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Flow over a change in roughness: experimental characterization of the transition region

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Abstract. *The present work uses PIV to characterize the transitional flow in regions where abrupt changes in surface momentum flux occur due to changes from one extensive uniform rough surface to another extensive uniform smooth surface. The work analyzes the statistics of the flow to show how the gradient method of Clauser and the turbulent shear stress profiles can be used to determine the wall shear stress. The concept of the error in origin is also investigated in detail. The extent of the transition region is characterized through the mean velocity profiles and the skewness coefficient.*

Keywords: *turbulence, roughness, PIV, error in origin, skewness.*

1. Introduction

The description of flow over natural terrain is pervaded by a very important issue: the specification of the lower boundary condition. Since most parts of the earth's surface are arbitrarily heterogeneous, changes in roughness from one extensive surface to another are very common.

In literature (see e.g. Kaimal and Finnigan (1994)), two types of changes are immediately identified: (i) those that produce a change in surface momentum flux and (ii) those that change the surface availability of some scalar, heat and moisture. The present work is concerned with abrupt changes in surface momentum flux that occur from one extensive uniform rough surface to another extensive uniform smooth surface. The work in particular discusses the statistics of the flow in the transition region to argue that the changes in properties are best characterized by the third order moments. In fact, the mean longitudinal velocity profile and the second order moment can be used to distinguish if a flow is in a state of self-preservation. However, the most sensitive and adequate parameter to differentiate states of self-preservation for flows over rough or smooth walls is the third order moment. The problem of finding reliable skin-friction data in the non-equilibrium, transitional region that is formed after a change in surface from rough to smooth is also addressed. The inapplicability of methods based on the existence of the classical law of the wall in principle implies that alternative methods must be used. However, if the structure of the transitional flow is taken into account, it can be shown that a local solution in the inertial layer can be used to find the friction velocity provided some questions regarding the displacement in origin are correctly assessed.

The present work adds to the previous contributions by investigating the transition region through a new set of experiments. The experiments are performed with a two-dimensional particle velocimetry system. The skin-friction in the transition region is obtained by linear fits to the logarithmic profile and through turbulent shear stress profiles. New data on skewness and flatness are also presented.

Many other investigations have been carried out on flows with a change in surface properties. Typical examples are the classical theoretical works of Townsend (1965, 1966) and experimental works of Bradley (1968), of Antonia and Luxton (1971, 1972), of Mulhearn (1978). Townsend (1965) has shown that the dynamical conditions for self-preservation can only be achieved if the changes in friction velocity are small and if the logarithmic ratio of the depth of the modified flow by the effective roughness length is large. In real flow situations these two conditions are most likely not to be met. Therefore, working relations for flows in a state of non-equilibrium must be sought. Other investigations on the statistical properties of a turbulent flow passing from a rough surface to a smooth surface include the works of Ligrani and Moffat (1985), of Perry et al. (1987), Bandyopadhyay (1987), Bandyopadhyay and Watson (1988), Krogstad and Antonia (1994).

2. Theoretical background

2.1 The lower boundary condition for flow over a rough surface

The attached turbulent boundary layer, irrespective of the type of surface, if smooth or rough, exhibits a canonical asymptotic structure whose reference lengths and velocities in the inner surface region scale with the friction velocity.

Indeed, for a smooth wall, the viscous and fully turbulent regions are known to scale with $(\nu/u_\tau,\, u_\tau)$ and $((u_\tau^2/U_e^2)L,\, u_\tau)$ respectively, where u_τ stands for the friction velocity and U_e and L for the external flow reference velocity and length. For a rough wall, the viscous region is destroyed so that a new reference length has to be introduced to characterize the inner region. Several formulations can be found in literature, depending on the different areas of application. Even in this case, $((u_\tau^2/U_e^2)L,\, u_\tau)$ remain as important scales of the flow. Detailed discussions on the asymptotic structure of turbulent boundary layers can be seen in Cruz and Silva Freire (1998) and Sychev and Sychev (1987).

Unfortunately, most methods that are used to find the skin-friction rely on the existence of self-preservation, and, in particular, on the universality of the parameters appearing in the law of the wall, the constant of von Karman and the additive parameter. For example, the two most popular methods to determine the skin-friction, the Preston tube and the velocity gradient method of Clauser, can only be used in regions where the flow is known to be in a state of self-preservation.

The method developed by Clauser to find the skin-friction was specialized by Perry and Joubert (1963) and by Perry et al. (1969) with the introduction of the concept of displacement in origin.

