PIV STUDY OF LONGITUDINAL VORTICES IN A TURBULENT BOUNDARY LAYER FLOW

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Abstract

Digital Particle Image Velocimetry has been applied to the study of a flat plate turbulent boundary layer "manipulated" by streamwise large scale vortices. The vortical field was generated by a series of jets at 45 degrees with respect to the wall and in a plane transversal to the mean flow direction. Images in planes perpendicular and parallel to the wall were analyzed to obtain mean and turbulent velocity profiles.

Results from the manipulated flow were compared to the ones from the natural boundary layer. Measurements in planes at y+»20 revealed a sensible variation of streamwise turbulence intensity but, at least for the experimented flow condition, there was no evidence of disruption of the velocity streaky pattern or differences in the velocity band spacing.

1 Introduction

The development of the flow field produced by vortex generator jets (VGJ) has been the subject of many studies [1, 2, 3, 4], whose aim was the control of flow separation in adverse pressure gradient flows. Recently Schoppa and Hussain [5], using DNS data of turbulent channel flows, demonstrated that spanwise integrated skin friction reduction may be obtained by counter rotating large scale streamwise vortices. They showed that this technique may break the boundary layer vortex regeneration cycle by disrupting the unstable low speed wall streaks generated by previous or pre-existing streamwise vortices. Jimenez and Pinelli [6] also performed a numerical experiment showing that the streaks are responsible for the generation of the inner layer streamwise vortices and demonstrated the principle that the turbulence production cycle may be interrupted through weakening the streaks by some external perturbation.

In the present paper the development of large scale longitudinal vortices produced by VGJ is analyzed using PIV technique and their action on the turbulence of the boundary layer is examined.

2 Experimental Technique

The experiment was carried out in the Hydra water tunnel of CNR-CSDF. This facility is a closed loop, open flow channel with 350x500x1800 mm^3 test section. Measurements were taken over a flat plate 2050mm long, spanning the whole test section, with imposed transition at the leading edge. An array of longitudinal vortices is generated by water jets, injected at x=0mm through 6 holes (2mm diameter), drilled at pitch angles of alternatively 45 and -45 degrees, through the plate along its span (fig.1). The jets configuration produces three couples of counter-rotating vortices. The distance between two adjacent holes is 30 mm, corresponding to about 500 viscous lengths at the natural test condition. The ratio between the mass flow rate of the 6 jets and the mass flow rate of the boundary layer is 0.003.
The flow is seeded with spherical solid particles, 2 microns nominal diameter. A double-pulsed light sheet is provided by a Nd-YAG laser source (200mJ and 8ns per pulse).

Images are captured by a digital video camera Kodak MEGAPLUS ES1.0 (1008x1012pixels) and analyzed via cross-correlation technique. Results obtained lighting planes (y,z) and planes (x,z) respectively perpendicular and parallel to the flat plate will be commented in this paper.
In the (y,z) planes the interrogation window is 16x16pixels which correspond to a physical dimension ranging from $1.4x1.4\,mm^2$ at x=50mm to $1.2x1.2\,mm^2$ at x=250mm. An interrogation spot size of 32x32pixels (corresponding to $1.2x1.2\,mm^2$) and a 50% window overlap are used for the (x,z) planes.
The natural boundary layer at the injection section is caracterized by $Re_\theta = 1160$ and $u_\tau / U_e = 0.052$.

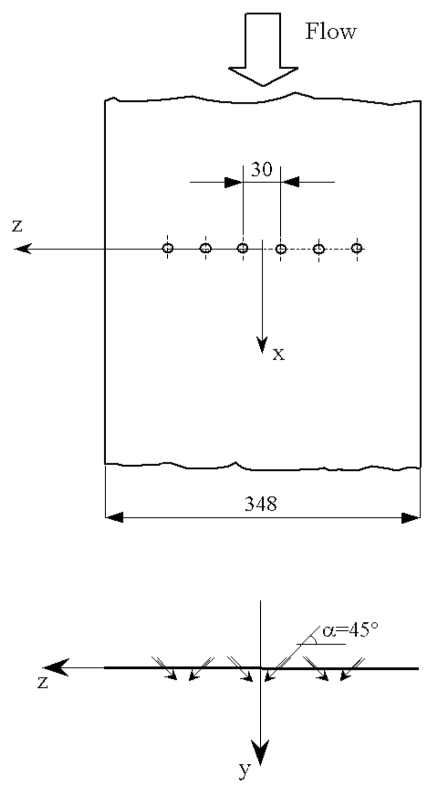

Fig. 1 Sketch of the flat plate with jet holes configuration and reference system. All dimensions in millimeters.

