WALL TURBULENCE MANIPULATION BY OUTER LAYER DEVICES

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Abstract

The purpose of the present work is to contribute to a better understanding of the mechanisms leading to drag reduction by outer layer devices since the means by which they operate are still not clear. In the performed experiments a tandem configuration over a flat plate (zero pressure gradient) is assumed; this configuration has been optimized by earlier studies to achieve maximum drag reduction at laboratory Reynolds numbers.

Measurements of different turbulence quantities, including intermittency factors, Reynolds stresses, flatness and skewness distributions, have led to the identification of some of the mechanisms involved in skin-friction reduction.

The manipulated boundary layer exhibits a reduced intermittency and indicates that the scale affected by the manipulation process is of the same order of the boundary thickness, i.e.,of the largest eddies.

Introduction

In the past decade a great amount of work has been done aimed at viscous drag reduction. Various schemes have been proposed to alter the characteristics of the turbulent boundary layers in order to decrease the skin friction, such as addition of polymers, alteration of the wall boundary conditions by various surface geometries, and modification of the turbulent structure of the boundary layer by flow manipulators. A comprehensive review of the various techniques employed as well as potential applications is given by Coustols and Savill[1]. Among the various approaches investigated, one that has received most attention is the parallel plate manipulators, also referred to as Large Eddy Break-Up devices (LEBUs). They consist in thin rectangular plates or airfoils introduced into the external part of the turbulent boundary layer, and arranged in single or tandem configuration, parallel to the solid wall and transverse to the flow. The use of in-flow manipulator devices, such as LEBU, originated from research on the optimization of screens and honeycombs for controlling (reducing) free-stream turbulence in wind tunnels. Different authors have shown that a carefully designed pair of two-dimensional flat plates placed in a tandem configuration within the boundary layer can yield skin-friction reduction up to 35% [2,3]. Comparable configurations have been investigated with various degrees of success.

Even if all authors found the same results of reduced skin-friction through this devices, there is no general agreement about the possibility to obtain a net drag reduction (the word 'net' means taking into account the additional drag due to the introduction of the devices in the flow). In spite of the work done, the mechanism leading to the skin friction reduction are still not clear. Nevertheless such studies provide a better appreciation of the turbulence response to imposed in-flow distorsion and thus allow a deeper comprehension of the flow dynamics as well as of the means by which it may be controlled.

Flow visualization suggested that one of the key effects of the manipulators is the suppression of the large scales. Bradshaw[5] hypothesized that the strength of the large-scale motions is related directly to the shear stress at the wall. Hence, it is reasonable to expect that the alteration or suppression of the large scales will have a direct impact on the shear at the wall. It is also of paramount interest to investigate the downstream evolution of the *manipulated* boundary layers and to examine the possible relaxation of the manipulation and the return toward *regular* condition.

Other possible mechanisms for the skin-friction reduction involve the interaction of the shed vorticity in the manipulators wake with the turbulent eddies, the turbulent kinetic energy redistribution away from the wall, and the introduction of energetic new scales.

In the performed experiments a tandem configuration over a flat plate (zero pressure gradient) is

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Experimental set up

The experiment was performed in the low-speed wind tunnel of the DIASP (Politecnico di Torino), this facility has been completed in 1990 and designed for boundary layer investigations. It is an open-return tunnel, powered by two $0.96\,m$ diameter co-rotating fans, aligned with the flow direction. The nominal top speed of the tunnel is $30\,m/s$. The working section is $4\,m$ long, and has a rectangular cross-section $0.7\,m$ by $0.5\,m$ at the contraction end. The side walls diverge by 0.5 degree each to compensate for the blockage effects of wall boundary layer growth.

The turbulent boundary layer was developed over a smooth flat plate. A strip of sand paper was placed just downstream the leading edge to fix the transition at that location.

The freestream velocity used throughout the experiment was nominally $V_e = 4\,m/s$: In this configuration the turbulent boundary layer thickness at the manipulator position, δ_o, is $40\,mm$,(δ is defined as the height at which the velocity reaches 99.5% of its freestream value), so the Reynolds number based on δ_o is $Re_{\delta_o} = 10960$.

