11th Australasian Fluid Mechanics Conference
University of Tasmania, Hobart, Australia
14-18 December 1992

2E-5

EXPERIMENTAL DETERMINATION OF THE VELOCITY FIELD WITHIN AND OVER RIBLETS IN A TURBULENT BOUNDARY LAYER

F. ANSELMET, M. BENHALILOU and L. FULACHIER

Institut de Mecanique Statistique de la Turbulence
12 Avenue du General Leclerc, 13003 Marseille, FRANCE

ABSTRACT

The turbulent boundary layer developing over triangular riblets is investigated in a water tunnel. In order to determine the velocity field over and within the grooves their dimensions are quite large (h=3.5 mm, $h^+ \approx 17$, s/h=2). Emphasis is given here on experimental results obtained very close to the wall. Particular attention is paid to streamwise velocity profiles and to the distributions of the standard deviations of the three velocity components, and the riblet influence on the turbulence kinetic energy is inferred. Extensive comparison with the streamwise velocity statistics obtained by Vukoslavcevic et al. is performed.

INTRODUCTION

In turbulent boundary layers, triangular riblets of suitable dimensions can achieve drag reduction by about 10 % (see, for instance, Coustols and Savill, 1992). This result is now beyond doubt and is of considerable practical interest in relation to either the impact on the "direct operation cost" (Robert, 1992) in aeronautical applications or the improvement of performance in competitive water and motor sports.

Numerous global skin friction measurements have been performed, but detailed experiments allowing a better understanding of the mechanism responsible for that drag reduction are still quite rare (Choi, 1989; Pulles et al., 1990; Tardu, 1991). Indeed, following the observation that riblets result in an upward shift of the spanwise averaged mean velocity profile that could be characteristic of a thickening of the sublayer, these authors investigated the influence of riblets on the bursting process. Though the restriction of spanwise movement of the near-wall longitudinal vortices is quite obvious and clearly visible from flow visualizations (Choi, 1989; Clark, 1990), results from various authors regarding the burst frequencies or the conditional averaging of the velocity field during a detected event are still conflicting. As a consequence, the development of efficient modelizations -which would be very useful to guide the optimization of riblet surfaces and to make low-cost parametrical studies- is suffering from the lack of strong enough guidelines, so that the predicted drag reduction levels are so far quite different from those obtained experimentally (Launder and Li, 1992).

Nevertheless, though the detailed mechanism responsible for the turbulent flow stabilization is still quite unclear, recent studies by Djenidi et al. (1989) and Liandrat et al. (1990) have clearly shown from a combined experimental and numerical investigation of a laminar boundary layer over riblets that viscous effects are very important in drag reduction. In particular, the velocity field reorganisation within a rib is such that the balance between the increase of wall velocity gradients in the crest vicinity and their strong reduction within the groove with respect to the gradient over a flat plate is compensating the very large wetted area enhancement (more than 100 % for V-grooves with the spacing s equal to the height h). Owing to the tiny size of riblets suitable for wind-tunnel investigations, spatially resolved velocity measurements in the close vicinity of a ribbed wall -where most of the effect seems to be confined (Hooshmand et al., 1983)- are quite difficult, and those extending within a groove are almost impossible. Bechert et al. (1992) have reported preliminary results obtained in a specially designed oil channel where efficient riblets can have lateral spacings lying between 3 and 10 mm. But, as far as we know, the only quantitative measurements within a large triangular groove are those by Vukoslavcevic et al. (1992), who obtained statistics related to the streamwise velocity field with hot-wire anemometry in a low-speed wind tunnel extending over an 8-m fetch.

The present paper is concerned with experimental results mainly relative to the mean longitudinal velocity U and to the statistics of the three fluctuating velocity components u, v and w (v is normal to the flat wall and w is along the spanwise direction).

