vortical structures in the boundary layers are studied. The examples of instantaneous structure for both cases are given in Fig. 4ab. The vector fields represent departures from the local mean velocity, which is given in Fig. 3.
We could recognize those signatures both in Fig. 4a and b.



(a)



(b)

Figure 5: **:** Instantaneous velocity (vectors), vorticity (color) and negative longitudinal velocity component fluctuations (lines) distributions in turbulent boundary layer on smooth (a) and rough (b) walls

In Figs. 5ab there are examples of instantaneous vector fields in the xz measuring plane for the rough and smooth walls respectively. The local mean velocity was subtracted (nearly constant value of about 3.6 m/s). The coloring represents vorticity value - red positive and blue negative. The black isolines round places with negative longitudinal instantaneous velocity forming the shape of “low-velocity streaks”.

We could distinguish different topology of packets of hairpin vortices in boundary layer on the rough and smooth walls. While for the smooth wall the hairpin vortex packets are oriented in streamwise direction exactly appearing evenly in space, the packets in rough wall boundary layer are oriented more diagonally, theirs appearance is not so regular. The size of structures seems to be twice as big as in the first case. Absolute values of vorticity are much higher in the case of smooth wall TBL.

Note that nearly all negative longitudinal velocity regions in Fig. 5 correspond to a hairpin vortex. The broad low velocity region in the middle in Fig. 5b for rough wall TBL represents very probably fractal system of hairpin vortices of various sizes located in the same place. These vortices we call primary, secondary, etc. and the system topology is described in [2].

5. Conclusions

The developed turbulent boundary layer was subjected to experiments using PIV technique. The velocity fields in plane parallel to the wall close to it were evaluated in time sequences. The hairpin vortices have been detected in both cases. Typical features and differences for smooth and rough walls have been shown. Further information could be found in [5].

6. Acknowledgement

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