All measurements were performed on the centerline of the plate at two different streamwise positions, namely A and B (7.5δ and $40\,\delta$ downstream of the manipulators respectively) to see the immediate manipulators effect and to check the evolution downstream. Unfortunately the limited length of the test section did not permit measurements at larger distance.

Two flow conditions were investigated: a *regular* case corresponding to a naturally developing turbulent boundary layer; and a *manipulated* case corresponding to the same boundary layer in which a pair of tandem flat-plate manipulators was placed.

The configuration adopted in these experiments has been optimized by earlier studies to achieve the maximum drag reduction.

The LEBU devices, in the chosen tandem configuration, consisted of $0.35\,mm$ thick, ribbon like, strips suspended parallel to the plate surface within the turbulent boundary layer at a height, $h = 0.75\,\delta_o$. The chord, c, was of the same order of δ_o, the spacing, s, was $6.5\,\delta_o$ (figure 1).

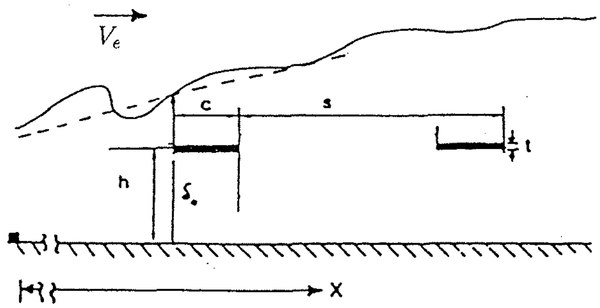

Figure 1: Adopted configuration

The measured effect is rapresented through the skin friction coefficient C_f defined as:

$$C_f = \frac{\tau_w}{\frac{1}{2}\rho V_e^2}$$

where τ_w is the shear stress at the wall. All of the optimum parameters result from a compromise between the additional drag due to the introduction of the devices into the flow and the reduction in skin friction drag they produce downstream.

This is particulary true for the chord length, since both the device drag and the integrated C_f reduction increase with c, but at different rates. There is a notable advantage in employing plates with $c = \delta_o$ largely due to the fact that this is the scale of the largest eddy structures in the flow.

The optimum heigth is determined by its influence on the shape of the C_f distribution behind the device, since placing this nearer to the wall, where the mean velocity and hence (in absence of any ground effect) the device drag is lower, results in a larger maximum C_f reduction, but a much more rapid recovery and thus a smaller integrated effect. However, mounting the manipulators nearer to the edge of the layer reduces their effect and increases their drag penality.

The device thickness does not appear to have a very large effect on its performance.

Also the spacing, s (between the leading edges), has a minor influence on either the skin friction reduction or devices drag. A closer spacing ensures that the drag of the second device is reduced because of the "shielding" influence of the first, but a wider spacing extends the region of maximum C_f reduction thus producing a larger integrated effect.

It might be expected that the optimum value for s rapresent a simple compromise between these two rather weak effects.

In order to minimize drag it became evident that the devices must be sufficiently tensioned to avoid vibration, to have sufficiently smooth surfaces and rounded leading edges to reduce their drag to essentially laminar one, and to have a sharp trailing edge to avoid separation.

In order to get the local skin friction coefficients at the wall, the stagnation pressure was measured through a Preston tube at the wall, and the static pressure through some static gates over the plate. The dynamic pressure was then related to the skin friction coefficient C_f through the Patel correlations. Figure 2 illustrates the effect of the manipulators on the local skin friction coefficient. The x coordinate is the distance from the flat plate leading edge, the position of the manipulators is indicated by two vertical lines. A clear reduction of the wall shear stress due to the boundary layer manipulation is shown, the effect persisting downstream up to at least $40\,\delta_o$. The reduction increases with downstream distance up to a maximum of about 40 %. The magnitude of the skin friction reduction is comparable with that observed by other investigators[(4)] .

For turbulence measurements an x hot wire probe was used, powered by a Dantec system at constant temperature. The length of the probe wire was $1.25mm$ and its diameter was $5\mu m$. The acquisitions were made at a frequency of $11\,kHz$ and with an integration time of 20 seconds.