EXPERIMENTAL CONDITIONS

Experiments are carried out in the IMST water tunnel (20 x 20 x 120 cm^3). On one of the side walls of the vertical working section, three dimensional roughness elements have been placed in order to trip the boundary layer (Antonia et al., 1988). With the centreline mean velocity U_e about 9 cm/s, a fully developed turbulent boundary layer is obtained at the downstream distance X=43 cm from the trip where is located the riblet wall (19 x 28 cm^2). At this station, the friction velocity u^* is about 0.5 cm/s, the boundary layer thickness δ is 32 mm and the momentum thickness Reynolds number R is about 300. Very good agreement (Fig. 1) with the classic Van Driest law is observed in the boundary layer inner region and especially in the region very close to the wall. Nevertheless, the law of the wall is only extending over a quite narrow zone owing to the low value of the Reynolds number. In the external zone, the wake law is almost nonexisting since R is weak and turbulence is

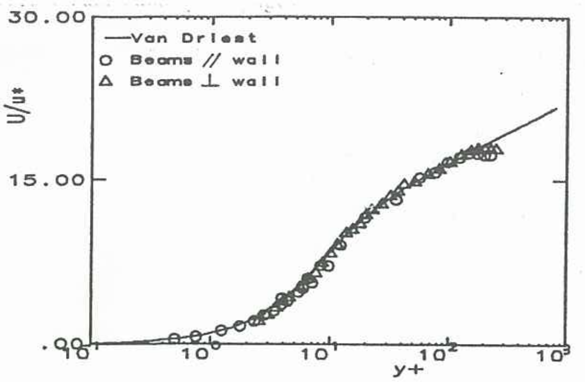

Fig. 1 Smooth wall mean longitudinal velocity.

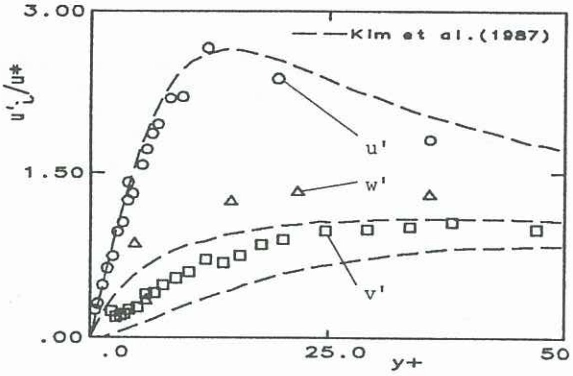

Fig. 2 Smooth wall velocity standard deviations.

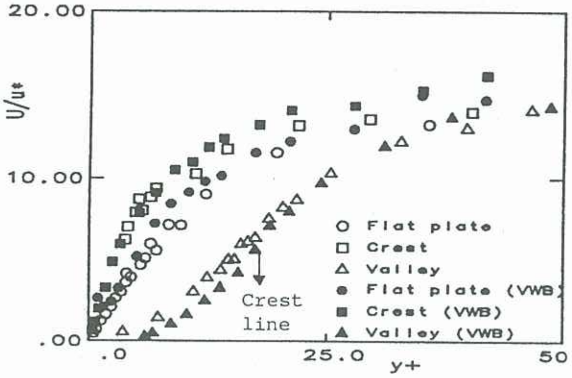

Fig. 3 Mean longitudinal velocity profiles.

tripped with large roughnesses. In addition, the distribution of u'/u* (Fig. 2, with $u'=\overline{u^2}^{1/2}$) is in very good agreement with the direct numerical simulations of Kim et al. (1987) for which the ratio u^*/U_e (=0.055) is the same as in the present measurements. The value of $d(u'/u^*)/dy^+$ at the wall is 0.36, i.e. slightly larger than that obtained by Antonia et al. (1988) -0.30- in a boundary layer where u^*/U_e=0.04. The behaviours of v'/u^* and w'/u^* obtained by the calculations are different from those measured: our data are similar to those reported by Kreplin and Eckelmann (1979) and Karlsson et al. (1991).

Large triangular grooves ($s=2h=7$ mm, $h^+=hu^*/\nu\approx17$, with ν, kinematic viscosity) are considered in order to perform velocity measurements extending within the valleys. These riblets are machined in a stainless steel plate and polished, with their crests flush with the upstream and downstream smooth plates. All measurements relative to the riblet wall are performed at the station X=70 cm≈20δ just before the ribbed plate trailing edge.

