EXPERIMENTAL INVESTIGATION OF STREAKY STRUCTURES IN A RELAMINARIZING BOUNDARY LAYER

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ABSTRACT

An experimental investigation of a boundary layer subjected to a relaminarization process is performed. The boundary layer, artificially made turbulent, develops on a plate mounted inside a two dimensional convergent channel. The effects of an high level of free stream turbulence are also investigated. Results show that the mean velocity profiles of the boundary layer develop towards the self similar laminar solution for both levels of free stream turbulence tested.

Two-point correlation measurements performed by means of two miniaturized single-wire hot-wire probes with variable relative spanwise separation, show the presence of elongated longitudinal structures. The dimension of these streaks decreases in the downstream direction. Conversely, if the size is normalised by the displacement thickness of the boundary layer, the relative streak dimension shows a significant increase. Also, when scaled by the viscous length scale ℓ^* the streak dimensions increase from about $60\ell^*$ in the turbulent boundary layer to $150\text{-}180\ell^*$ in the relaminarizing region. Finally, to process only the laminar part of the velocity signals a filtering procedure based on a threshold value of the second derivative of the time signals has been applied showing a slight increase in the detected dimensions of the structures.

INTRODUCTION

It is well known that when a turbulent boundary layer is subjected to a strong favourable pressure gradient it may be forced to return to laminar conditions. This phenomenon was first observed by Sternberg (1954). Wind-tunnel contractions, entrances to pipes etc., are examples where strong favourable pressure gradients may appear. Considering the influence of the boundary layer characteristics on those types of flow it is important to be able to predict where relaminarization can be expected. Furthermore, a detailed knowledge of the flow characteristics in a relaminarized boundary layer is important, especially when considering that in most applications relaminarization is followed by a retransition to turbulence further downstream, a process which is strongly dependent on the upstream conditions of the boundary layer.

To determine whether a boundary layer is relaminarized one can normally define a criterion based on certain features of the flow, e.g mean velocity profiles, fluctuation levels, boundary layer thickness, shape factor, time signals etc., and require that these should be close enough to typical laminar characteristics. However, no satisfactory criterion has been given to identify where the relaminarization starts, i.e. when the flow first begins to deviate from the fully turbulent boundary layer. Different criteria have been introduced based on different parameters, viz. stress gradient, intermittency, shape factor and Reynolds number based on momentum thickness. A discussion on different criteria can be found in Narasimha and Sreenivasan (1973) and in the detailed review by Sreenivasan (1982). To identify the occurrence of relaminarization, Moretti and Kays (1967) used the *acceleration parameter* (or *pressure-gradient parameter*) defined as:

$$K = -\frac{\nu}{\rho \cdot U_e^3} \cdot \frac{dp}{dx} = \frac{\nu}{U_e^2} \cdot \frac{dU_e}{dx}$$

where U_e is the local free-stream velocity and ρ the air density. They suggested that the onset of relaminarization occurs when K reaches a critical value of $3\text{x}10^6$. The importance of the *K*-factor has been emphasised in a recent experiment carried out by Escudier et al. (1998).

It must be pointed out that, while several numerical studies have been made, relatively few experiments on turbulent boundary layers in accelerating flows are reported in the literature. Moreover, some of these experiments are focused on the evolution of the boundary layers to an equilibrium state (see e.g. Jones et al., 2001) and do not describe the laminarization process. As stated by Escudier et al. (1998) the complexity of relaminarization experiments can be ascribed to the wide velocity range involved, which requires very low velocity at the inlet and very high velocity and thin boundary layers at the end of the channel. An

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experiment on the relaminarization of a turbulent boundary layer in a two-dimensional contraction has been carried out by Parsheh (2001). In his analysis he showed that the mean velocity profiles approached the self-similar laminar solution if the following non-dimensional coordinate was introduced:

$$\eta = y\sqrt{\frac{U_e}{-\nu\left(x - x_0\right)}}$$

where x_0 is the distance between the contraction inlet and a virtual point where the two sides of the plane contraction meet if we let the contraction continue.