3 Results

Results referring to the manipulated field will now presented. Fig. 2 shows mean values of the secondary flow velocity vectors in a (y,z) plane

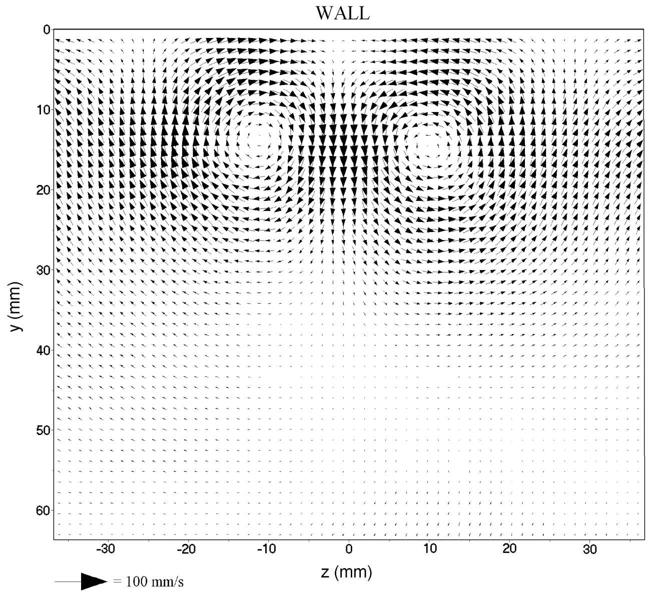

Fig. 2 Mean vectorial velocity flow field in the (y,z) plane at x=130mm.

located at x=130mm downstream from the injection section. The counter rotating vortex pair centered at z=0 is visible. It should be pointed out that at this location the boundary layer thickness for the natural flow is about 40mm. In the proximity of z=0, a common flow up region is present, in contrast with common flow down regions located at z≈±30mm; in between a cross flow region is present. It can be also seen that mean vortices interaxis is about 22mm.
From the observation of the two instantaneous vectorial velocity flow fields (fig. 3a and 3b) it comes out clearly the unsteady nature of the superimposed vortical field.
A more complete description of the vortices evolution is described in Di Cicca et al. [7].
In Fig. 4 the percent variation of the manipulated mean longitudinal velocity with respect to the natural boundary layer mean velocity is shown for two sections downstream the injection point and located at a distance of about 20 wall units from the plate. In both cases lacks and peaks in the velocity distributions are clearly visible. The losses of velocity, due to outflow are differently positioned: at x=130mm are present two valleys in the distribution while at x=312mm there is only one. The reason of these two different distributions has to be

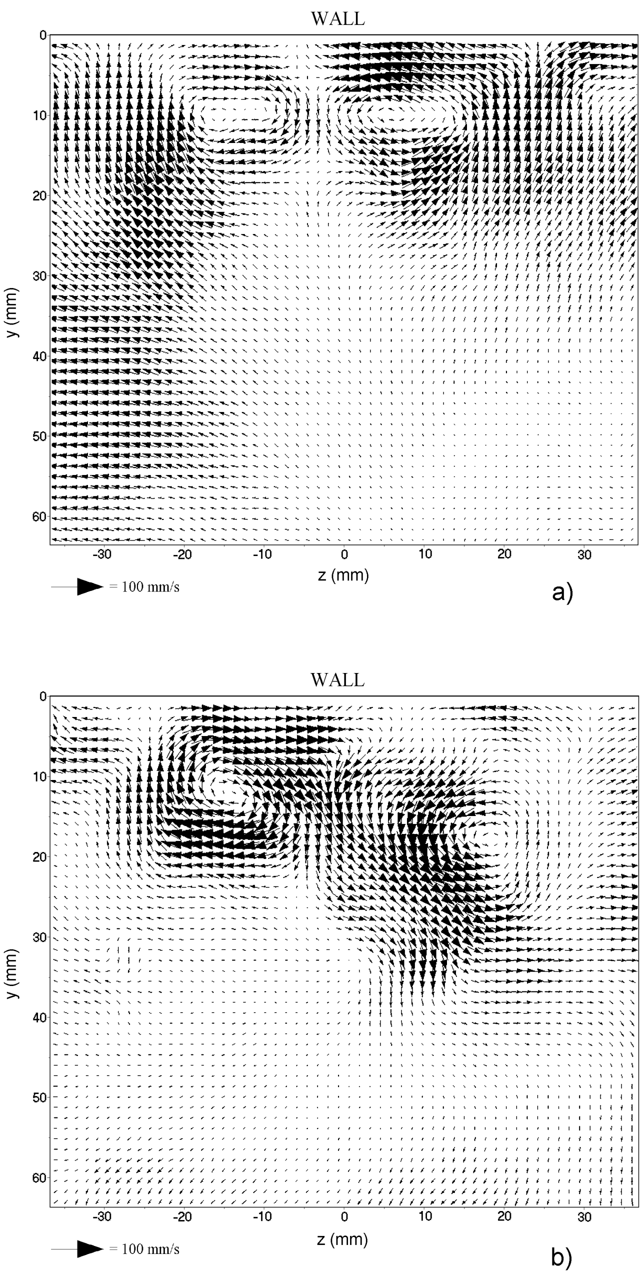

Fig. 3 Instantaneous vectorial velocity flow fields in the (y,z) plane at x=130mm.