Velocity components in the streamwise and spanwise directions are inferred from data obtained with a one component LDA system (He-Ne, 15 mW) fitted with a Bragg cell and a Burst Spectrum Analyser. The backscatter technique is used and the measuring volume is 0.12 x 1.3 x 0.12 mm^3. At each position, measurements are performed for three beam inclinations in order to determine U, W, u', and w'. For the simultaneous measurements of the components along the longitudinal and normal to the flat wall directions, a two component system (Ar, 4W, 2 B.S.A.) is used and the measuring volume is then 0.12 x 0.12 x 1.3 mm^3.

Owing to the limited number of pages available here, only results relative to distributions along the normal to the crest plane direction will be presented. For all measurements over riblets, y denotes the distance to the actual wall and, for data obtained over the valley, the position of the crest plane is pointed by an arrow.

RESULTS AND DISCUSSION

The following figures mainly concern measurements performed in the very close to the wall region of the boundary layer ($0 < y^+ < 50$). All results relative to the streamwise velocity (U, second and third moments of u) are compared to those obtained by Vukoslavcevic et al. (1992, hereinafter referred to as VWB). Their experimental arrangement is very similar to ours, $s^+=2h^+=35$. However, their momentum thickness Reynolds number R is higher (R=1000) and their turbulent boundary layer is only tripped by a small cylinder (ϕ=5 mm).

Figure 3 gives profiles of the streamwise mean velocity U normalized with the friction velocity u^* over the riblet surface, in the plane of symmetry above the peak and valley. Velocity distributions relative to the smooth plate are also given: as expected, the present velocity profile is the same as VWB's, however, their two points closest to the wall seem to be affected by wall proximity effects. Above the peak, the trend is practically the same in both experiments, but above the valley some discrepancy is appearing mainly within the groove. For the laser measurements, owing to the combined averaging effect of the probe volume (normal to the crest plane dimension, 1.3 mm, corresponding to 6.5 wall units) and the bias resulting from seeding -which are much more crucial inside the riblets-, it seems that in this region the present U velocity is overestimated. On the other hand, for the hot-wire measurements, despite the wall proximity effects which should be most important inside the groove where velocities are very small and result in overestimating U, data seem to be quite reliable since the wire length l is only 0.5 mm, i.e. about 2 wall units in the spanwise direction (l/s = 0.05). It is found that, with respect to the smooth wall, the velocity gradient above the crest is enhanced by almost 100% whereas, over most of the rib, velocity gradients are weakened: this is especially obvious above the trough where friction is almost zero. This behaviour is similar to what had been previously observed for the laminar boundary layer (Djenidi et al., 1989), but the detailed mechanism is somewhat different since, in the turbulent regime, on the one hand, over the crests the relative friction enhancement is smaller and, on the other hand, over the trough the friction reduction is also weaker. This seems to be related to turbulent mixing tending to smooth velocity gradients. All the modifications induced by riblets on the velocity profile are confined in the close to the wall region: beyond $y+\approx45$, i.e. y/δ about 0.3, all profiles collapse to the smooth wall one. There exists a spanwise position (not presented here) where the velocity profile is practically identical to the smooth wall one: this position is located at $z/s\approx0.15$ as it is the case in laminar regime (Djenidi et al., 1989).

The two other mean velocity components are much weaker than U and measurements are very tricky. However, spanwise distributions of these quantities suggest that there may exist secondary vortices sitting within the riblet valley. Though their strength is quite small, it may be argued (Tullis and Pollard, 1992) that their interaction with the near-wall streamwise vortices may tend to weaken these latter and impede their lateral oscillations.

