13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

EFFECTS OF A GROOVE ON THE NEAR-WALL STRUCTURE OF TURBULENT BOUNDARY LAYER FLOWS

Yves DUBIEF, Pierre COMTE and Marcel LESIEUR

Laboratoire des Ecoulements Géophysiques et Industriels
BP53, 38041 Grenoble-Cedex, France

ABSTRACT

A turbulent boundary layer manipulated by a tranverse square groove is investigated. Although the groove width is of the order of the boundary layer thickness, statistics are affected only in the near wall region. Significant changes in the streak system and vortical structures are observed.

INTRODUCTION

A significant amount of effort has been devoted to the study of near-wall coherent motions of turbulent wall-bounded flows. Experimental and numerical investigations have mainly focused on equilibrium flows, such as channel flows and the canonical turbulent boundary layer, defined by Robinson (1991) as a flat-plate smooth wall zero-pressure gradient turbulent boundary layer with low free stream turbulence and no body forces or compressibility. The key structures of the near-wall turbulence have been identified as high- and low-speed streaks and quasi-streamwise vortical structures (see Jeong *et al.*, 1997). Both structures have characteristic dimensions of the order of a few hundreds wall units (u_τ/ν, where u_τ is the skin friction velocity and ν the kinematic viscosity) in the streamwise direction. The streaks are intermittently subjected to a bursting process, generating outward ejections of low speed fluid and wallward sweeps of high speed fluid. Both events are responsible for the high level of turbulence in the buffer region and of the significant increase of the skin friction in comparison to laminar flows. Robinson (1991) proposed a conceptual model in which quasi-streamwise vortices located in the buffer layer produce ejections and sweeps on their sides. Although this model has proved to reproduce many characteristic features of the near-wall streak stystem (Orlandi and Jimenez, 1994), Robinson stressed out that the dynamics of the structures as well as their sensibility to various parameters are still not well understood. The latter issue is addressed in this paper by using wall roughness.

A spanwise square cavity embbeded in a flat plate is used to manipulate near wall structures in a low Reynolds number turbulent boundary layer. A first well-resolved Large Eddy Simulation (LES) shows the ability of the numerical procedure to reproduce realistic turbulent structures and to handle geometrical singularities. The width d of the groove is of the order of the boundary layer thickness, $d/\delta_0 = 1$. The disturbance caused by the groove is expected to be significant since the width normalised by u_τ anf ν is about 300, close to a streak length. This paper presents the effects of the groove on some conventional statistics and a few flow visualisations.

CALCULATION PROCEDURE

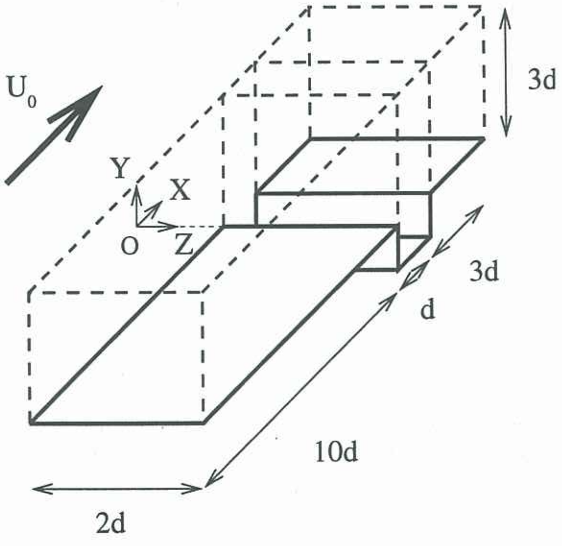

Figure 1: Sketch of the computational domain.

The simulation is carried out using a multi-domain compressible code. The conservative form of Navier-Stokes equations are solved with a Mac Cormack scheme which is second order accurate in time and fourth order accurate in space (Comte *et al.*, 1995). Periodicity is prescribed in the spanwise direction. A non reflective outflow boundary condition (Poinsot and Lele, 1992) is applied at the upper side of the domain and at the outlet. The grid is orthogonal and streched in the different near-wall regions. An eddy-viscosity model, the Filtred Stucture Function Model (Ducros *et al.*, 1996), takes into account the contribution of scales smaller than the grid resolution. This model consists of filtering the large scale simulations before applying the classical structure function model of Métais and Lesieur (1992).

The computational domain is sketched in figure 1. The large dimension of the upstream domain is required by the inlet condition. The coordinate system is located at the upstream edge of the groove. The resolution for the inlet, the groove and the downstream flat plate blocks are respectively $101 \times 51 \times 40$, $41 \times 101 \times 40$ and $121 \times 51 \times 40$. The minimal grid spacing at the wall in the vertical direction corresponds to $\Delta y^+ = 1$. The streamwise grid spacing goes from $\Delta x^+ = 3.2$ near the groove edges to 20 at the outlet. The spanwise resolution is $\Delta z^+ = 16$.