wanted in the fact that the two vortices exhibit characteristics very similar to Rankine ones and moreover at x=130mm they are smaller and stronger than at x=312mm where they are partially merged and their shape is flattened.

In Fig. 5 the mean spanwise velocity distributions are shown. Going downstream the spanwise disturbance velocities became lower confirming a reduction of the vortical field intensity.

As concerns streamwise turbulence intensity (Fig. 6) in the section at x=130mm, there is an increase in the central part between the two vortices with respect to the unmanipulated case,

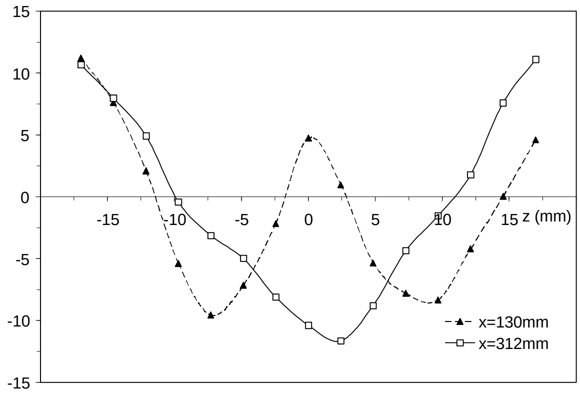

Fig. 4 Percent variation of mean longitudinal velocity for two different sections downstream the injection point and located at a distance y+≈20 from the plate.

whereas a reduction can be noticed going towards inflow regions. A quasi-opposite behavior can be seen in the section at x=312mm.

In order to explain these modifications of the boundary layer mean and turbulent velocity distributions caused by the experimented

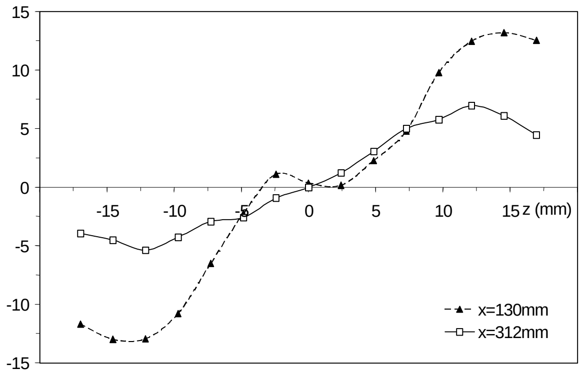

Fig. 5 Mean spanwise velocity distributions for two different sections downstream the injection point and located at a distance y+≈20 from the plate.

manipulation, a first correct thinking is toward the transport of mean momentum and turbulent energy away from the wall for the outflow region and in the direction of the wall for the inflow region. Fluid outflow in the central part

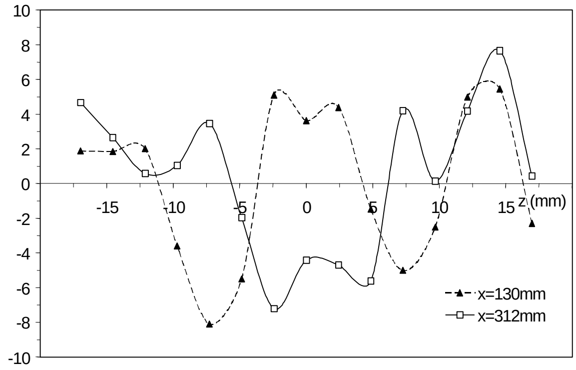

Fig. 6 Percent variation of streamwise turbulence intensity for two different sections downstream the injection point and located at a distance y+≈20 from the plate.

of the vortex couple decreases the mean momentum in the inner region of the boundary layer, supposedly lowering the local skin friction value, τw, with respect to the natural boundary layer case. On the contrary fluid inflow increases mean momentum in the inner region of the boundary layer, which supposedly

