Proc. 30^{th} IAHR Thessaloniki, Greece, 25.-31.8.2003

IDENTIFICATION OF COHERENT FLOW STRUCTURES IN OPEN-CHANNEL FLOW OVER ROUGH BED USING LARGE EDDY SIMULATION

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ABSTRACT

In this paper we simulate a rough-wall open channel flow using large eddy simulations (LES) in order to gain insight into the physics of this flow. The channel bed is artificially roughened with a matrix of staggered cubes and the Reynolds number *Re* is *60,000*. The relative submergence of roughness elements is approximately *13*, such that the elements are considered to roughen the channel bed, rather to block the flow as present in roughness height to water depth ratios below 5. The quadrant analysis is used for the detection of sweeps, ejections, inward and outward interactions. The results show the dominance of the sweep and ejection events near the boundary layer over the rough wall. Furthermore, with help of the instantaneous streamwise velocity fluctuations the identification and quantification of low and high speed streaks is accomplished. All observations made by the large eddy simulations are in good agreement with the theory and with recent laboratory results.

Keywords: Large eddy simulation, LES, rough channel flow, coherent flow structures

INTRODUCTION

Turbulent boundary layers over roughness elements have considerable engineering interest. Especially in the field of hydraulic engineering, nearly all practical flows are hydraulically rough, i.e. the grain Reynolds number $Re_* = (u_* \cdot d)/n$ (where u_* is the friction velocity, d is a characteristic roughness height and n is the dynamic viscosity) exceeds a certain value ($Re_* > 70$) and the roughness effects the flow outside the laminar sublayer. This results in a mean velocity profile, that differs considerably from the velocity profile over a smooth bed (e.g. Patel, 1998), since surface drag is significantly larger in comparison to a turbulent flow field over a smooth surface. The presence of organized structures near the walls, which are responsible for the transport of heat and mass and momentum across the boundary layer (Grass, 1971) is, irrespective of surface condition, conclusive from immense research endeavours in the past. However, increased surface roughness may enhance the organization of coherent structures in a turbulent boundary layer, an issue being investigated since. Furthermore, the streamwise velocity field in the sublayer and in the buffer regions is organized into alternating narrow streaks of high and low speed fluid that are persistent, only vary on a long time scale, and exhibit a preferential spanwise spacing (Grass et al., 1991). The majority of turbulence production occurs, when these low speed streaks are lifted away from the wall-layer in a violent ejection and during inrushes of high speed fluid from the outer layer back towards the wall. The complete cycle of lift-up of fluid, oscillation, ejection and sweep motion is usually called the bursting phenomenon (see papers e.g. by Kline et al., 1967, Corino and Brodkey, 1969, or the summary by Robinson, 1991). Since the late 1960's intensive experimental research on the mechanisms has been conducted in order to throw light on the bursting phenomenon and the associated structures by means of different techniques.

Flow visualisations of streaky patterns with help of passive tracers (e.g. Defina, 1996) or the use of hydrogen bubble flow visualisation (Grass et al., 1991) in order to observe the bursting process were carried out in a qualitative sense. More quantitatively, different conditional sampling techniques were used in order to detect coherent structures from velocity fluctuation signals. Among others, the quadrant analysis by Lu and Willmarth (1973) is to date the most popular and probably the most used. The streamwise and wall-normal velocity fluctuations u' and w' are divided into four quadrants in order to evaluate the contributions of ejections and sweeps to the Reynolds stress. The definition and terminology of "sweeps" with $u' > 0,\ w' < 0$, "ejections" with $u' < 0,\ w' > 0$, "inward interaction" with $u' < 0,\ w' < 0$ and "outward interaction" with $u' > 0,\ w' > 0$ is since then applied systematically. High temporal and spatial resolution computer simulations have been performed either as direct numerical simulation (DNS) (e.g. Miyake et al, 2002) or large eddy simulation (Yang and Ferziger, 1993) and have contributed to the understanding of the mechanisms of near wall turbulence. However, both DNS and LES are very demanding of computational resources and the investigations are rare and have been restricted to very simple geometries and mostly smooth walls so far. In this paper we show the results of LES calculations of an open-channel flow over an artificially roughened bed. The main purpose of this study is to provide further insight into the turbulent flow over rough boundaries and to enhance the understanding of the effect of surface roughness geometry on the formation of coherent structures.