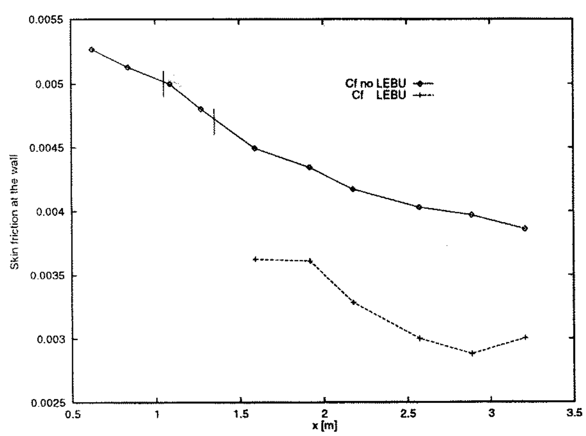

Figure 2: Skin friction at the wall

Results

Reynolds stresses

The ratio of the Reynolds stresses of the manipulated case and the corresponding natural evolving boundary layer are plotted in figure 3. The probe dimensions did not permit to approach the wall more than $0.5\,cm$, however at the wall the velocity fluctuating component tends to zero. With the x-wire probe used it was not possible to get the correlation $v'w'$; the correlation $u'w'$ is almost zero (where u' is the streamwise velocity fluctuating component, and v' is the velocity fluctuating component normal to the wall and w' is transversal velocity fluctuating component).

In the region just downstream the devices, the Reynolds stresses profiles exhibit a drastic reduction below the wake of the manipulator and a growth in the external part of the turbulent boundary layer. This may be explained as a consequence of the manipulator wake - boundary layer interaction. The counter-clock-wise vorticity shedded in the wake under the manipulator acts to cancel the clock-wise vorticity originating in the turbulent boundary layer. In the external part of the turbulent boundary layer, both vorticity are clock-wise and the interaction provides a growth of the Reynolds stresses (vortex unwinding). As the wake decays with downstream distance, the Reynolds stresses deficit is redistributed throughout the boundary layer and gradually relaxes back to the normal value. This evolution of the Reynolds stresses in the manipulated boundary layer illustrates the important role played by the wake in the large scales suppression through an interaction of the shed vorticity with the large eddy.

Intermittency factor

The intermittency factor is defined as the ratio between the time during which the flow is turbulent and the time during which the flow is laminar at a certain point. Considering that the turbulent field is inherently three-dimensional, measurements over only one fluctuating component of the velocity could be misleading in defining whether the flow is laminar or turbulent. For this reason it is necessary to choose a basic detection function which incorporates information at least from both u' and v' signal. A double component function which involved the derivatives of u' and v' separatley has been choosed as criterion function to increase its discriminatory capability:

$$\left(\frac{\partial u'}{\partial t}\right)^2 + \left(\frac{\partial v'}{\partial t}\right)^2$$