Flow visualisations, measurements and DNS generated data have shown that in the near-wall region of turbulent boundary layers elongated regions of low and high speed fluid (denoted streaks) are present. Measurements show that the spanwise spacing of the streaks is fairly regular, with a typical spanwise scale of 50-55 ℓ^*, where ℓ^* is the viscous length scale (recent measurements by Österlund et al. 2000, suggest a spanwise scale of approximately 55 ℓ^*). Streaky structures can also be observed in laminar boundary layers subjected to high levels of free stream turbulence (FST). Several experiments have demonstrated that free-stream turbulence enhances the transition from laminar to turbulent flow, and it is also shown that the streaks play an important role in this process.

An hypothesis, relating the streak spacing to the transition Reynolds number, was reported by Alfredsson and Matsubara (2000). They compared the transition Reynolds numbers based on a typical spanwise length scale for a number of canonical flows, viz. Couette flow, pipe flow, Poiseuille flow and boundary layer flow, and found that, if transition occurs, the size of the disturbances must be larger than about 50 spanwise viscous units. The importance and generality of this observation is not clear, but one possible explanation could be that a spanwise scale of the near wall streaks of the order of $50\ell^*$ (which can be viewed as a critical Re of the streaks) might be a necessary condition for the existence of self-sustained turbulence.

Piomelli et al. (2000) numerically analysed the presence and the dynamics of the streaks and vortical structures in accelerating boundary layers in the presence of an undisturbed free stream. Firstly they observed that when the acceleration is mild the boundary layer tends toward an equilibrium state. However, when the free-stream acceleration is strong the flow deviates significantly from the zero pressure gradient case. They found that the streaks become more ordered, longer and with less spanwise oscillations. In absolute terms they become stronger, but the fluctuation levels become lower if normalised with the velocity outside the boundary layer. However, the near-wall region of a turbulent boundary layer is not only characterized by streaks, but also turbulent eddies and vortical motion causing ejections to the outer regions of the boundary layer. The study by Piomelli et al. shows that in the strongly accelerating region the coherent eddies become more restricted to the region close to the wall, with less excursions of vorticity in the wall-normal direction. They also show that, despite the presence of vortex stretching, the magnitude of the streamwise vorticity slightly decreases when moving downstream. Probably, the small stretched vortices dissipate because of viscous effects.

Blackwelder and Kovasznay (1972) studied experimentally the dimension of the streamwise coherent structures in the boundary layer by measuring the space-time correlation coefficient. They found that the acceleration process did not change the shape and the dimension of the structures. However the analysis was limited to the very beginning of the acceleration phase and probably the considered region was too short to significantly alter the streamwise velocity of the eddies.

In the present paper an experimental investigation on the relaminarization of a turbulent boundary layer subjected to a strong favourable pressure gradient is described. The main purpose is to verify experimentally the presence of streaks in a relaminarized boundary layer, and to characterise their typical dimensions and their development in the relaminarization process. Moreover, the influence of the presence of an enhanced level of free stream turbulence on such structures is considered.

EXPERIMENTAL SET-UP

The experiment has been carried out in an open wind tunnel at the Royal Institute of Technology (KTH) in Stockholm. The air is accelerated in the test section which consists of a two dimensional contraction (see Fig. 1). Tests were made on a 3 mm thick aluminium flat plate, mounted at the symmetry plane of the test section. Fig. 1 shows also the chosen coordinate system: the streamwise, wall-normal and spanwise directions are denoted *x*, *y* and *z* respectively, and origin is located on the centreline at a streamwise position corresponding to the beginning of the contraction.