NUMERICAL METHOD

The LES code LESOCC developed at the Institute for Hydromechanics (Breuer and Rodi, 1996) is used to perform the simulations. The code solves the filtered Navier-Stokes equations on a curvilinear, block-structured grid discretised with the finite volume method. A non-staggered grid with Cartesian velocity components is used. Both, convective and diffusive fluxes are approximated with central differences of second order accuracy. The SIMPLE algorithm is employed in order to conserve mass and to couple the pressure to the velocity field. Time advancement is achieved by a second order, explicit Runge-Kutta method. LESOCC is highly vectorised and parallisation is accomplished by domain decomposition and explicit message passing via MPI. The subgrid stress of the filtered Navier Stokes equations is computed using the dynamic approach of Germano et al. (1991). The no-slip boundary condition of Werner and Wengle (1999) is used for all impermeable walls of the fully resolved rough surface texture, i.e. on and between the roughness elements.

FLOW CONFIGURATION

Figure 1 shows both, the configuration of the present numerical simulations and the laboratory experiment of Dittrich et al. (1996) of the open channel flow over artificial roughness elements. The Reynolds number $Re_h = (u \times h)/n$, defined with the water depth h in the experiment and in the simulations is $Re_h = 60{,}000$ and the average shear velocity is $u_* = 0.0575\ m/s$ yielding Re_t » 6000. Several simulations with different grid resolutions and domain sizes were carried out. In this paper we will only present the results from the finest grid calculations on the largest domain, of size $15d \times 7.5d \times 13d$, where d is the cube height, taken as a reference length throughout this paper. The calculations performed in this domain gave the best agreement with the laboratory experiment, to which the results of the simulation are compared to.

RESULTS AND DISCUSSION

AVERAGE FLOW FIELD AND STATISTICS

The flow develops several separation and reattachment zones near the roughness elements causing a strong shear layer and a strong disturbance of the flow field in the vicinity of the cubes. This influence prevails up to approximately half of the channel depth. Figure 2 shows the distribution of mean streamwise velocity in comparison to the measurements from a detailed laboratory investigation at three locations (depicted in Figure 1b). The agreement of the simulations with the observations along the measurement verticals in Points A and B is fairly good. However, the recovery of the flow behind the obstacle is underestimated in the simulations as illustrated by the obvious mismatch of the streamwise velocity for $z/d < 1$ at Point C. When comparing the second order statistics i.e. the *rms* values of the streamwise velocity fluctuations, at the same locations (Figure 3) it is apparent that along all three measurement verticals a relatively good match is achieved. The general feature of rough wall channel flow, i.e. a fairly thick boundary layer and, as a consequence, a relatively large shift of the logarithmic region away from the wall is reproduced. Furthermore, the peaks of streamwise turbulence intensities just above the cubes and the relatively weak gradient observed in the laboratory is matched. A comparison of our results to different data sets of other artificial roughness elements such as spheres suggests that the shape of roughness plays a significant role. For instance, the same flow with spheres instead of cubes, at the same Reynolds number and with the same roughness height yields a form-induced roughness layer half the size the one shown herein.

INSTANTANEOUS FLOWFIELD

Figure 4 shows instantaneous velocity distributions of the streamwise Reynolds stress u'u' together with the perturbation velocity vectors (v'-w' and u'-w', respectively) in a x-z and a y-z plane. It illustrates the presence of vortical motion, especially near the elements. At *x » 7.5* just above the crest of the cubes, a sweep event, where faster fluid is pushed towards the wall, can be detected. The rather weak but steady decay of the turbulent motions towards the free surface is also clearly visible.

Figures 5 and 6 show the average event frequency distribution along the three measurement verticals in Points A, B and C, and a contour plot of the probability distribution of the four events, respectively averaged over 960 samples within a y-z plane, Here, the general feature of fully developed turbulent flow over a rough surface is apparent, i.e. the sweep phase is especially significant near the wall, whereas ejections are influential in the whole boundary layer. Also noticeable the peak of sweep events at *z » 1* between the cubes. This is in good agreement with, e.g., Nezu and Nakagawa (1977), who state that the region close to the rough surface is mainly dominated by sweeps. The dominance of these two events gradually decreases from *z* » 1 until *z » 8*, above which the fluctuations are isotropic. Both figures can be regarded as complementary to Figure 3, that the roughness layer occupies half channel depth. In the region of recirculation below the cube height (Point B) all four events appear to be evenly distributed reflecting a rather homogenous turbulence distribution.