For a rough surface, it is normally possible to identify an inertial region where the flow properties are horizontally homogeneous so that the turbulent statistics are approximately constant and the mean velocity profile is logarithmic. According to Cheng and Castro (2002), this region is on the scale of the roughness elements height $\approx 5K$. Thus, it is possible to write

$$\frac{u}{u_\tau} = \frac{1}{\varkappa} \ln\left[\frac{(y_T + \varepsilon)u_\tau}{\nu}\right] + A - \frac{\Delta u}{u_\tau} \tag{1}$$

where,

$$\frac{\Delta u}{u_\tau} = \frac{1}{\varkappa} \ln\left[\frac{\varepsilon u_\tau}{\nu}\right] + C_i \tag{2}$$

$\varkappa$ = 0.4, A = 5.0, and $C_i, i = K, D$ is a parameter characteristic of the roughness (see, for example, Perry and Joubert (1963)).

The origin of the coordinate system y_T is set at the top of the roughness elements. Parameter ε, therefore, represents the displacement in origin below this level.

Equations (1) and (2), depend on three unknown parameters for their definition, the skin-friction velocity, u_τ, the error in origin, ε and the roughness function, Δu. In fact, once ε is known, the skin-friction velocity follows directly from the slope of Eq. (1). This defines, in principle, a simple procedure that can be used to determine u_τ for flows over rough surfaces. The difficulty is that ε is a quantity that varies from one type of rough surface to another and is hard to determine.

Following a change from a rough to a smooth surface, the no-slip condition forces the near wall flow characteristics to immediately adjust themselves to the new surface. The outer region on the other hand remains mostly insensitive to the near wall phenomena. In between these two layers, in the fully turbulent region where Eqs. (1) and (2) are valid, a fetch is required before the flow properties adjust to the equilibrium conditions dictated by the underlying surface. In this transition region, the validity of Eq. (1) can be questionable.

However, provided one can still consider that Eq. (1) holds in the transition region, where the flow is still relaxing to an equilibrium condition, the graphical method of Perry et al. (1969) developed for rough surfaces of types 'K' and 'd' could still be used to determine the wall shear stress. In this case, the displacement in origin, ε, would correspond to the memory effects of the upstream fully rough turbulent boundary layer.

2.2 High-order moments

Important aspects of turbulent flow over rough wall can be further investigated by consideration of the high-order moments of the fluctuating velocities. In particular, structural information can be extracted without ambiguity from third and fourth moments (Gad-el-Hak and Bandyopadhyay 1994). The triple velocity products are particularly helpful in characterizing the near wall flow. Flow regions where S_u (defined below) is positive are associated with acceleration-dominated velocity fluctuations resulting from the arrival of external high-speed fluid (sweep events) (Gad-el-Hak and Bandyopadhyay 1994). For flow over rough surfaces very high and positive values of S_u are observed for the near wall region. Over a smooth wall the flow in the viscous region is negative.

The skewness and flatness factors for the longitudinal velocity fluctuations are defined by

$$S_u = \overline{u'^3}/\left(\overline{u'^2}\right)^{3/2}, \tag{3}$$

$$F_u = \overline{u'^4}/\left(\overline{u'^2}\right)^{2}. \tag{4}$$

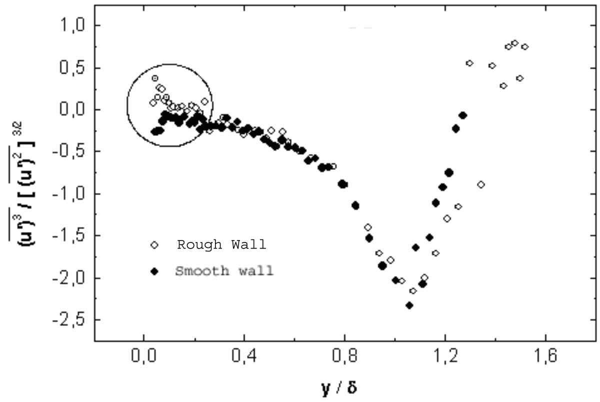

Figure 1: The near wall behaviour of S_u for flows over rough and smooth walls.

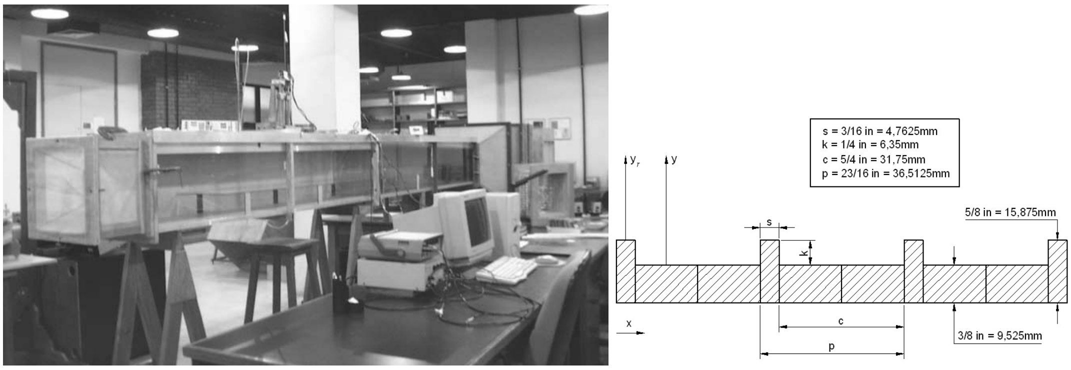

Figure 2: General view of wind tunnel and rough wall.

