ICAS-98-3,1,2

DPIV ANALYSIS OF WALL TURBULENT SHEAR FLOWS

Marco Gottero, Michele Onorato
Dipartimento di Ingegneria Aerospaziale, Politecnico di Torino, Italy

Abstract

The results of the DPIV analysis of the inner layer of a flat plate turbulent boundary layer, at $Re_\theta=1010$, in planes parallel to the wall, is presented.

The streaky structure of the flow in the buffer layer is quantitatively examined. Two-dimensional Fourier analysis shows that in the buffer layer the most energetic spanwise mode occurs at the scale $\lambda^+=250$, in spite of the fact that a mean streak spacing of about $\lambda^+=100$ is visually observed.

VISA technique is used to detect internal shear layers. The spatial relationship between the low speed streaks and internal shear layer motions is apparent in the DPIV data from planes parallel to the wall. An attempt at interpretation of the present results in the light of trains of quasi-longitudinal vortices populating the buffer layer region is given.

Introduction

After decades of research the structure of turbulent boundary layer is still only partially understood. The experimental research as been limited by the fact that only one or a small number of fixed probes are not adequate to observe the characteristics of three-dimensional turbulent structures with large variations in space and time. While the numerical simulation is limited to simple geometry and low Reynolds number flows.

Contributions to the understanding of wall turbulence have been made by the simultaneous use of flow visualisation and probe arrays. Various non random events (organised motions, coherent structures) have been identified as wall low-speed streaks, internal wall shear layers, vortical structures, ejections and sweeps. An important part of experimental investigation into organised motions deals with the detection methods and hence with the frequency of occurrence and with conditional analysis of the part of the signal corresponding to the event (1)-(10). Recent analyses of databases from turbulence numerical simulation are giving important new insights into the spatial and temporal character of the organised motions, their spatial relationships and their generation and evolution (11)-(14). Advanced experimental methods, that can be applied to complex flows, are now becoming available, most of them are based on optical anemometry techniques. Utilising these new techniques in experimental fluid-dynamics, a method for quantitative flow visualisation, suitable for turbulence investigation, has been developed at the *Laboratorio di Anemometria Ottica* of the *Centro di Studio per la Dinamica dei Fluidi (CNR), Politecnico di Torino*.

In this paper some results relating to the application of the technique to the canonical flow in the inner layer of a turbulent boundary layer over a flat plate will be shown. The main objective of the study was to contribute to the understanding of the spatial relationship between low speed streaks and internal shear layer motions.

Experimental set-up and procedure

Experiments were carried out in the "Hydra" water tunnel. This facility is a closed loop, open flow channel, with a 350x500x1800 mm^3 test section. Measurements were performed using a flat plate positioned in the test chamber, with transition to turbulence fixed at the leading edge. The observed section is characterised by $Re_x=4\ 10^5$, $Re_\theta=1010$ and $u_\tau/u_e=0.046$. The flow is seeded with spherical solid particles with a nominal diameter of 2μm. A double pulsed light sheet was provided by a Nd-YAG laser source (200mj and 8ns per pulse). Frozen images of the seeded flow in the illuminated plane are captured on a high resolution photographic 24x36 mm^2 film or with a digital CCD video camera, with a resolution of 800 by 600 pixels. The spatial accuracy and resolution required when analysing turbulent flows has been verified for both techniques (15). The image analysis algorithms used were based on a two-dimensional digital particle image velocimetry technique, DPIV (16).

Results and discussion

To demonstrate the accuracy of the experimental technique, a time statistic analysis of the flow was carried out on series of more than 500 video-camera images in the illuminated plane (x,y), normal to the wall, parallel to the mean flow and located at the centreline of the plate. The mean longitudinal velocity U, as a function of the distance from the wall, y, shown in Fig.1, is compared with the law of the wall. Variables are normalised using wall viscous units, the friction velocity $u_\tau=(\tau_w/\rho)^{1/2}$ and the wall characteristic viscous length ν/u_τ; τ_w is the wall shear stress, ρ is the fluid density and ν is the kinematic coefficient of viscosity of the fluid.