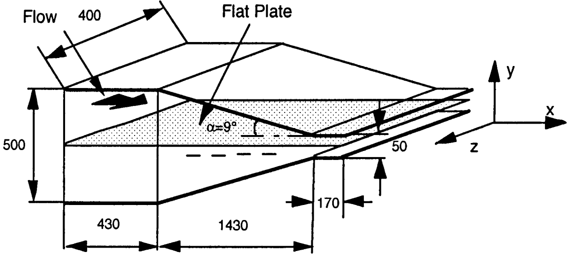

Figure 1: Schematic of the contraction

The inlet velocity is about 3 m/s and the corresponding pressure gradient parameter is K=3.1x10^{-6}. The Reynolds number, based on free-stream velocity U_e and the height of the channel *h*, is constant and equal to Re=10000. The boundary layer is made turbulent by means of a sand paper trip positioned close to the leading edge of the plate.

Measurements are taken with and without a free-stream turbulence generating grid installed approximately 285 mm upstream of the leading edge. The solidity of the grid, defined as the ratio between the grid geometric blockage area and the total area, is equal to 0.32. Because of the grid, the turbulence level u_{rms}/U_e, measured at x=55 mm, changed from 0.73% to about 2.3%.

The axial velocity is measured at two points by means of two constant temperature hot-wire anemometers (CTA), using single wire probes. The probes and their holder are specifically designed and built for this experiment. In order to obtain correlation measurements one probe is kept fixed, whereas the other can be moved in the spanwise direction (see Fig. 2). The minimum separation between the probes, defined as the distance between the centre of each hot-wire, was measured by a microscope and determined to ΔZ_0=1.3 *mm*. Both of the wires have a sensing length of 0.50 mm. The probe holder is mounted on a traversing mechanism, in which a micrometer provides the motion along the wall-normal direction with a precision of 5 µm. The motion along the streamwise direction is guaranteed by two suitable horizontal guides mounted on the test section. The spanwise separation of the probes is obtained by means of a wedge mechanism controlled by a speedometer wire extending through the exit of the test section.

The two probes are operated at 40% overheat and are calibrated with a Prandtl tube in the free stream at x=1 m. During the correlation measurements 30000 samples are collected at a rate of 2000 Hz, which corresponds to a sampling time of 15s, and four separate measurements are acquired in each measurement point.

One concern is the possible influence from blockage effects, especially when the probe holder is near the end of the contraction causing a 5% blockage of the cross-sectional area. Measurements have been taken simulating the presence of the probe holder at the channel exit, and the results give us confidence that the blockage effect does not significantly affect the experiment, since the maximum change in both mean velocity and axial fluctuations were approximately 2%.

The experimental estimation of the boundary layer thickness parameters, viz. the displacement thickness δ^*, the momentum loss thickness θ and the shape factor *H,* is strongly affected by the minimum distance between the plate and the probe (y_0). In order to get an accurate estimate of this quantity, different criteria were considered depending on the nature of the flow. In the turbulent region and where the boundary layer is not completely relaminarized a linear extrapolation of the u_{rms}–profile using the first measured points may be accomplished. From the mean velocity profile it may be ascertained if there are any points very close to the wall which must be discarded due to the extra cooling from the plate. Conversely, in the relaminarized region, y_0 can be easily determined by comparing the mean velocity profile with the self-similar laminar solution. Indeed, if the flow is relaminarized, measurement data should coincide with the self-similar solution.

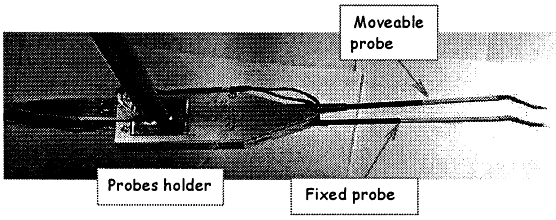

Figure 2: Photo of the probes and the probe holder

To obtain an estimate of the viscous length scale, ℓ^*, in the turbulent region the wall shear was approximated by a linear extrapolation from the first near-wall measurement point of the mean velocity profile (after discarding points affected by wall cooling). At the last streamwise position where the boundary layer is relaminarized ℓ^* was obtained from the self-similar solution.