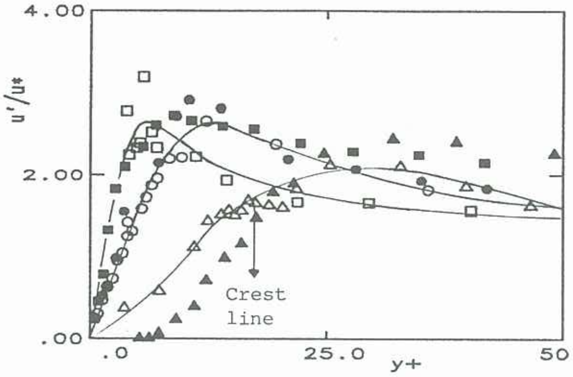

Fig. 4 Streamwise velocity standard deviations (cf.Fig.3).

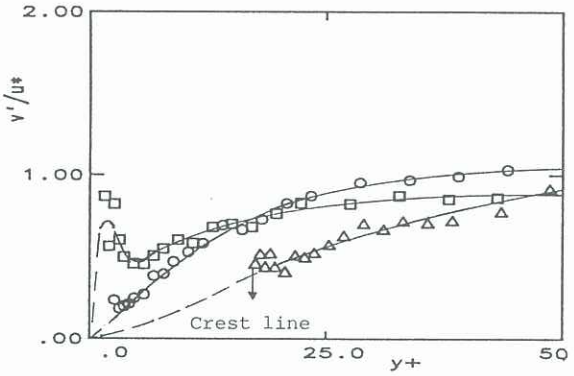

Fig. 5 Normal to the crest plane velocity standard deviations (cf.Fig.3).

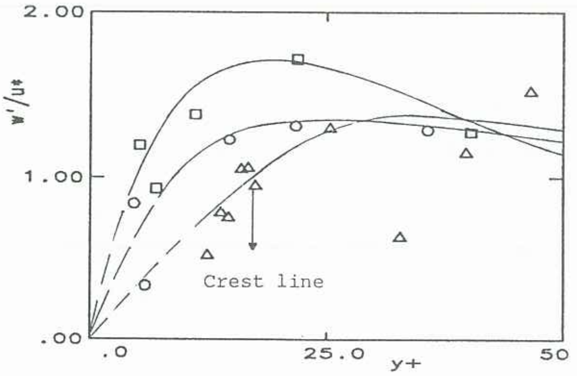

Fig. 6 Spanwise velocity standard deviations (cf.Fig.3).

Distributions of streamwise velocity standard deviations are reported on figure 4 in a way similar to figure 3. Generally speaking, the riblet influence on u' is similar to that previously discussed for U. It seems that present measurements overestimate u' inside the valley. Noise contamination may then be quite important since, for that position ($z/s=0.5$), the laser beams are perpendicular to the crest plane and the scattering of light impacting the V-wall is probably most penalizing in the trough vicinity. Present measurements suggest that the maximum value of u' may be slightly stronger over the crest than on the smooth plate: VWB's results indicate a somewhat different behaviour. Figure 5 presents normal to the crest plane velocity standard deviations v' -but only over the crest plane owing to the beam orientation necessary to perform such measurements- and figure 6 gives spanwise standard deviations w'. These quantities present variations quite similar to those observed for u'.

From these three sets of data, the turbulent kinetic energy $k^+(=(u'^2+v'^2+w'^2)/2u^{*2})$ is deduced (Fig. 7): for each case, close to the wall, the curves obtained for v' and w' have been extrapolated, which is justified since these quantities are much smaller than u'. results relative to the smooth plate are very similar, especially very close to the wall, to those obtained from Karlsson et al.'s (1991) measurements and from Kim et al.'s (1987) numerical simulations. As regards the riblet wall, k^+ exhibits trends similar to those of u'^{+2}: with respect to the smooth wall, one observes a significant enhancement above the crest and a large damping above the valley.

However, despite the previously observed large variations of the mean velocities U and standard deviations u', it is interesting to note (Fig. 8) that the corresponding turbulence intensity profiles determined over the peak and over the trough are almost the same as the smooth wall one. VWB's data are in general quite good agreement with ours, except for those obtained within the valley since our results suggest an increase of turbulence intensities in this region whereas VWB's ones reveal a tremendous reduction. It is also worth noticing that experiments are in remarkable good agreement as regards the trend over the crest, where turbulence intensities are obviously smaller than those over the smooth plate in spite of the significant enhancement of both U and u' (Figs. 3 and 4). A similar behaviour (not presented here) is obtained for v'/U and w'/U.