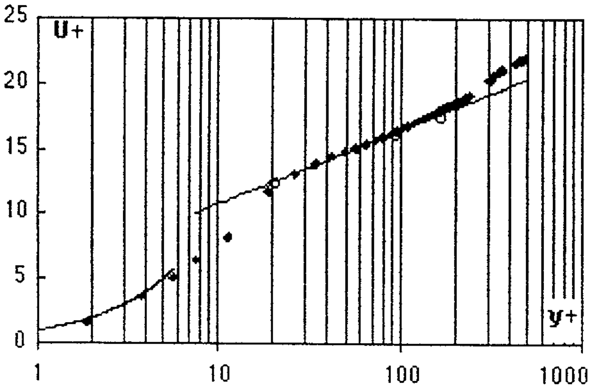

FIGURE 1 - Law of the wall.

The profiles of rms longitudinal and normal to the wall components of the fluctuating velocity, u'/Ue and v'/Ue, are shown in Fig.2; Ue is the external flow velocity. The two figures demonstrate the potential of the present experimental technique to accurately measure mean and fluctuating velocities very near the wall, in the viscous layer, down to $y^+=2$. Values and positions of the peaks in the fluctuating velocity profiles are in good agreement with the LDA data of Wei and Willmarth (17).

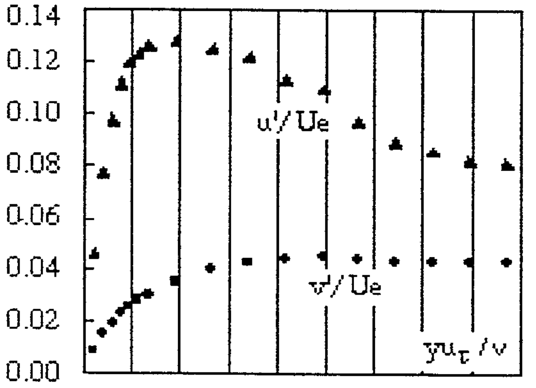

FIGURE 2 - Turbulent velocity profiles.

In the following, results from photographic frozen velocity fields in planes (x,z) parallel to the wall are discussed. In Fig.3 a grey-level map of the instant longitudinal fluctuating velocity u, in a plane (x,z) at a distance from the plate of 20 wall viscous length, $y^+=20$, is shown. The dimensions of the observed flow field are 700 viscous units in the longitudinal direction, $\Delta x^+=700$, and 1050 viscous units in the transversal direction, $\Delta z^+=1050$. Superimposed on the map are contour lines showing where the local averaged variance of u exceeds the mean variance. As expected in the buffer-layer region, quasi-streamwise low speed streaks characterise the flow. The streamwise extent and spanwise spacing of the streaks have been the subject of several investigations, both experimental and numerical (18)-(20). Several authors report estimations of streamwise scales varying from 500 to more than 1000 wall units and a mean spanwise spacing of about 100 viscous units, $\lambda^+=100$, in the buffer layer. This is confirmed by the present DPIV results. In the logarithmic region, at a larger distance from the wall, the streak streamwise length decreases and the mean spanwise spacing increases. Values of λ^+ have generally been obtained by visual inspection of flow visualisations or of numerically simulated data. An objective criterion to define appropriate lenghtscales is based on the evaluation of the energetic content of each scale determined using spectral analysis. DPIV data allows quantitative evaluation of the spanwise modes of the streaky motions by two-dimensional Fourier analysis. In Fig.4 the Fourier spectrum obtained by averaging 15 realisations, similar to that in Fig.3, is displayed. S_{uu} is the two-dimensional power spectrum of the u-velocity component normalised with respect to the u-variance; k_z^+ and k_x^+ are the transversal and longitudinal wave numbers. The power spectrum, S_{uu}, is multiplied by the spanwise wave number, indicating the energy of modes, centred on k_z^+, corresponding to a wave number of bandwidth k_z^+. Fig.4 reveals that the most energetic spanwise mode occurs at $k_z^+=2.5\ 10^{-2}$, relating to the scale $\lambda^+=250$, and not to the $\lambda^+=100$ mode, as observed in the visual examinations of the flow. This is in agreement with the results of similar analysis (20) in a turbulent channel flow.