Equivalent expressions can be written for the other flow properties. A signal with a Gaussian distribution satisfies S_u = 0 and F_u = 3.

Typical skewness profiles for flows over rough and smooth surfaces are shown in Fig. 1. Thus, an alternative way to characterize the transition region is through an inspection of S_u. Positions where positive S_u's are found over the smooth surface can be considered to be in a transitory state. The transition length can then be defined in terms of variations in the velocity profile or in the third-order moment. An important discussion to settle concerns the coincidence or not of these two reference lengths.

3. Experimental procedure

The experiments were performed in a low-turbulence wind tunnel in the Laboratory of Turbulence Mechanics of PEM/COPPE/UFRJ. The tunnel is an open circuit tunnel with a test section of dimensions 300 mm x 300 mm x 8.000 mm. The test section is divided into two sections of equal length which can be fitted with surfaces having different types of roughness. In the present experiment, the first two and a half meters were fitted with a rough surface. The remaining three meters were then fitted with a glass smooth surface. A general view of the wind tunnel and of the rough wall is shown in Fig. 2. The origin of the coordinate system was set exactly at the surface change point. Negative values indicate position over the rough wall.

The rough surface was a transversely grooved surface constructed with rectangular aluminum bars of 6.35 by 4.76 mm rectangular cross section (see Fig. 2). The flow before reaching the rough surface traveled through a short smooth surface section whose leading edge was faired into the wind-tunnel floor by a 400-mm long ramp.

Every roughness element was made removable so that another element constructed with pressure taps could be fitted anywhere in the roughness pattern. The pressure taps, seven in all, were drilled directly onto an aluminum bar. The pressure tubes were connected directly to an inclined manometer that was operated at an angle of 2^o and was filled with alcohol. Pressures were therefore measured to an accuracy of 0.028 mm of water.

The measurements were performed for values of the free-stream velocity of 8 m/s; the free stream-level of turbulence was about 0.2%.

4. PIV system

The PIV measurements were performed with a two-dimensional Dantec system. The light source was furnished by a double pulsed Nd:YAG laser that produced short duration (10 ns) high energy (120 mJ) pulses of green light (532 nm). The collimated laser beam was transmitted through a cylindrical (15 mm) and a spherical (500 mm) lens to generate a 1 mm thick lightsheet. The reflected light was recorded at 15 Hz by a CCD camera with 1280x1024 pixels and 12-bit resolution. The camera was fitted with a Nikkor 105 mm f/2.8D lens. The air was seeded through a smoke generator that burned a mixture of water and glycerin. Image calibration was made by taking pictures of a reference target specially designed for the present purpose.

For all the measurements, the velocity vectors computational conditions were fixed. Adaptive correlation has been processed through FlowManager software on 32x32 pixels-size final interrogation spots, with 50% overlap, which gives a 64x64 vectors grid. The pixel resolution is 6.45 x 6.45 μm. Particle image treatment consists in using subpixel cell shifting and deformation, allowing bias and random error reduction. A widely accepted estimation of the absolute displacement error using these algorithms is 0.05 pixels. Different thresholds including signal-to-noise ratio and velocity vector magnitude were used as post-processing steps. Residual spurious vectors have been detected using a comparison with the local median of eight neighbour vectors for each grid points. No further filtering has been applied to the velocity fields in order to keep the whole measurement information.

5. Results

The general flow pattern that is formed in the first two cavities before the smooth surface is reached is shown in Fig. 5as given by the PIV measurements. Two large regions of recirculating flow are identified with the formation of stable vortices. Shedding from the protuberances into the flow is significant. In this case, the external flow after passing over the top of the protuberances penetrates deeply into the cavity. In fact, major disturbances are limited to a distance above the crest of the roughness elements of the order of their height, K. These flow features are typical of 'K' type surfaces. In fact, it must be pointed out that the present flow pattern is somewhat different from the flow visualization studies that were presented in Perry et al. (1969) since two large eddies are apparent. A distinct feature of a 'K' type roughness is the absence of a stagnation streamline on the leading face of the cavity. The flow rather is observed to divide around a streamline near the front of the crest. The absence of separated flow on the leading edge of the crest and the presence of trapped stagnant fluid on the trailing side on the cavity are also characteristic of 'K' type surfaces.