Skewness factors of u fluctuations have also been obtained from these data and their distributions are plotted on figure 9; comparison with VWB is also provided. For the smooth plate, our results are in very good agreement with Kim et al.'s (1987) profile. On the contrary, VWB's data are significantly overestimated in the wall vicinity, probably due to wall proximity effects, and do not become negative as they should for larger y^+ values, for unexplained reasons. For the riblet wall, present measurements indicate slight reductions in the crest vicinity and larger ones further away from it. Similarily, over the valley, there is an obvious reduction if one considers the shift of origin with respect to the crest plane; unfortunately, these quantities could not be determined within the groove. These observations suggest that the bursting process is only slightly affected by riblets, which is in good agreement with usual observations (e.g. Choi, 1989; Tardu, 1991).

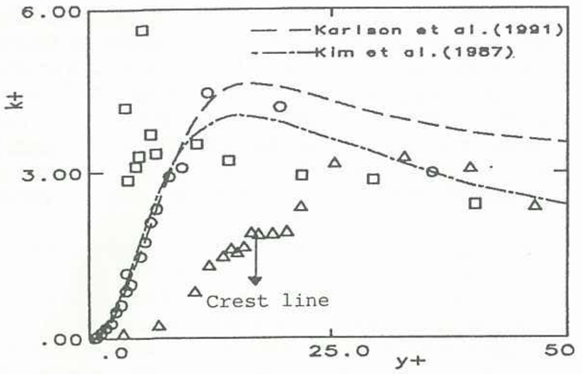

Fig. 7 Distributions of turbulent kinetic energy (cf.Fig.3).

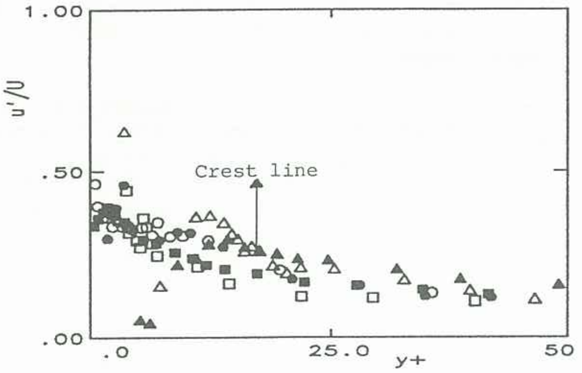

Fig.8 Streamwise velocity turbulence intensities (cf.Fig.3).

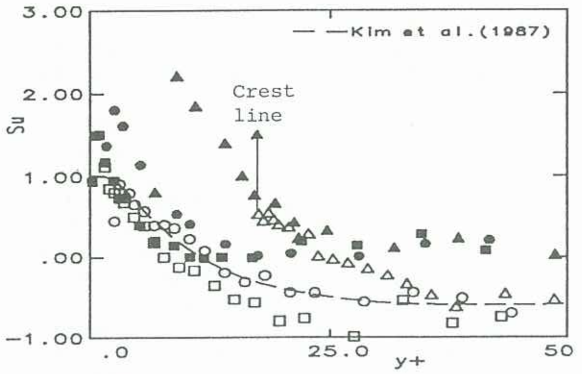

Fig. 9 Longitudinal velocity skewness factors (cf.Fig. 3).

CONCLUSION

The effects of the riblet surface on the mean and fluctuating velocity field are clearly exhibited in the data shown earlier. Despite the quite specific conditions of these experiments -low Reynolds number turbulent boundary layer tripped by large roughness elements-, there is sufficient evidence supporting the relevance of these unique data for a better understanding of the intricate mechanism involved in drag reduction and for their help in the development of efficient engineering models. These results support the concept of flow stabilisation by riblets and strengthen the argument relative to the important role of viscous effects in drag reduction.