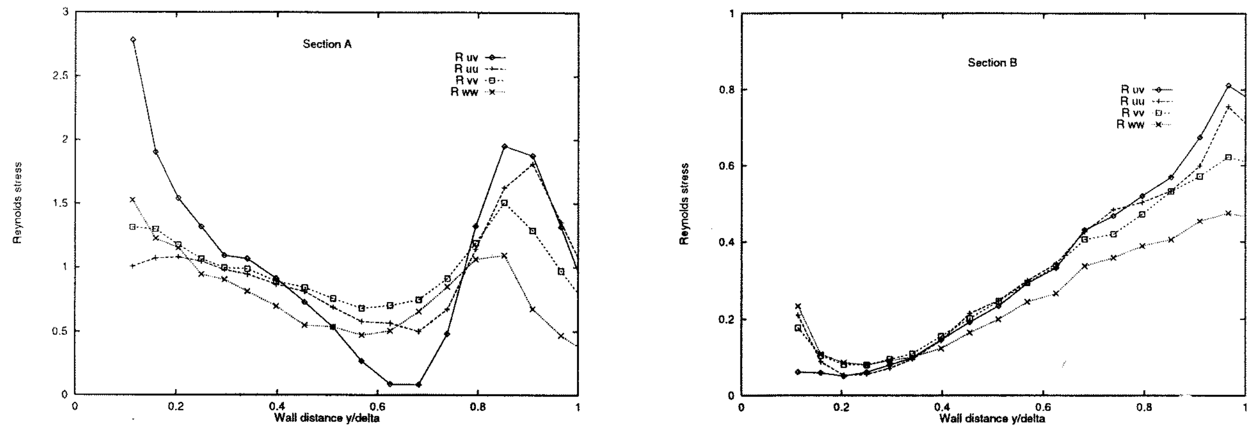

Figure 3: Reynolds stresses in the two measurement sections A and B

This criterion function does not prevent to consider, as deriving from a laminar flow, some very low velocity values belonging to turbulent fluctuations, if the velocity fluctuation is evaluated in each single time instant. The conventional method to eliminate this effect is to integrate the signal over a short period of time T_s, which produces a criterion function $T(\bar{x},t)$. Next it is necessary to establish a threshold level S, to discriminate between the true turbulence and the signal 'noise' which will inevitably exists regardless of the choise of the detection function[6]. Applying the threshold level then produces an indicator function satisfying:

$$I(\bar{x},t) = \begin{cases} 1 & \text{when } T(\bar{x},t) > S \\ 0 & \text{when } T(\bar{x},t) < S \end{cases}$$

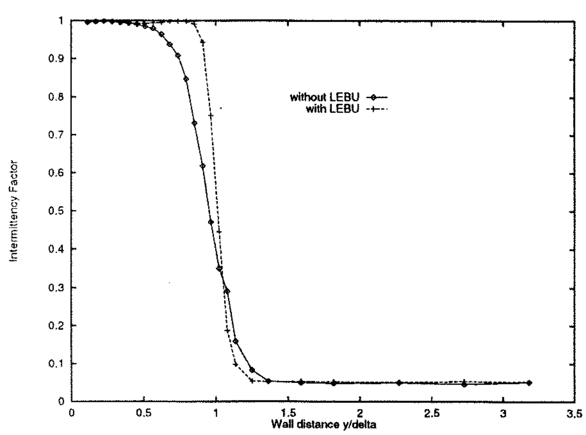

Figure 4: Intermittency factor γ at the section A

Figure 4 shows the comparison of the intermittency distribution between the regular and manipulated boundary layers. The thickness of the regular boundary layer at the manipulators position was used to non-dimensionalize the vertical coordinate. In the manipulated boundary layer it is evident a substantial reduction of the region where the intermittency takes place, and an intermittency decrease at the wake position. The manipulated case is characterized by steepening of the intermittency profiles or, in other words, a less corrugated interface between turbulent and non turbulent fluids. This confirms the results of former visualization studies[7]. The thinning of the manipulated boundary layer with respect to the regular case is also evident.

Flatness and Skewness

Flatness and skewness are two parameters used to study the statistic behaviour of the fluid motion. They are defined as the ratio of different power of the fluctuating component:

$$F = \frac{\overline{u'^4}}{(\overline{u'^2})^2}; \; S = \frac{\overline{u'^3}}{(\overline{u'^2})^{\frac{3}{2}}}$$

In a completeley random phenomenon, these parameters would be $F = 3$ and $S = 0$. Diverging from these value means that a sort of coherence in the flow exists. Figures 5 and 6 report the trends for the different velocity fluctuating components and suggest that the effect of the manipulators is to break the large eddy structures in the outer part of the boundary layer. It is important to remark that the effect is more important for the velocity component in the direction normal to the wall.

Conclusion

The different mechanisms proposed above have been studied and investigated.