The Reynolds number of the flow is 5100, similar to the intermediate simulation of Spalart (1988) at $R_\theta = 670$. The inflow is generated using the method of Lund *et al.* (1996). This method is based on the similarity properties of canonical turbulent boundary layers. At each time step, the mean and fluctuating velocities, temperatures and pressures are extracted from a plane, called the recycling plane and rescaled at the appropriate inlet scaling. The statistics are in good agreement with Spalart's data (figures 2 and 3).

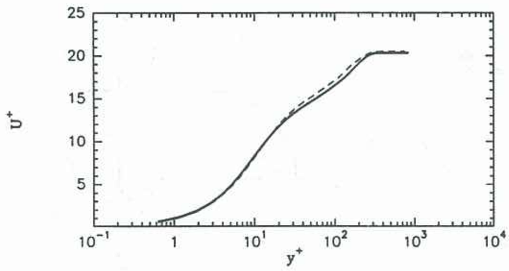

Figure 2: Mean streamwise velocity profiles in wall coordinates. DNS of Spalart $Re = 5100$, ——; present study $x/\delta_0 = -1.5$, ----.

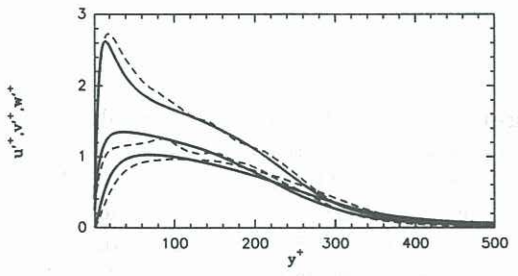

Figure 3:RMS u (upper curves), v (middle curves), w (lower curves) distributions in wall coordinates.

STATISTICAL RESULTS

Figure 4 shows the distribution of the skin friction coefficient C_f normalised by its smooth wall value on the downstream flat plate. Immediatly downstream of the groove the skin friction coefficient experiences a sharp rise, followed by a small undershoot. The skin friction eventually relaxes towards its smooth wall value in an oscillatory manner. This behavior is constistent with previous experimental results of Pearson *et al.* (1997) and Ching and Parsons (1998) with a smaller ratio d/δ_0. The local drag reduction observed in our simulation is smaller than that obtained by these authors, probably because of a larger width of the groove in our case. The high magnitude of the skin friction at the edge is caused by the impingment of the internal shear layer of the cavity. A similar overshoot is found at the upstream edge (not shown here), due to a local favorable pressure gradient which accelerates the near wall fluid approching the groove. The undershoot is still an unsolved issue. Mean velocity profiles (not shown here) exhibit a log-law distribution shifted accordingly with respect to the increase or decrease of u_τ.

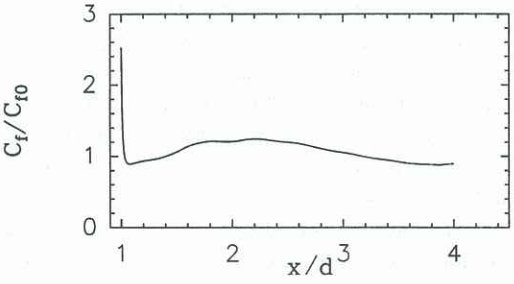

Figure 4: Longitudinal evolution of the skin friction coefficient normalised by its smooth wall value

Downstream of the cavity, the velocity RMS are affected only in the near-wall region (Figures 5,6 and 7), for $y^+ \leq 30$. The flow in the viscous sublayer and the buffer layer is more turbulent. The most significant increase is observed for the wall-normal turbulent intensity. The change in the boundary condition created by the recirculation inside the groove weakens the damping of w fluctuations in comparaison to a no-slip condition. In the reattached boundary layer, this component sustains almost all its energy gained above the groove. The extent of the manipulated layer of the flow is larger than that observed by Pearson *et al.* (1997), due to their small ratio $d/\delta_0 = 0.2$. However the qualitative change in statistics are consistent with single groove (Pearson *et al.*) and d-type rough wall (Djenidi *et al.*, 1994) experiments.