Streaky structures are present just above the roughness elements as was shown e.g. by Defina (1996) in the laboratory experiment with the help of dye. Figure 7 below shows an instantaneous distribution of u' normalized with the shear velocity u_*. Here, the presence of coherent structures of high and low speed streaks alternating in the spanwise direction is visible. As was pointed out by several researchers in the past (e.g. Smith and Metzler, 1983, Grass, 1991) the streak spacing is constant at l^+ *» 100* at low roughness Reynolds numbers increasing linearly with roughness Reynolds numbers above that value, which was determined to be valid for spherical roughness. In the present LES the average dimensionless streak spacing is l^+ *» 500,* but as a much higher roughness Reynolds number of Re_* » 490, proving a similar behaviour for cubical roughness elements.

CONCLUSIONS

In this paper we have shown the results of a large eddy simulation of open channel flow over an artificially roughened channel bed. A strong-form-roughness-induced shear layer is developed above the elements such that instantaneous and mean velocities differ significantly from the velocities over smooth beds. The LES computations revealed typical characteristics of the bursting process, that is dominance of sweeps and ejections near the wall. Over a given period the two events of bursts and sweeps dominated the flow near the wall and are found to prevail near the roughness elements up to *80%* over the sampled period. Additionally, the event frequency distribution of the four events of the bursting process showed the strong effect of the roughness elements suggesting the influence of these elements prevail above the half channel depth. Also, the near wall streak formation is shown and the spacing of these streaks is found to agree well with the values reported in the literature. Further research is currently undertaken investigating different roughness shapes together with comparisons to the results of laboratory experiments.

ACKNOWLEDGEMENTS

This work is part of the research project funded by the German Research Foundation (DFG) under project number JI 18/10-1. The authors would like to thank Professor Andreas Dittrich for the provision of the experimental data.

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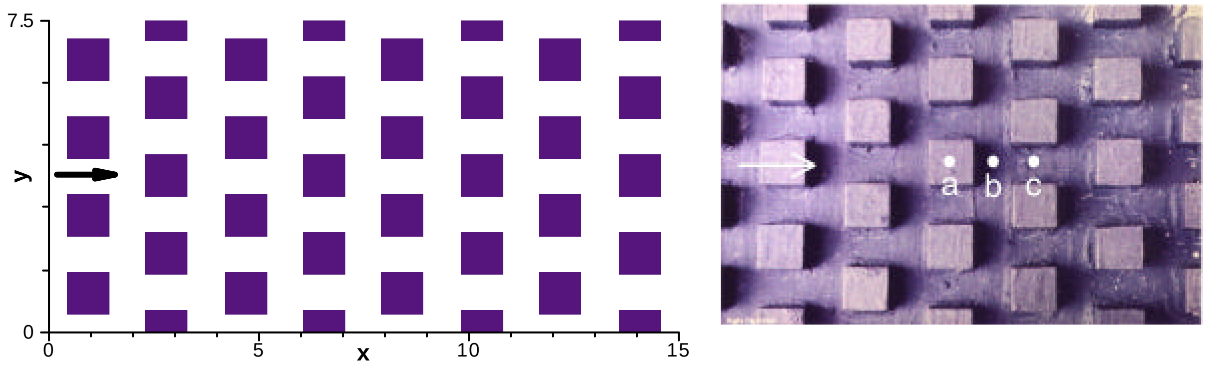
FIGURES



a.) b.)

Figure 1: Configuration of numerical simulation (a.) and laboratory experiment (b.)