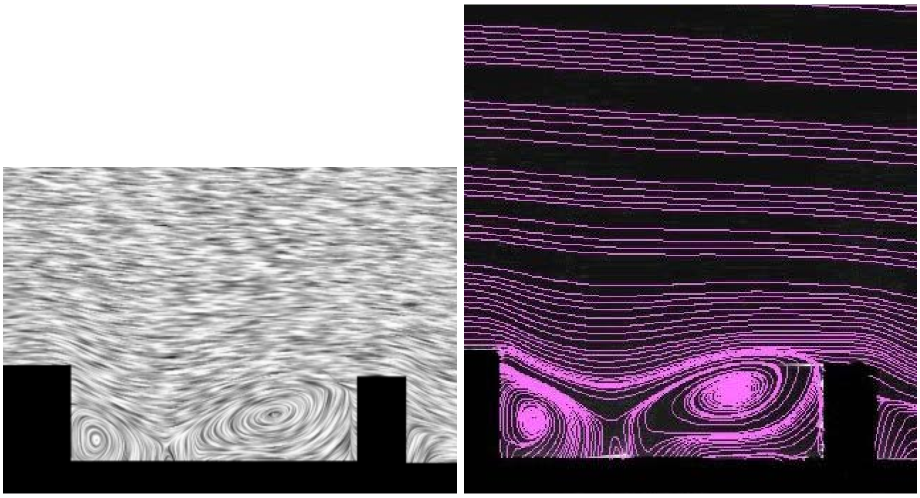

Figure 3: Flow streaklines and streamlines between roughness elements. Flow is from right to left.

Over a rough surface, the flow structure must contain at least two regions: an inertial sublayer where similarity theories apply and the flow is horizontally homogeneous and a roughness sublayer where the the individual influence of the protuberances is felt. After a step change in roughness, from rough to smooth, a viscous sublayer is immediately developed downstream of the change. Above this region, in the early stages of transition, a non-equilibrium layer exists which retains most of the properties of the flow over the rough surface. This layer will then change slowly with fetch until a new equilibrium region is reached.

Mean velocity profiles obtained at several positions are presented in Figs. 4 and 5. Despite the immediate adjustment of the near wall profile to satisfy the no-slip condition, the external region is observed to keep the properties of the rough wall profile. In fact, for $y \geq 100$ mm, the longitudinal mean velocity profiles seem undisturbed (Fig. 4). No differences resulting from the wall change are noted. In the inner layer, however, the changes are dramatic. At location x = 100 mm

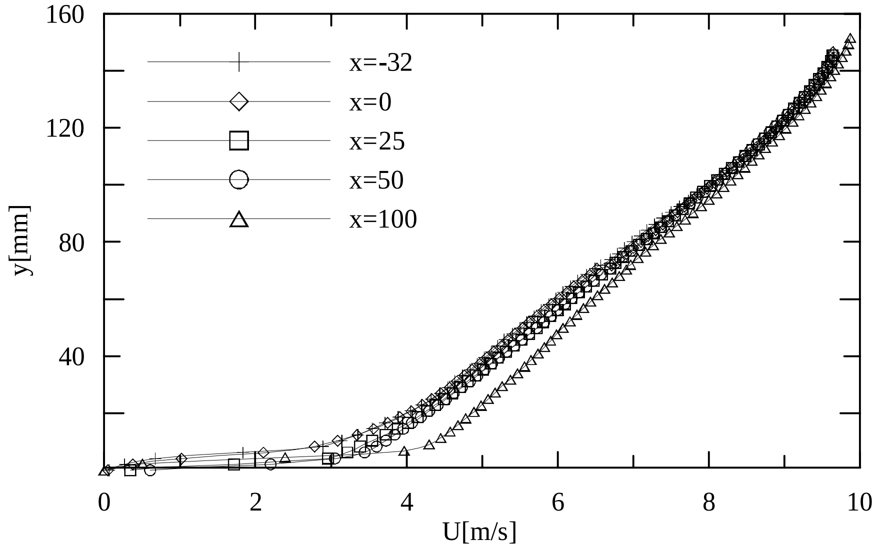

Figure 4: Longitudinal mean velocity profiles.