RESULTS AND DISCUSSION

Free stream behaviour

In order to characterise the flow in the convergent channel, the velocity has been measured outside the boundary layer at different streamwise position. Fig.3 shows a comparison between the inviscid solution and measured velocity. The x coordinate has been normalised with the length of the converging channel *(L)* while the velocity has been divided by its value at the channel inlet *(U_0)*. As can be seen the agreement between the inviscid solution and the measured data is fairly good providing an accurate estimate of U_e at each streamwise position.

Development of the boundary layer to a relaminarized state

The inlet velocity to the test section was chosen in order to obtain a turbulent boundary layer at the beginning of the contraction as well as a relaminarized boundary layer before the exit. Fig. 4 shows the mean velocity at the first measurement position (X/L=0.04) plotted in wall-coordinates. The turbulent Reynolds number is rather small (Re_θ=735), but the mean profile shows a clear resemblance with the semi-logarithmic law of the wall. Figure 5 shows three different mean velocity profiles measured further downstream in the contraction. X/L=0.62 corresponds to the relaminarizing region and X/L=0.83 is almost at the end of the channel.

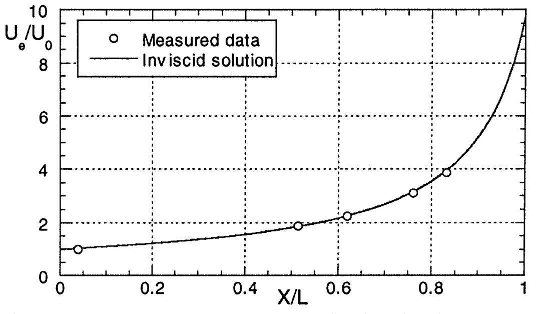

Figure 3: Free stream velocity distribution in the contraction (axial component)

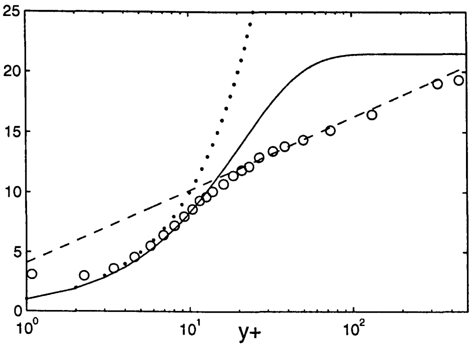

Figure 4: Mean velocity profile in the turbulent region (X/L=0.04) plotted in wall-coordinates. o: measured data; —: self-similar solution; ---: $u^+=1/0.38*\log(y^+)+4.1$; ···: $u^+= y^+$.

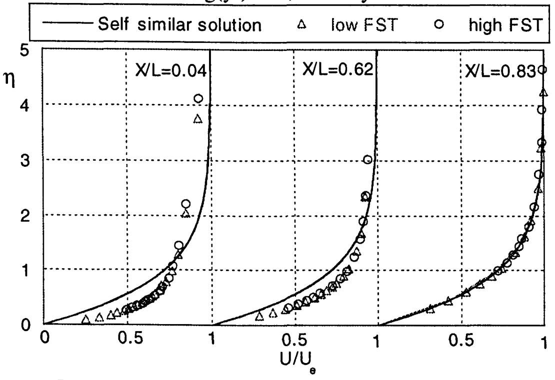

Figure 5: Mean velocity profiles vs. non-dimensional wall coordinate η (see Parsheh et al., 2001) at different streamwise positions.