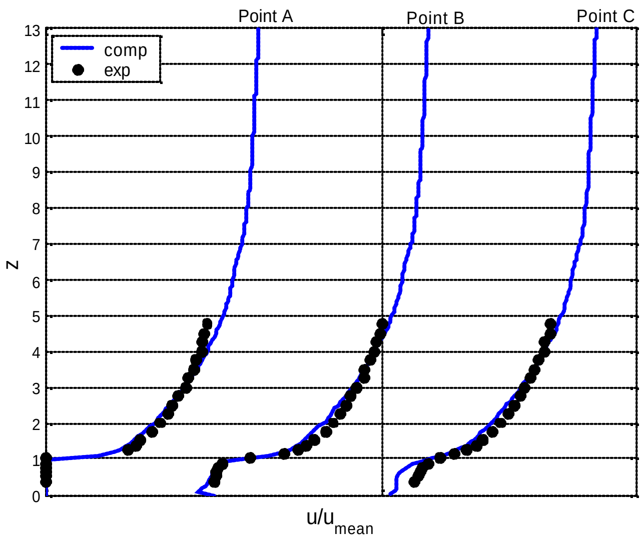


Figure 2: Distribution of 1st order statistics along the 3 measurement verticals.

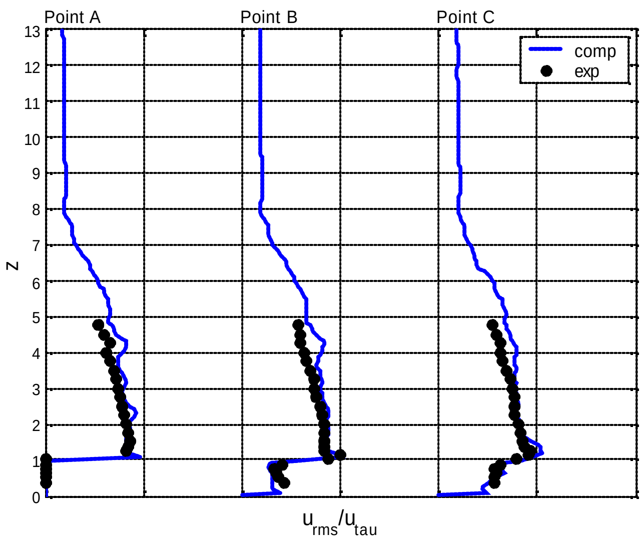


Figure 3: Distribution of 2nd order statistics along the 3 measurement verticals.

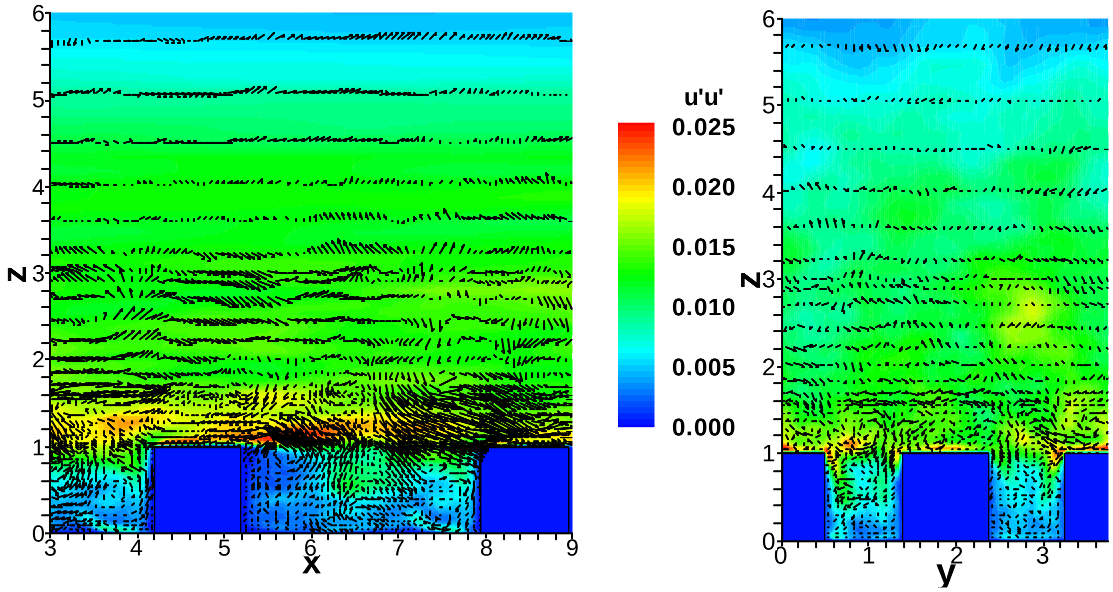


Figure 4: x-z and y-z planes of perturbation velocity (vectors) and u'u' distribution.