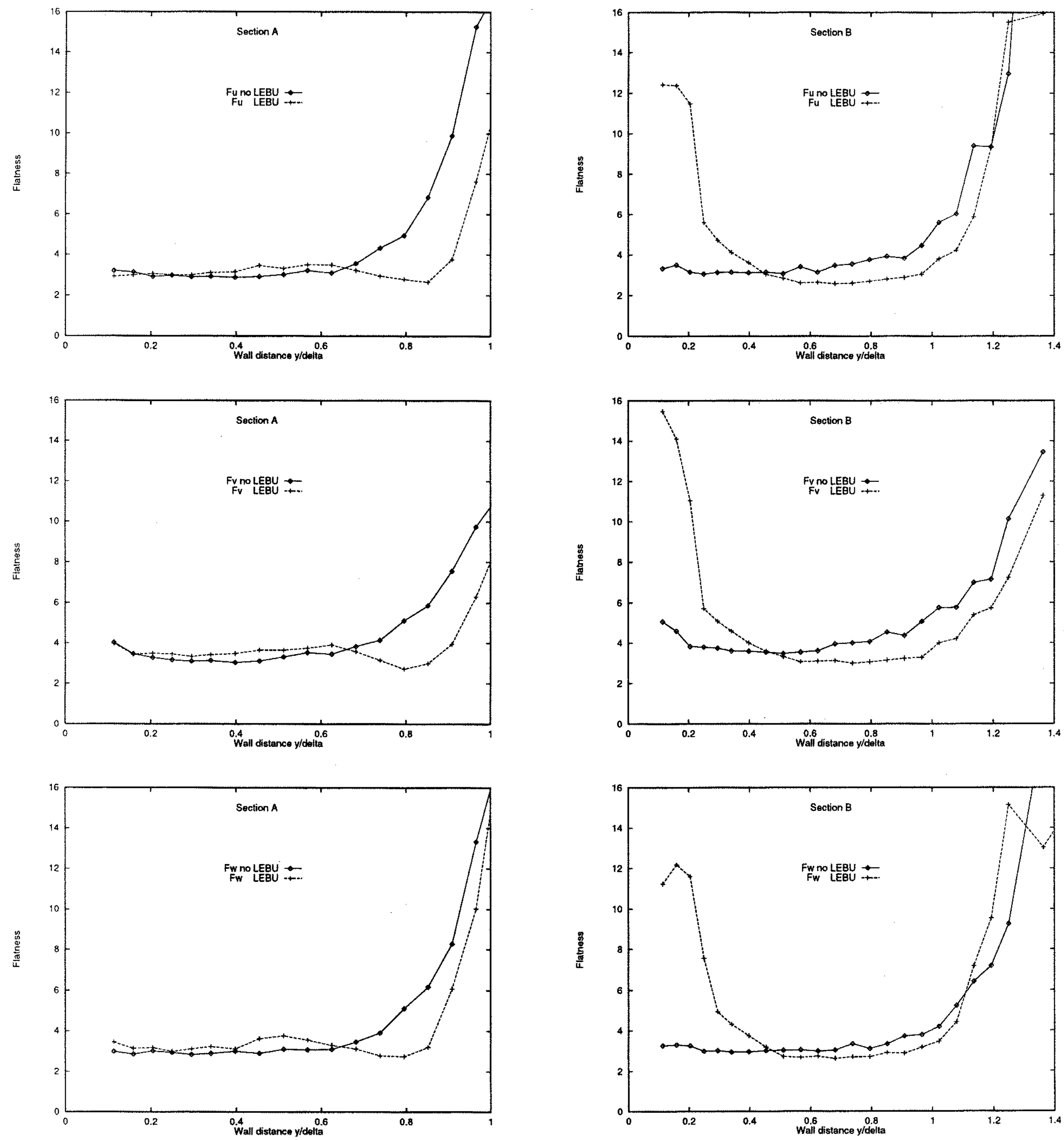

Figure 5: Flatness of the different component in the two different sections

Velocity fluctuations associated with oncoming large scales are significantly inhibited by the manipulators, as illustrated by the flatness and skewness profiles.

Moreover, the vorticity shed in the manipulator wake prevents the external coherent flow from reaching the wall (this acts as a shield effect). The Reynolds stresses profiles exhibit a drastic reduction below the wake of the manipulator. As the wake decays with downstream distance, the Reynolds stress deficit is redistributed throughout the boundary layer and gradually relaxes back to the normal values.