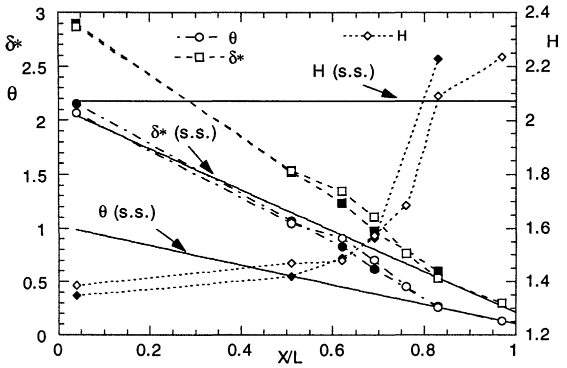

Figure 6: Streamwise development of boundary layer quantities. Full symbol: high FST; open symbol: low FST; (s.s.) self similar solution

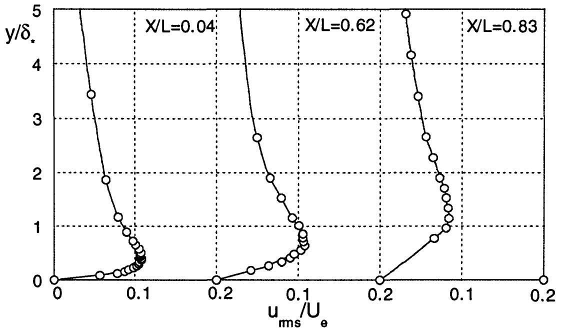

Figure 7: u_{rms} velocity profiles at different streamwise positions.

It is clear that the viscous sub-layer increases in thickness when the flow develops downstream, and at the last x-position the agreement with the analytical self-similar (laminar) solution is good. This is also confirmed by the streamwise distribution of δ^*, θ and H along the plate (see Fig. 6), which tend to values that are quite close to the self-similar ones. The influence of the increased level of FST on the mean flow parameters is quite small.

A further confirmation that the boundary layer is relaminarizing comes from the fluctuation profiles (Fig. 7). By comparing different fluctuation profiles, normalising the wall normal coordinate with the displacement thickness δ^* and u_{rms} with the free-stream velocity U_e, one can see that the turbulence level decreases when moving downstream while the position of maximum fluctuation moves away from the wall. These features are similar to the characteristics of a laminar boundary layer subjected to high levels of FST (Westin et. al. 1994).

Correlations

In Fig. 8 correlation functions measured in the laminarized region (X/L=0.83) are plotted for different wall-normal coordinates. The high level of FST is considered. A fitting procedure has been used to evaluate the minimum of the correlation function (Z_{min}.). In laminar boundary layers subjected to FST the measured values of Z_{min} are normally quite constant for different y-positions inside the boundary layer (Matsubara and Alfredsson, 2001). However, in the present analysis it is clear that the measured value of Z_{min} in the outer part of the boundary layer is considerably larger than for measurements closer to the wall. This suggests that the structures close to the wall are not dominant further out in the boundary layer. This behaviour was found also by Smith and Metzler (1983) investigating the characteristics of low-speed streaks using hydrogen bubble flow and an high speed video system. The reason for the increase of Z_{min} with y is probably due to a mixture of different scales at the outer region of the boundary layer, and the interpretation of the correlation become less clear. The wall-normal dependence of Z_{min} is particularly strong for the first measurement position in the turbulent boundary layer. Typically, the local minimum in the correlation function become less pronounced in the outer regions, indicating that there are not "distinct" structures present. The streaky structures that we are looking for should result in a fairly strong negative correlation (R_{uu} of about −0.2), and they are expected to appear close to the wall. In conclusion, the position where the analysis must be accomplished is still an open question, but in the present study a constant wall-normal position in terms of U/U_e is chosen when comparing different x-positions.