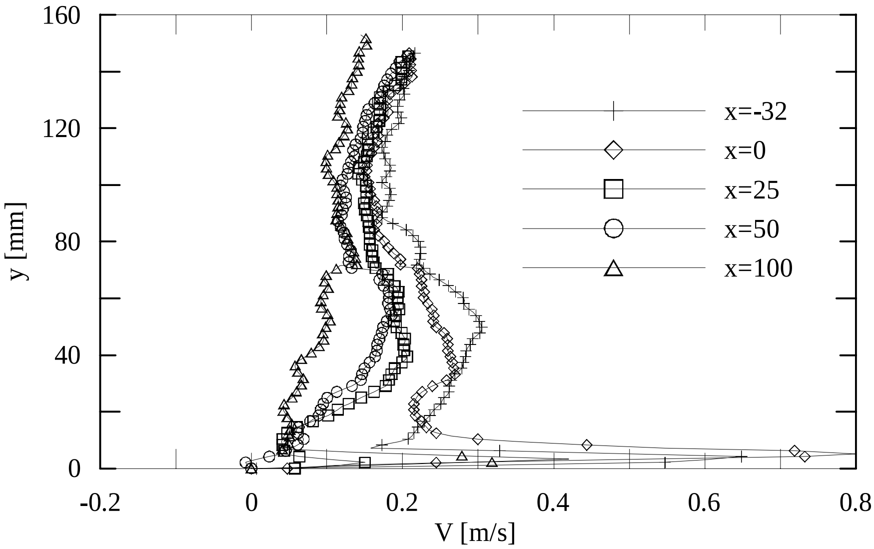

Figure 5: Transversal mean velocity profiles.

the flow is still accommodating to an equilibrium condition. The large changes in vertical velocity are illustrated in Figs. 5.

The changes in the inner region velocity profiles can be better appreciated in logarithmic coordinates (Fig 6). All three characteristic regions of the flow are salient: the near wall viscous region, the fully turbulent logarithmic region and the external wake region. The distortion of the profiles due to the displacement in origin can be noticed.

The error in origin and the friction velocity were estimated through the procedures of Perry and Joubert (1963) and of Perry et al. (1969). These procedures are very rigorous so that the data resulting from them must be seen as very reliable. To find ε and u_τ, the raw undisturbed velocity profiles were added 0.1 mm from their distance to the wall. Then, a best fit logarithmic curve was searched in the near wall region by inspection of the maximum coefficient of determination (R_{sq}), R-squared (Loureiro et al. 2007, Bevington 1969). The process was repeated – using the same increment – until the curve with the best R-squared coefficient could be identified. This curve, written in terms of the format defined by Eqs (1) and (2), then furnishes ε and u_τ.

The graphical method described above is illustrated in Fig. 7. The R_{sq} values obtained for the various ε-tries are plotted in Fig. 7b and correspond to station x = 200 mm. The existence of a well defined maximum value is clear. A quick inspection of Fig. 7b reveals that the appropriate value of ε is about 1.8 mm.

The consolidated ε and u_τ results are shown in Table 1. The overshoot in friction velocity at position 25 mm (= 1.33 ms^{-1}) is a well documented fact in literature. The present procedure based on an investigation of the mean velocity profile is thus capable of capturing this important flow feature. At the downstream positions, both ε and u_τ are observed to

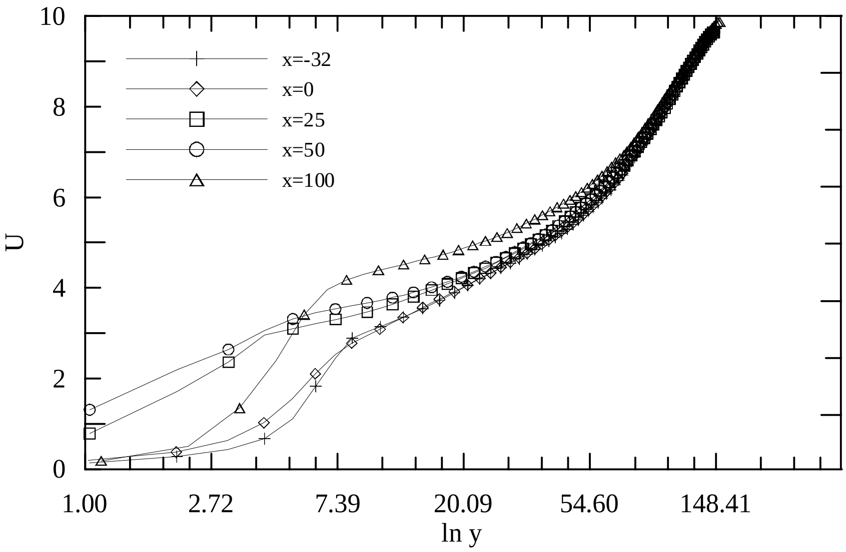

Figure 6: Longitudinal mean velocity profiles in logarithmic coordinates.