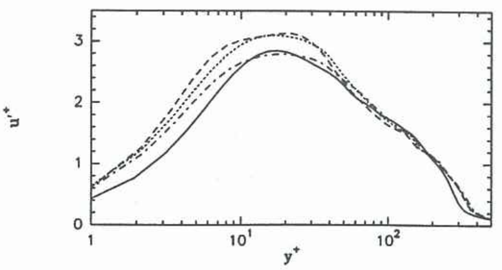

Figure 5: RMS of the streamwise velocity component in wall coordinates. $x/d = -3.5$ (reference) ——; $x/d = 1.1$ ----; $x/d = 2$ ·····; $x/d = 3$ —-—

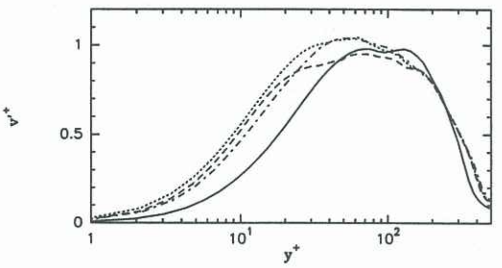

Figure 6: RMS of the wall-normal velocity component in wall coordinates. For explanation of symbols see figure 6.

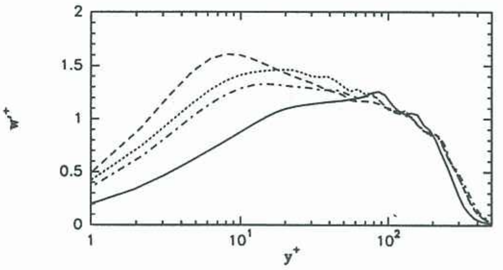

Figure 7: RMS of the spanwise velocity component in wall coordinates. For explanation of symbols see figure 6.

The distribution of energy among the velocity components is analysed using the Anistropy Invariant Mapping (Lumley and Newman, 1977). The invariant of the anisotropy Reynolds stress tensor writes $b_{ij} = (\overline{u_i u_j}/\overline{u_i u_i} - \delta_{ij}/3)$. The AIM representation is a cross plot of the second invariant $-II$ *vs* the third III of b_{ij} where $-II = b_{ij}b_{ij}/2$ and $III = b_{ij}b_{jk}b_{ki}/3$. The top vertex of the triangle (drawn lines of figure 8) is the one-component state, *i.e.* one velocity component dominates the others, while the bottom cusp indicates the isotropic state ($II = III = 0$). Figure 8 clearly shows a return towards a more isotropic state downstream of the groove. A similar trend has been observed over k-type rough wall (Shafi and Antonia, 1995). An increase in isotropy of smaller magnitude has also been reported in boundary layer flows above riblets by Dubief *et al.* (1997) and Suzuki and Kasagi (1994) when riblets increase the drag. Although near-wall layer manipulated by roughness seems to share the same property of being more isotropic, the mechanism is not likely to be similar. In our case, the recirculation inside the groove enhances the transfer of energy among the three velocity components.

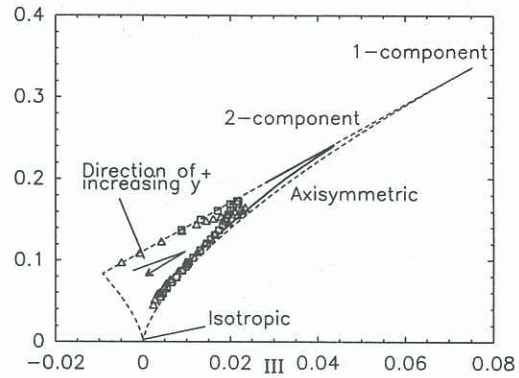

Figure 8: Anisotropy invariant map. Upstream boundary layer $x/d = -3.5$, ——; downstream of the groove Triangle, $x/d = 1.1$; □, $x/d = 3$.

COHERENT STRUCTURES

Spanwise correlations of u, v and w (not shown here) indicate a slight change in the streak spanwise wavelength. In the buffer layer, while negative u correlation peaks at $z^+ = 50$ in the upstream boundary layer, giving the right streak spacing $\lambda_z^+ = 100$, the spanwise wavelength is reduced downstream of the groove ($\lambda_z^+ = 70$). Figure 9 shows contours of instantaneous u fluctuations near the wall. Above and downstream of the groove, the streaks are intensified and their length is significantly reduced.3D visualisations (not shown here) indicate an increase of the vertical extent of low-speed streaks as they pass over the groove. Pearson *et al.* (1997) observed the existence of ejections of fluid out of the groove. They suggested that these ejections may be initiated by large scale structures passing over the groove. The present study tends to link these ejections with low-speed streaks. Since the streaky structure is closely related to quasi-streamwise vortices, figure 10 shows isosurfaces of positive $Q = (\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij})/2$ where Q can be interpreted as the local balance between shear strain rate and vorticity magnitude. Consistently with AIM analysis, the structures downstream of the groove are smaller and less elongated in the streamwise direction . The flow inside the groove (not shown here) is highly unsteady and there is obviously a high level of communication between the recirculating vortex and the turbulent boundary layer.