To better appreciate the variation of the minimum in the correlation curves with y, the behaviour of Z_{min} with respect to U/U_e and normalised with both δ^* and ℓ^* is presented in Fig. 9. The figure is relevant to the relaminarized region (X/L=0.83). In the figure the error bars show the uncertainty in the estimation of the minimum for each y-position (U/U_e). It is clear from the figure that Z_{min} increases with y for

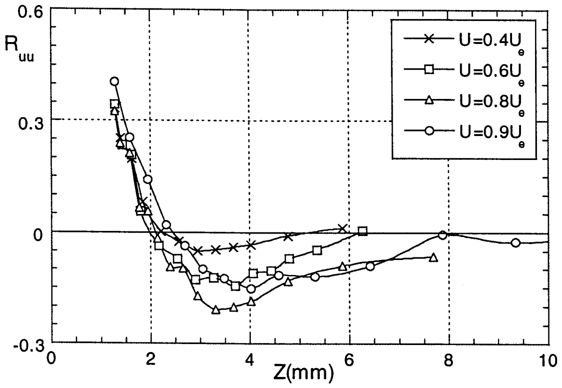

Figure 8: Correlation functions at different wall-normal coordinates y; X/L=0.83, high FST

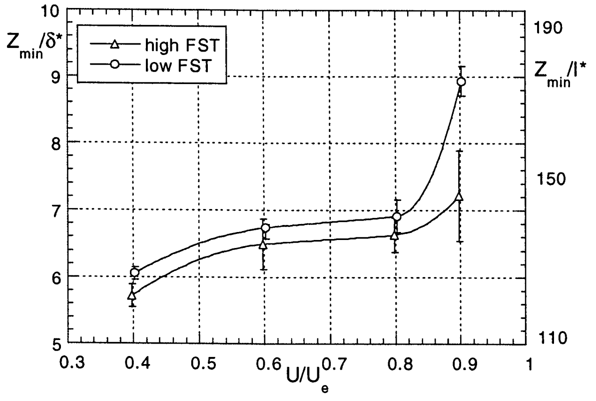

Figure 9: variation of normalised Z_{min} inside boundary layer; X/L=0.83.

both cases with low and high FST. It can also be deduced from the figure that the general influence from the FST is small, especially when approaching the wall, while some effects can be observed in the upper part of the boundary layer where the enhanced level of FST makes Z_{min} slightly smaller. However a different behaviour is found for the upstream positions.The role of the FST in the upper part of the boundary layer is still unclear and further analysis must be performed. In order to study the dimension of the streaky structures in the boundary layer during the laminarization process changes of Z_{min} at $U(y)/U_e$=0.6, for different stream-wise coordinates, are reported in Fig. 10. The figure shows clearly that the absolute scale of the structures in the relaminarizing region (X/L=0.62) and in the relaminarized one (X/L=0.83) is smaller compared to the one found in the turbulent region (X/L=0.04). For instance at U/U_e=0.7 and with low FST, Z_{min} is less than 4 mm in the relaminarizing region, whereas the scale for U/U_e=0.6 at X/L=0.04 is about 7 mm. From an absolute point of view, this means that the spanwise scale of individual streaks become smaller while the boundary layer relaminarizes. This effect is clearly due to the converging channel, which stretches the boundary layer and the related structures.However, if Z_{min} is normalised with a characteristic local boundary layer dimension, i.e. the viscous length scale ℓ^* or the displacement thickness δ^*, then the relative dimensions of the streaks can be determined. Figures 10 and 12 show that in these cases the relative dimensions of the streaks (Z_{min}/ℓ^* and Z_{min}/δ^*) increase with the streamwise coordinates. It can be noticed that Z_{min} is around 95ℓ^* at X/L=0.62 and around 135ℓ^* at X/L=0.83: these are considerably different values compare to the typical turbulent value of 50-55ℓ^*.