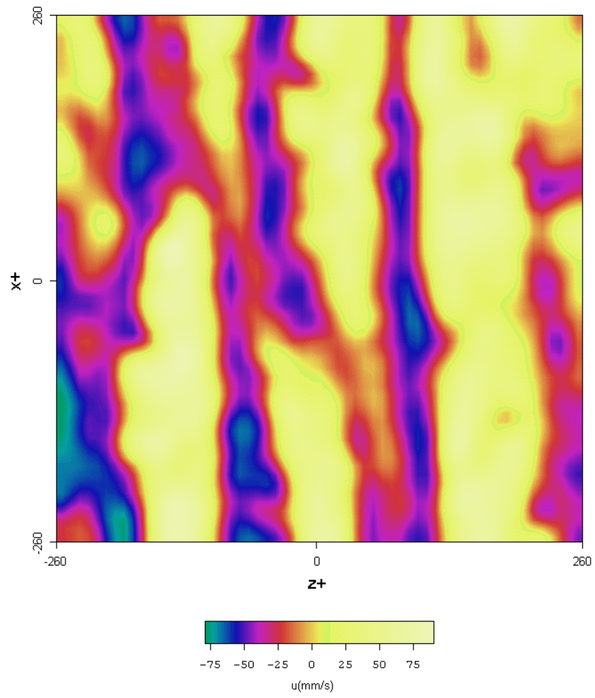

Fig. 7 Grey level map of streamwise fluctuating velocity component in the (y,z) plane centered at x=312mm. Jets off; y+≈20.

raises the local value of τw. Moreover the observed variation of turbulence intensity shown in fig.6 may be related (as predicted by Schoppa and Hussain) to the action of the imposed large scale longitudinal vortices on the frequency occurrence of turbulence producing events, as ejections and sweeps.

The structure of the boundary layer was also examinated. In Fig. 7 a grey level map of streamwise fluctuating velocity in a (x,z) plane located at a distance of about 20 wall units from the plate and centered at 312mm downstream from the injection section is presented for the case of a natural boundary layer. The observed flow field spans about 500 viscous units in the longitudinal (streamwise) and transversal (spanwise) direction. As expected, in the buffer layer region, quasi-streamwise low speed streaks characterize the flow. A similarly organized flow field can be observed for the case of vortex manipulated boundary layer, and no evidence of disruption of streaky structure was observed [8], at least for the examined flow conditions.

4 Conclusions

The development of longitudinal vortices produced by an array of flow transversal jets has been described. About their action on the turbulence, the weak control imposed by the embedded longitudinal vortices has produced, in the measurement plane at y+≈20, a sensible variation of streamwise turbulence intensity. The exam of the flow organization shows, at least for the present flow condition, no evidence of disruption of the velocity streaky pattern or differences in the velocity band spacing.

Further investigations are required in order to optimize the several parameters involved in the problem, such as the ratio between jet mass flow rate and boundary layer mass flow rate, the jet orientation or the jet location.

References

[1] Pauley W. R. and Eaton J. K. Experimental study of the development of longitudinal vortex pairs embedded in a turbulent boundary layer. *AIAA Journal*, Vol. 26, No. 7, pp 816-823, 1998.

[2] Hasegawa H., Matsuuchi K., and Yamakami J. The mechanism of active boundary layer control using vortex generator jets. *Proceedings of the 21st ICAS*

Congress, Melbourne, Australia, A98-31545 ICAS Paper 98-3.4.3, 1998.

[3] Shelby G. V., Lin J. C., and Howard F. G. Control of low-speed turbulent separated flow using jet vortex generators. *Experiments in Fluids*, Vol. 12, pp 394-400, 1992.

[4] Johnston J. P. and Nishi M. Vortex generator jets - means for flow separation control. *AIAA Journal*, Vol. 28, No. 6, pp 989-994, 1990.

[5] Schoppa W. and Hussain F. A large-scale control strategy for drag reduction in turbulent boundary layers. *Physics of Fluids*, Vol. 10, No. 5, pp 1049-1051, 1998.

[6] Jimenez J. and Pinelli A. The Role of Coherent Structure Interactions in the Regeneration of Wall Turbulence. *Advances in Turbulence*, Vol. 7, pp 155-, Kluiwer Academic Publishers, 1998.

[7] Di Cicca G. M., Onorato M., Iuso G., Bollito A. and Spazzini P. G. Experimental study of near wall turbulence using Particle Image Velocimetry, *Proceedings of the 3th International Symposium on Turbulence and Shear Flow*, Santa Barbara, CA., USA, 1999.

[8] Soldati A., Fulgosi M. and Banerjee S. On the use of large-scale vortical streamwise structures to control turbulence in channel flow. *Proceedings of the 3th International Symposium on Turbulence and Shear Flow*, Santa Barbara, CA., USA, 1999.