Figure 9: Contours of instantaneous streamwise velocity fluctuations in the (x, y) plane located at $y^+ = 8$.

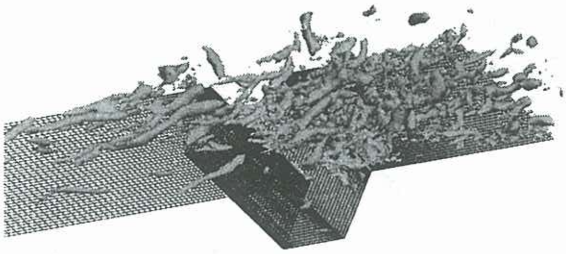

Figure 10: Isosurfaces of positive Q. $Q = 0.01\omega_i^2$

CONCLUSIONS AND PERSPECTIVES

A numerical simulation of a spatially developing turbulent boundary layer manipulated by a square groove has been presented. The cavity under investigation has dimensions of the order of the boundary layer thickness. The results are consistent with experiments involving much smaller cavities. It is assumed that the cavity width is too large to obtain a drag reduction even though the skin friction, normalised by its smooth wall value, exhibits a small undershoot downstream of the groove. The level of turbulence is increased over the downstream flat plate, and the flow tends to be more isotropic. The spatial extent of coherent structures is reduced above and after the groove.

Numerical simulations of much smaller cavities are underway and will be presented at the conference. The main objective of this study is to simulate Pearson *et al.* (1997) experiment and to further investigate the communication between the flow inside the groove and the boundary layer flow.

ACKNOWLEDGMENTS

The CPU time used for this simulation was allocated by The French National Computing Center IDRIS.

REFERENCES

CHING, C.Y. and PARSONS, B.L., "Drag Characteristics of a turbulent boundary layer over a flat plate with transverse square grooves", *To be published in Expts. in Fluids*, 1998.

COMTE, P., SILVESTRINI, J.H. and LAMBALLAIS, E., "A straightforward 3D multiblock unsteady Navier-Stokes solver for direct and large-eddy simulations of transitional and turbulent compressible flows", In *77th. AGARD Fluid Dynamic Panel Symposium "Progress and Challenges in CFD Methods and Algorithms"*, 2-5, Seville, Spain, 1995.

DJENIDI, L., ANSELMET, F. and ANTONIA, R.A., "LDA measurements in a turbulent boundary layer over a *d*-type rough wall", *Expts. in Fluids* **16** 323-329, 1994.

DUBIEF, Y., DJENIDI, L. and ANTONIA, R.A., "The measurement of $\partial u/\partial y$ in a turbulent boundary layer over a riblet surface", *Int. J. Heat and Fluid Flow* **18** 183-187, 1997.

DUCROS, F., COMTE, P. and LESIEUR, M., "Large-eddy simulation of transition to turbulence in a boundary layer developing spatially over a flate plate", *J. Fluid Mech.* **326** 1-36, 1996.

METAIS, O. and LESIEUR, M., "Spectral large-eddy simulation of isotropic and stably stratified turbulence", *J. Fluid Mech.* **239** 157-194, 1992.

JEONG, J., HUSSAIN, F., SCHOPPA, W. and KIM, J., "Coherent structures near the wall in a turbulent channel flow", *J. Fluid Mech.* **332** 185-214, 1997.

LUMLEY, J.L. and NEWMAN, G.R., "The return of isotropy of homogeneous turbulence", *J. Fluid Mech.* **82** 161-178, 1977.

LUND, T.S., WU, X. and SQUIRES, K.D., "On the generation of turbulent inflow conditions for boundary layer simulations" *Ann. Briefs of the Center For Turbulent Research* 287-295, 1996.

ORLANDI, P. and JIMÉNEZ, J., "On the generation of turbulent wall friction", *Phys. Fluids* **6** (2) 634-641, 1994.

PEARSON, B.R., ELAVARASAN, R. and ANTONIA, R.A., "The Response of a Turbulent Boundary Layer to a Square Groove" *To be published in J. Fluids. Eng.*, 1997.

SHAFI, H.S. and ANTONIA, R.A., "Anisotropy of the Reynolds stress in a turbulent boundary layer over a rough wall", *Expts. in Fluids* **18** 213-215, 1995.

SPALART, P.R., "Direct simulation of a turbulent boundary layer up to $R_\theta = 1410$" *J. Fluid Mech.* **187** 61-98, 1988.

POINSOT, T.J. and LELE, S.K.,"Boundary conditions for direct simulations of compressible viscous flows", *J. Comp. Phys.* **101** 104-129, 1992.

ROBINSON, K.S., "Coherent motions in the turbulent boundary layer", *Annu. Rev. Fluid Mech.* **23** 601-639, 1991.