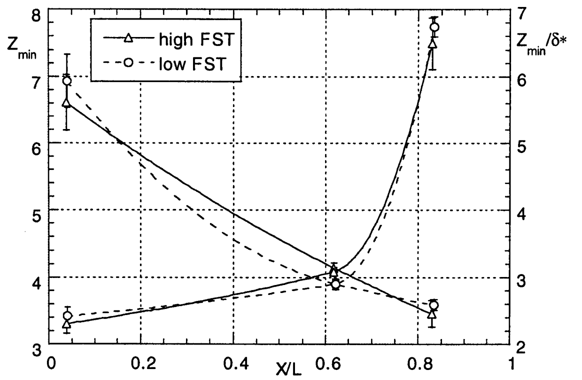

Figure 10: Streamwise development of Z_{min} and Z_{min} normalized by the boundary layer displacement thickness.

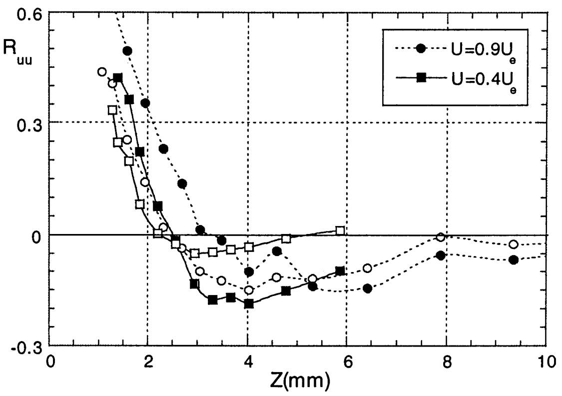

Figure 11: Effects of filtering on correlation functions at different wall normal distance, X/L=0.83; low FST; open symbol: unfiltered correlations; full symbol: filtered correlations

Filtered correlations

The measured correlation functions and the dimension of the streaks estimated above may be considerably affected by the intermittency of the relevant velocity signals. In order to split the laminar from the turbulent part of the signal, different conditional averaging techniques can be used. A selection of these techniques is reported in Österlund et al. (2000). In this paper a very simple low-pass technique based on the second time derivative d^2u/dt^2 as the criterion function is used. It must be pointed out that in the present analysis the filtering process show no significant dependence of the results for a large variation of the cut-off parameter.

If the flow at X/L=0.83 with a low level of FST is considered, Fig. 11 shows that the effects of the filtering are larger inside the boundary layer. Close to the wall the minimum value $(R_{uu})_{min}$ of the correlation coefficient is smaller (which means more negative correlation) than the unfiltered one. Conversely, near the free-stream (U/U_e=0.9) the value of $(R_{uu})_{min}$ remains almost unchanged. This is probably related to the fact that the signal in the core of the boundary layer is more intermittent than the signal close to the free-stream region. Note that the dependence of Z_{min} on the wall-normal coordinate y is present also after filtering. Z_{min} remains almost constant inside the boundary layer, whereas it increases drastically for $U/U_e > 0.8$ as it happens for the unfiltered data.

There seem to be no differences concerning the effects of the presence of a high level of FST with respect to the unfiltered data. The effects on the correlation functions are strong for high values of y (close to the free-stream) and they are considerably reduced when approaching the plate.

Finally the behaviour of Z_{min}, Z_{min}/δ^* and Z_{min}/ℓ^* with respect to the streamwise coordinate has been considered. Although the absolute dimensions of the structures decrease with increasing x, the values normalised with the viscous units increase. By filtering the data larger streaky structures are obtained (see Figure 12). At X/L=0.62 the dimension of the streaks in terms of viscous units is about 110, whereas it increases up to about 150-180 at X/L=0.83.