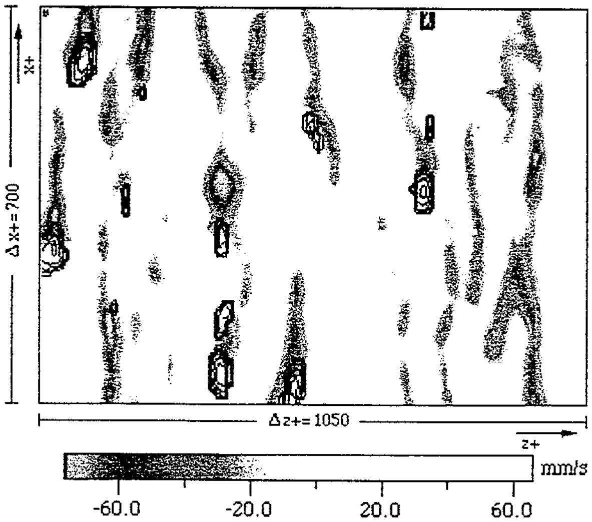

FIGURE 3 - Instant u-velocity map and VISA events. $y^+=20$.

Back to Fig.3, the local averaged u-variance contour lines exceeding the mean variance represent "VISA (Variable Interval Space Average) events". The VISA technique (11),(21) is the spatial counterpart of VITA (Variable Interval Time Average) technique, extensively used to detect internal shear layer motions. The local variance was averaged over a *short* distance in the streamwise direction of 115 viscous units. This length, assuming a propagation velocity of the shear layers of 10.6 u_τ (11), corresponds to a *short* averaging time of 10 viscous units. This averaging time, $T^+=10$, has been used in most studies to detect VITA events from hot wire probe signals. In order to compare the present DPIV experiments with fixed probe results, the number of events per unit time has been deduced from 15 realisations as shown in Fig.3. A non-dimensional frequency $f^+=f\nu/u_\tau^2$ of 3.2 10^{-3} has been found, in agreement with hot wire data (4). No distinction has been made between accelerated (du/dt>0 or du/dx<0) and decelerated (du/dt<0 or du/dx>0) events.

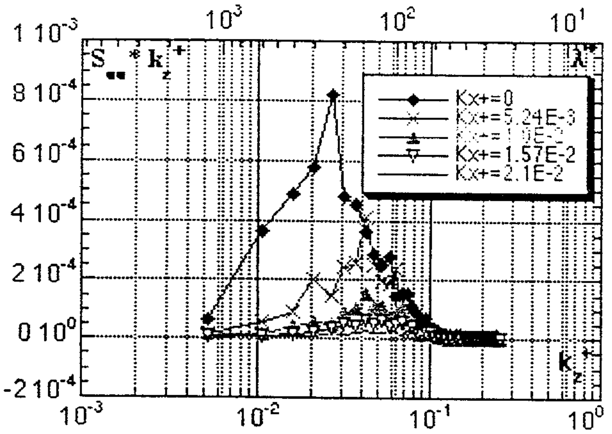

FIGURE 4 - Fourier spectrum. $y^+=20$

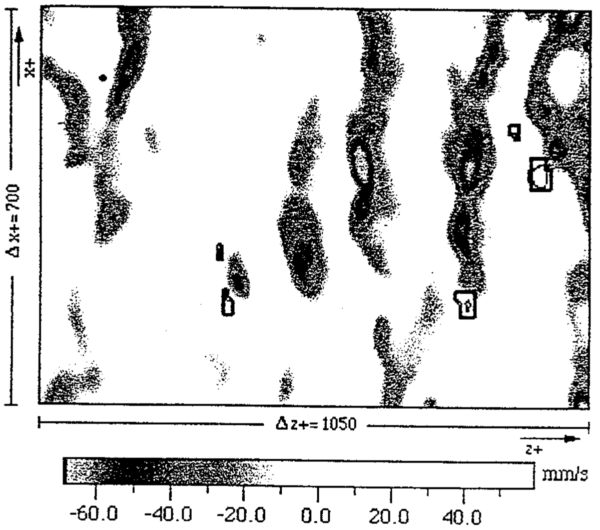

FIGURE 5 - Instant u-velocity map and VISA events. $y^+=70$.