ACKNOWLEDGEMENTS

This work is supported under a "Service Technique des Programmes Aéronautiques" grant. We are grateful to M. Astier for his technical assistance, to E. Mérigaud for his help in some of the measurements and to Drs J. Cousteix and E. Coustols (ONERA-CERT) for discussions.

REFERENCES

ANTONIA, R.A., FULACHIER, L., KRISHNAMOORTHY, L.V., BENABID, T. and ANSELMET, F. (1988) Influence of wall suction on the organized motion in a turbulent boundary layer. J. Fluid Mech., 190, 217-240.

BECHERT, D.W., HOPPE, G., VAN DER HOEVEN, J.G. and MAKRIS, R. (1992) The Berlin oil channel for drag reduction research. Expts.in Fluids,12,251-260.

CHOI, K.S. (1989) Near-wall structure of a turbulent boundary layer with riblets. J. Fluid Mech., 208, 417-458.

CLARK, D.G. (1990) Boundary layer flow visualization patterns on a riblet surface. In Turb. Control by Pass. Means, ed. Coustols, E., Kluwer Acad. Press, 79-96.

COUSTOLS, E. and SAVILL, A.M. (1992) Turbulent skin friction drag reduction by active and passive means. In AGARD-VKI Special course on skin friction drag reduction , Brussels (also in AGARD Report N°786).

DJENIDI, L., LIANDRAT, J., ANSELMET, F. and FULACHIER, L. (1989) Viscous effects in drag reduction over riblets. In Drag Red. in Fluid Flows, eds. Sellin, R.H.J., Moses, R.T., Ellis Horwood, 35-41.

HOOSHMAND, D., YOUNGS, R., WALLACE, J.M. and BALINT, J.L. (1983) An experimental study of changes in the structure of a turbulent boundary layer due to sur-face geometry changes. AIAA Paper n° 83-0230, 1-10.

KARLSSON, R.I., TINOCO, H. and SVENSON, U. (1991) An improved form of the near-wall k-ε model based on new experimental data. In Proc. T.S.F. VIII Munich, 26.3.1-26.3.5.

KIM, J., MOIN, P. and MOSER, R. (1987) Turbulence statistics in fully developed channel flow at low Reynolds number, J. Fluid Mech., 177, 133-166.

KREPLIN, H. and ECKELMANN, H. (1979) Behaviour of the three fluctuating velocity components in the wall region of a turbulent boundary layer, Physics of Fluids, 22,1233-1239.

LAUNDER, B.E. and LI, S.P. (1992) on the prediction of riblet performance with engineering turbulence models, TDF/92/9, UMIST, Manchester.

LIANDRAT, J., COUSTOLS, E., DJENIDI, L., ANSELMET, F., de SAINT-VICTOR, X., FIOC, F. and FULACHIER, L. (1990) Effect of riblets on either fully developed boundary layers or internal flows in laminar regime. In Turb. Control by Pass. Means, ed. Coustols, E., Kluwer Acad. Press., 141-157.

PULLES, C.J.A., PRASAD, K.K. and NIEUWSTADT, F.T.M. (1990) Simultaneous flow visualisation and LDA studies over longitudinal micro-grooved surfaces, In Turb. Control by Pass. Means, ed. Coustols, E., Kluwer Acad. Press, 97-108.

ROBERT, J.P. (1992) Drag reduction: an industrial challenge. In AGARD-VKI Special course on skin friction drag reduction, Brussels (also in AGARD Report N°786)

TARDU, S. (1991) Investigation of the structure of the turbulence in an internal flow manipulated by riblets, Report IMHEFT-91-19, EPFL, Lausanne.

TULLIS, S. and POLLARD, A. (1992) Modelling the time dependent flow over riblets in the viscous wall region. To appear in Proc. 6th European Drag Red. Meeting, Applied Scient. Res.

VUKOSLAVCEVIC, P., WALLACE, J.M. and BALINT, J.L. (1992) Viscous drag reduction using streamwise aligned riblets, AIAA Journal, 30, 1119-1122.