This may be due to the interaction of the boundary layer vorticity with the one of the manipulator wake. In the downstream region, under the devices, both vorticities have opposite signs (this may cause

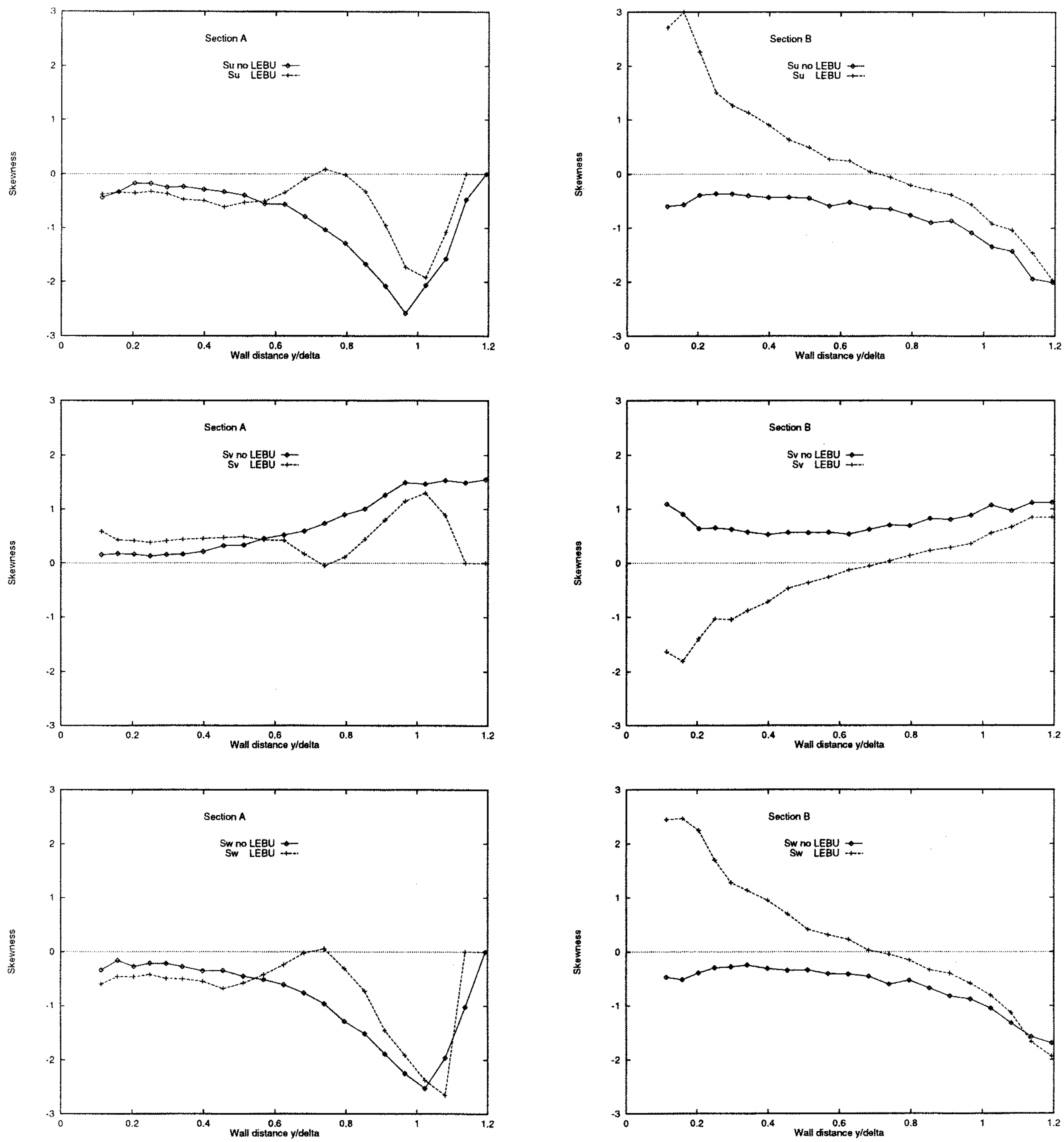

Figure 6: Skewness of the different component in the two different sections

a vortex unwinding effect).

Intermittency factor measurements show a less corrugated interface between turbulent and non turbulent fluids.

A redistribution of the turbulent kinetic energy through the wake of the manipulators takes place. This results in a lower turbulence production in the wall region under the wake. New energetic scales introduced in the manipulators wake interact with the existing scales in the boundary layer and this affects the global energy production and transfer between the wall region and the rest of the layer.

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