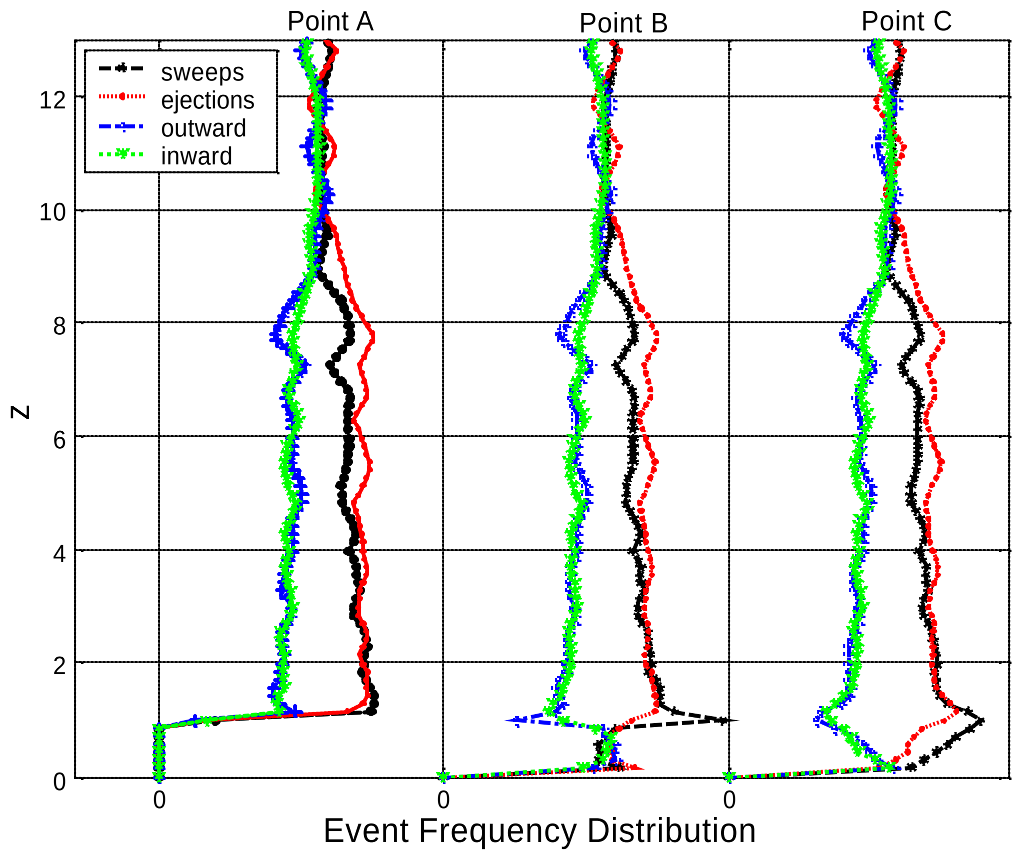


Figure 5: Event frequencies of the four bursting events along the 3 measurement verticals.