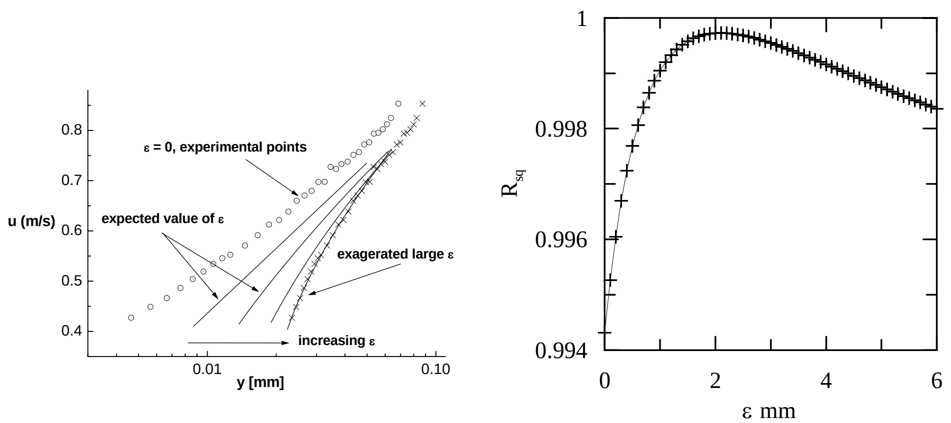

Figure 7: Graphical method to find the displacement height. a: velocity profile reduction technique, b: best fitting statistics for profile at position x = 200 mm.

accommodate to the equilibrium conditions. Table 1 includes u_τ data obtained through the turbulent shear stress profiles. This is explained next.

Table 1: Results for ε and u_τ.

x (mm)	-32	25	50	100	200	400
ε (mm)	3.4	3.3	3.1	2.8	1.8	0.0
u_τ (ms^{-1}) (Eq. (1))	0.68	1.33	1.08	0.86	0.504	0.22
u_τ (ms^{-1}) (-$\overline{u'v'}$)	0.63	0.62	0.59	0.58	—-	—-

The development of the Reynolds stresses downstream of the point of surface change is shown in Figs. 8 to 10. The overshoot phenomenon described for the friction velocity is not observed for the Reynolds stresses. A permanent decrease in the general level of turbulence is observed. As expected, the peaks of maximum u'^2 move away from the wall with increasing x and drop from about 2 to 1.55 m^{2}s^{-2} for positions -32 and 100 mm respectively. The v'^2-profiles adjust very slowly in the transition region. Only at position x = 100 mm any appreciable change in v'^2 can be observed.

The practice of using the average measured shear stress profile to find u_* for flow over a rough wall, has been discussed by Cheng and Castro (2002). Clearly, the shear stress shows an appreciable longitudinal variation depending on its distance from the wall. In the roughness sublayer, a wavy variation in phase with the crest of the roughness elements can be observed. Farther away from the wall, in a region where the variations drop below 10%, the inertial sublayer is defined. The interesting fact reported by Cheng and Castro (2002) is that better logarithmic fits can be found for the mean velocity profile if spatially averaged data in the roughness sublayer are used in preference to data in the inertial sublayer. Here, we

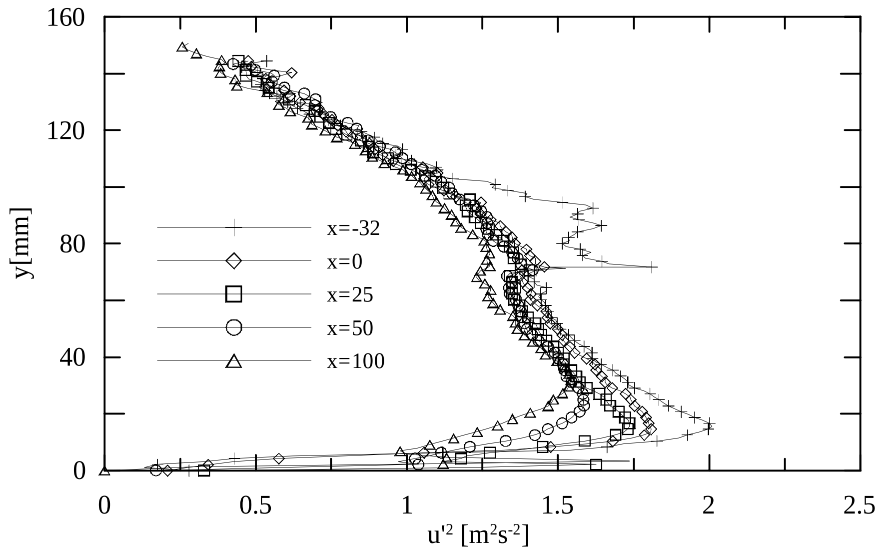

Figure 8: Behaviour of Reynolds longitudinal stress.