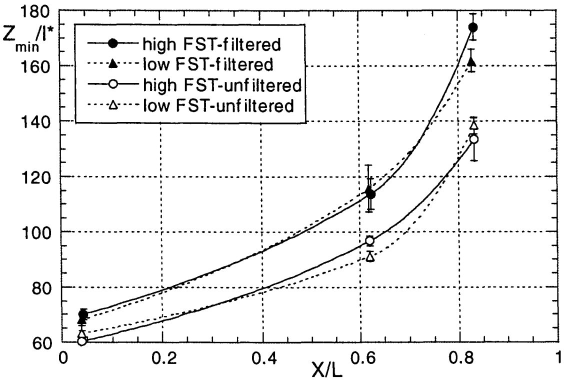

Figure 12: Streamwise development of Z_{min} in wall units

CONCLUSIONS

An experimental investigation on the characteristic dimensions of the streaky structures in a relaminarizing boundary layer has been accomplished. The effects of the presence of an enhanced level of free stream turbulence have also been studied. It was found that the mean velocity profiles tend to approach the self-similar solution for both levels of free-stream turbulence. Streaky structures, similar to those usually found in the transition-scenario (laminar to turbulent), have been observed for both cases. The effect of the increased level of free-stream turbulence due to the grid does not seem to influence the scales in the lower part of the boundary layer, while some effects can be observed in the outer region.

The typical spanwise dimension of the streaks decreases while moving downstream inside the contraction. However, the relative size increases when normalised by the displacement thickness of the boundary layer. Moreover, if the spanwise scale is normalised with the local viscous length scale ℓ^*, the dimension increases from about $60\ell^*$ in the turbulent region to about $150\text{-}180\ell^*$ at the end of the contraction. This is an interesting observation, since it is known that the near-wall streaks in a turbulent boundary layer normally have spanwise scales of about $50\text{-}55\ell^*$.

Finally, the data have been processed in order to educe the streaky structures by neglecting the contribution of time intervals when the signal is turbulent. The analysis shows a slight increase in the dimensions of the structures when only the laminar parts of the signals are included in the calculation of the correlation.

Acknowledgements

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References

Alfredsson, P.H., Matsubara M., 2000, “Free stream turbulence, streaky structures and transition in boundary layer flows”, AIAA-2000-2534

Blackwelder, R.F., Kovasznay L.S., 1972, “Large-scale motion of a turbulent boundary layer during relaminarization”, J. Fluid Mech. Vol. 53, pp. 61-83

Escudier, M.P., Abdel-Hameed, A., Johnson, M.W., Sutcliffe, C.J., 1998, “Laminarization and retransition of a turbulent boundary layer subjected to favourable pressure gradient”, Exp. Fluids, Vol. 25, pp. 491-502

Jones, M.B., Marusic, I., Perry, A.E., 2001, “Evolution and structure of sink-flow turbulent boundary layers”, J. Fluid Mech., Vol. 428, pp. 1-27

Matsubara M., Alfredsson, P.H., 2001, “ Disturbance growth in boundary layers subjected to free-stream turbulence ”, J. Fluid Mech., Vol. 430, pp. 149-168

Moretti, P.H., Kays, V.M.,, 1965, “Heat transfer in turbulent boundary layer with varying free-stream velocity and varying surface temperature-an experimental study”, Int. J. Heat Mass Trans., Vol. 8

Narashima, R., Sreenivasan, K.R., 1973, “Relaminarization in highly accelerated turbulent boundary layers”,J.Fluid Mech., Vol. 61, pp.417-447

Parsheh, M., 2001, “Flow in Contractions with Application to Headboxes”, Doctoral Thesis, TRITA-MEK 2000-16, KTH, Stockholm, Sweden.

Smith, C.R., Metzler, S.P., 1983, “The characteristics of low speed streaks in the near wall region of a turbulent boundary layer”, J. Fluids. Mech., Vol. 129, pp. 27-54

Sreenivasan, K.R., 1982, “Laminarescent, relaminarizing and retransitional flows”, Acta Mechanica, Vol. 44

Sternberg, J., 1954, U.S. Army Bal. Res. Lab. Rep. 906

Westin K.J.A., Boiko, A. V., Klingmann, B.G.B., Kozlov,V.V., Alfredsson, P.H., 1994, “Experiments in a boundary layer subject to free-stream turbulence Part I. Boundary layer structure and receptivity”, J. Fluids Mech., Vol. 281, pp. 193-218