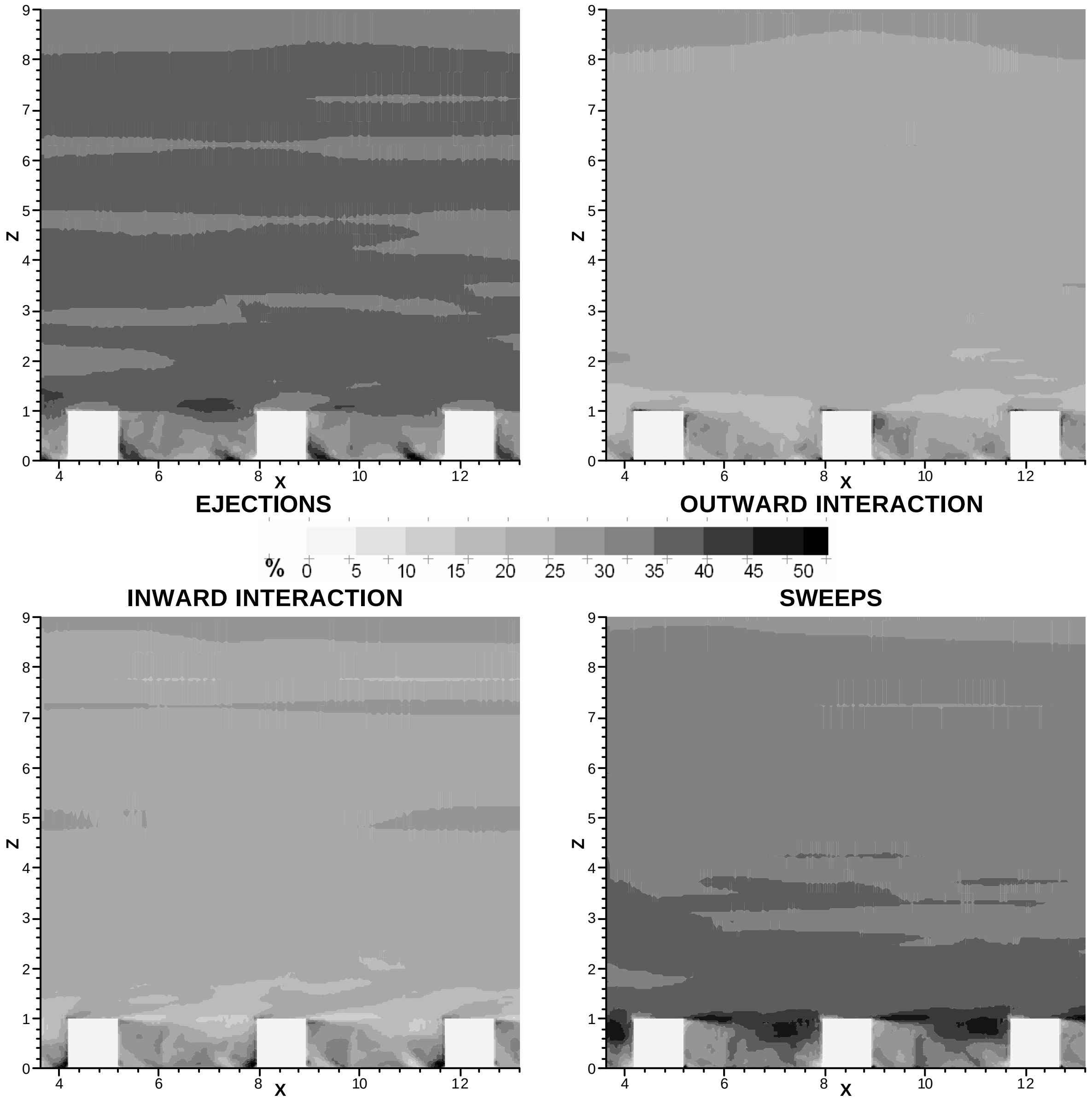


Figure 6: Probability distribution of the four bursting events in a selected x-z plane.

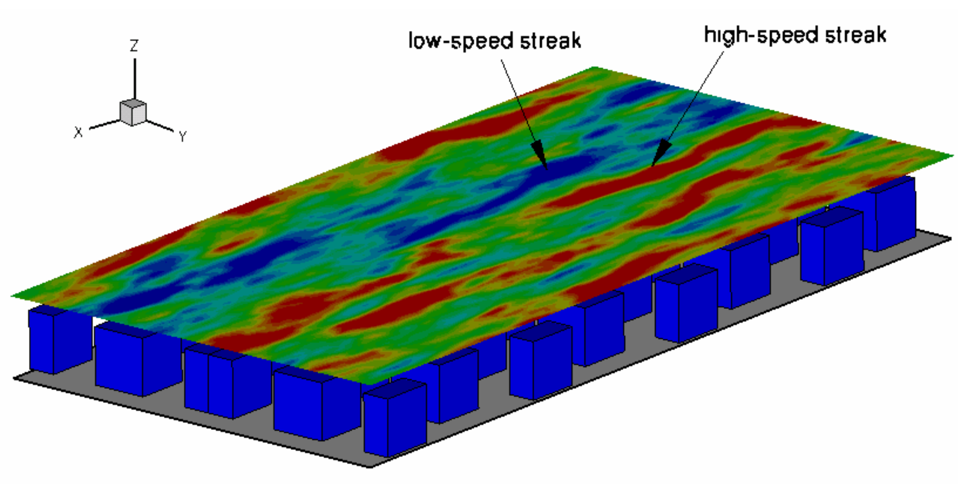


Figure 7: Distribution of instantaneous velocity fluctuation u' in a plane at z » 1.3d above the roughness elements.