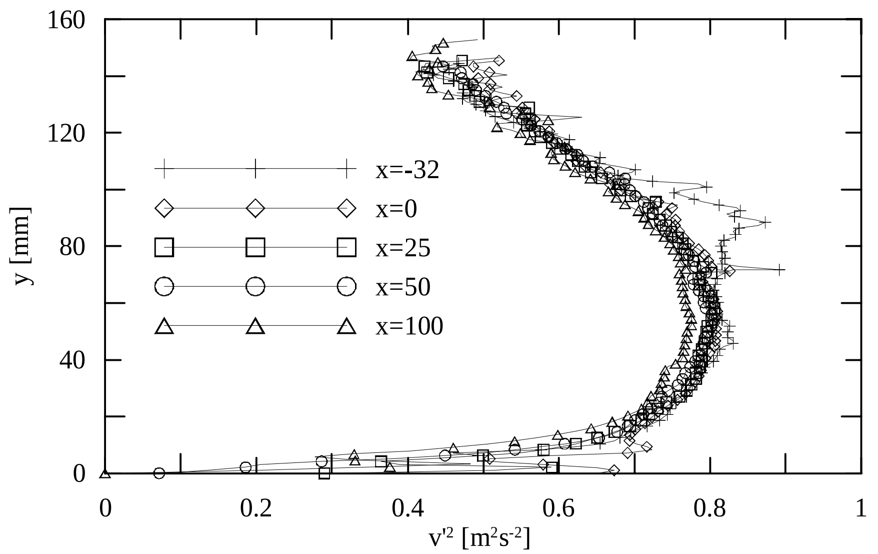

Figure 9: Behaviour of Reynolds transversal stress.

have followed this recommendation.

To evaluate u_* from the Reynolds shear stress profile, a near wall region with an approximate constant distribution of $-\overline{u'w'}$ was searched. The friction velocity was then evaluated from $u_* = \sqrt{-\overline{u'w'}}$. The results are shown in Table 1. Clearly, the absence of the overshoot phenomenon makes this method not appropriate for the determination of u_*. The values shown in the last line of Table 1 are well below the values determined using the gradient method of Clauser.

The third- and forth-order moments are shown in Figs. 11 and 12. They shown that only at position x = 100 mm the flow has returned to equilibrium with the smooth surface. In fact, the third-order moments are negative near the wall just for the profile at position 100 mm. At all other positions, the skewness coefficient is always positive.

Profiles for the flatness in a boundary layer show very high values near the wall and in the outer layer, where turbulence is highly intermittent. In the log-region, F_u should approach 2.8.

Profiles of F_u are show in Fig. 12. Far away from the wall, in the log-region, F_u approaches 2.6. In the wall region F_u can be as high as 27. This value is not shown in Fig. 12 to keep the axis limits restricted to adequate values. The difficulty in characterizing roughness through F_u lies on the fact that the profiles in all stations keep the same form. Thus, establishing an arbitrary reference value to define how far downstream of a surface change the return to equilibrium conditions occurs may lead to non representative results.

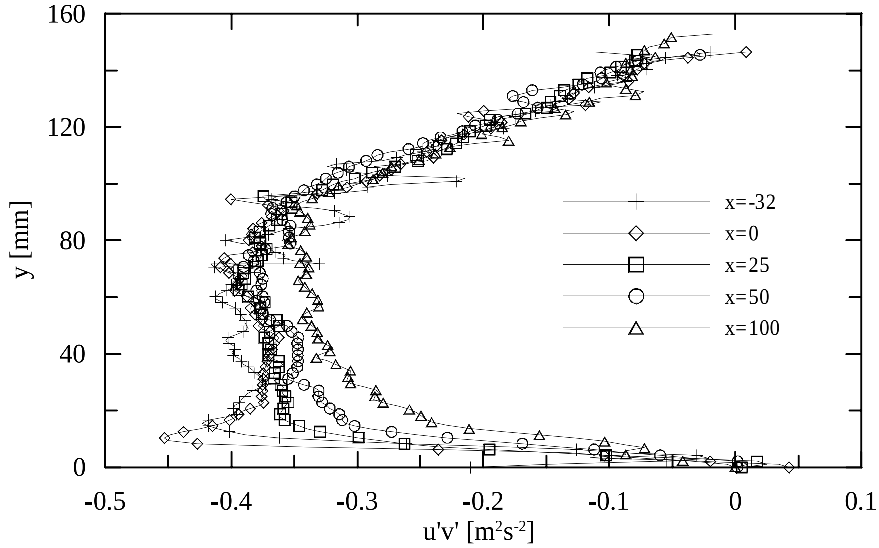

Figure 10: Behaviour of Reynolds shear stress.