Representations of the flow field as in Fig.3 are suitable to allow the study of the spatial relationship between low speed streaks and internal shear-layer motions. High levels of local variance are found in the vicinity of the upstream (du/dx<0) or downstream (du/dx>0) ends of the streaks; but the strongest events, always with du/dx<0, are seen adjacent to the streaks, near the upstream end of the region where the streak seems to divide or to change the tilting direction. The characteristics of the streaks, to appear as segmented shorter elements tilted alternatively in opposite directions with respect to the mean flow, seems to be essential in the production of strong internal shear layers. The fact that the strong internal shear layers are found at the junction region of two adjacent asymmetrically tilted segments of a low speed streak suggests the following physical scenario. A low speed streak, composed of asymmetrically tilted segments, is the footprint of a train of likewise asymmetrically tilted quasi-longitudinal vortices of alternating sign. The organisation of the flow into low (and high) speed streaks comes from the velocity induced by the vortices away from (and towards) the wall and the strong shear layers are produced by the motions of opposite sign induced by two counter-rotating vortices in the junction region. This scenario is consistent with the conceptual model of the dynamics of coherent structures in reference (14).

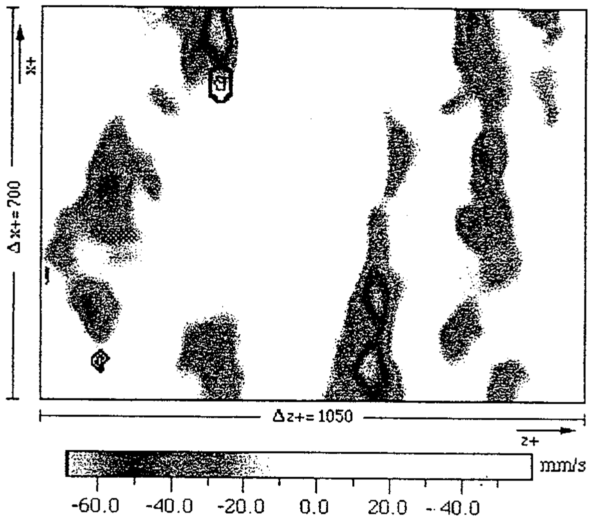

FIGURE 6 - Instant u-velocity map and VISA events. $y^+=130$.

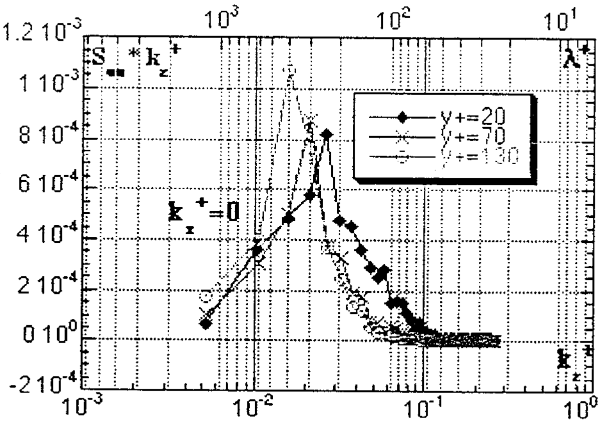

FIGURE 7 - Fourier spectra. $y^+=20, 70, 130$

In Figs.5 and 6 maps of the instant longitudinal fluctuating velocity, in planes (x,z), at a distance from the plate of 70 and 130 viscous lengths respectively, are shown. As already found (19),(20) in the logarithmic layer, increasing the distance from the wall, the streak spanwise spacing increases and the streamwise scale decreases. At larger distances from the wall the streaks are hard to locate. This result is consistent with the given scenario, the population of the quasi- longitudinal vortices being resident in the near wall region, below y^+=60 (14).

Finally in Fig.7 power spectra are shown for the three planes, for $k_x{}^+$=0. This quantitatively confirms the increasing of the spanwise scales in the logarithmic region. The most energetic modes occur with scales of λ^+=370 and λ^+=490 respectively for y^+=70 and y^+=130.

Conclusions

Results of measurements in the inner layer of a turbulent boundary layer on a flat plate have been shown.

A DPIV technique has been used to quantitatively observe the flow in planes parallel to the wall, demonstrating that the technique is suitable for the study of wall turbulent flows.