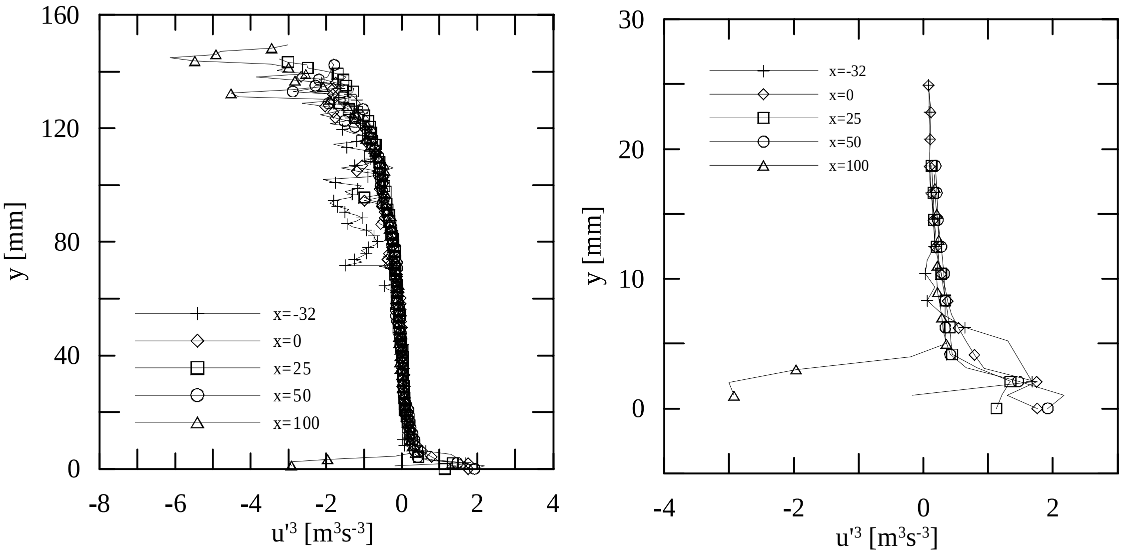

Figure 11: Behaviour of longitudinal third-order moments.

6. Final remarks

The present work has shown how ε and u_τ can be estimated in regions of transitional flow, from smooth to rough surfaces, through the methods of Perry and Joubert (1963) and of the turbulent shear stress profiles. In the first method, by systematically adding an arbitrary value to the distance from the top of the roughness elements, a least square procedure was built to furnish the best discriminated straight line fit. This method was capable to capture the overshoot phenomenon in u_τ. On the other hand, determination of u_τ via the turbulent shear stress profiles showed a serious flaw: the non-sensitivity to capture the overshoot phenomenon. This difficulty resulted in lower values for u_τ.

Determining the wall shear stress has always been a difficult problem that has plagued many authors. In transitional, non-equilibrium regimes, we remind the reader that this problem is much aggravated. Therefore, this work adds much to the present knowledge of the problem by showing that the derivative method can be used to find u_τ.

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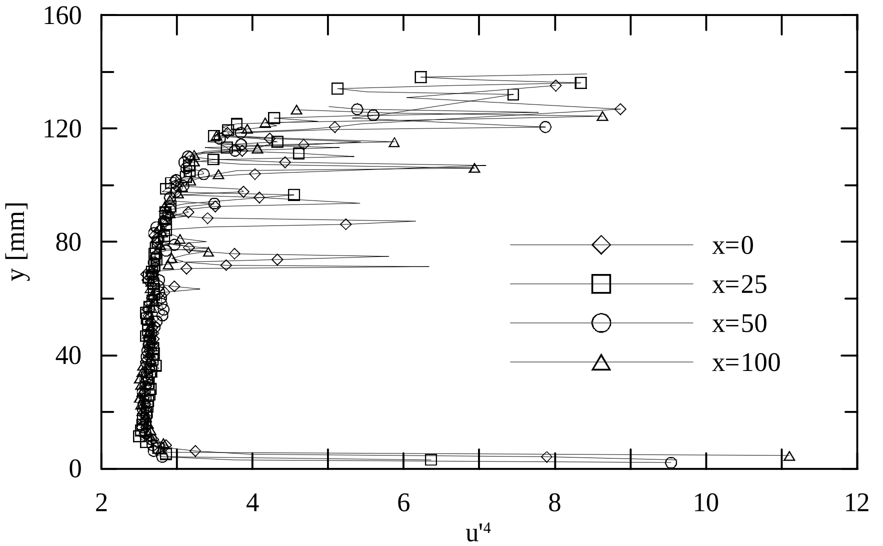

Figure 12: Behaviour of longitudinal forth-order moments.

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