The flow field in the buffer layer appears to be characterised by low speed streaks, having a streamwise extent and a spanwise spacing in agreement with previous investigations. Fourier analysis of the DPIV data has permitted quantitative evaluation of the spanwise modes of the streaky structures; it has been found that the most energetic spanwise modes occurs at scales higher than those apparent from visual examination of the streak patterns. Such scales increase in the logarithmic region at larger distance from the wall.

The spatial relationship between low speed streaks and internal shear layer motions has been analysed by observing frozen flow field images from the (x,z) plane. The segmented nature of the low speed streaks has been recognised as important for the existence of strong accelerated internal shear layers. The results are consistent with the conceptual model of the dynamics of coherent structures in reference (14).

Acknowledgements

The authors are grateful to Mr Gaetano Di Cicca and Mr Carmelo Cannì for the great help given in collecting the data. This research is in part sponsored by the M.U.R.S.T. and in part by the C.N.R..

References

(1) Lu, S.S., Willmart, W.W. 1973 Measurements of the structure of the Reynolds stress in a turbulent boundary layer. *J. Fluid Mech..* 60, 481.

(2) Blackwelder, R. F., Kaplan, R. E. 1976 On the wall structure of turbulent boundary layer. *J. Fluid Mech..* 76, 89.

(3) Johansson, A.V., Alfredsson, P.H. 1982 On the structure of turbulent channel flow. *J. Fluid Mech..* 122, 295

(4) Blackwelder, R. F., Haritonidis, J.H. 1983 Scaling of the bursting frequency in turbulent boundary layers. *J. Fluid Mech..* 132, 87.

(5) Alfredsson, P.H., Johansson, A.V. 1984 On the detection of turbulence-generating events. *J. Fluid Mech..* 139, 325.

(6) Bogard, D.G., Tiederman, W.G. 1986 Burst detection with single point velocity measurements. *J. Fluid Mech..* 162, 389.

(7) Luchik, T.S., Tiederman, W.G. 1987 Time scale and structure of ejections and bursts in turbulent channel flows. *J. Fluid Mech..* 174, 529.

(8) Bogard, D.G., Tiederman, W.G. 1987 Characteristics of ejections in turbulent channel flow. *J. Fluid Mech..* 179,1.

(9) Robinson, S.K. 1991 Coherent motions in the turbulent boundary layer. *Annu. Rev. Fluid Mech.* 23, 601.

(10) Lu, L.J., Smith, C.R. 1991 Use of flow visualization data to examine spatial-temporal velocity and burst-type characteristics in a turbulent boundary layer. *J. Fluid Mech..* 232, 303.

(11) Johansson, A.V., Alfredsson, P.H., Kim, J. 1991 Evolution and dynamics of shear-layer structures in near-wall turbulence, *J. Fluid Mech.* 224, 579.

(12) Bernard, P.S., Thomas, J.M., Handler, R.A. 1993 Vortex dynamics and production of Reynolds stress, *J. Fluid Mech.* 253, 385.

(13) Blackburn, H.M., Mansour, N.N., Cantwell, B.J. 1996 Topology of fine-scale motions in turbulent channel flow, *J. Fluid Mech.* 310, 269.

(14) Jeong, J., Hussain, F., Schoppa, W., Kim, J. 1997 Coherent structures near the wall in a turbulent channel flow, *J. Fluid Mech.* 332, 185.

(15) Gottero, M. 1997 Sviluppo di un sistema di visualizzazione quantitativa per l'indagine sperimentale di flussi turbolenti, *tesi di dottorato, DIASP Politecnico di Torino.*

(16) Willert, C.E., Gharib, M. 1991 Digital particle image velocimetry, *Exp. in Fluids* 10.

(17) Wei, T., Willmart, W.W. 1989 Reynolds-number effects on the structure of a turbulent channel flow, *J. Fluid Mech.* 204, 57.

(18) Kline, S.J., Reynolds, W.C., Schraub, F.A., Runstadler, P.W. 1967 The structure of turbulent boundary layers, *J. Fluid Mech.* 30, 741.

(19) Smith, C.R., Metzler, S.P. 1983 The characteristics of low-speed streaks in the near-wall region of turbulent boundary layer, *J. Fluid Mech.* 129, 27.

(20) Liu, Z.C., Adrian, R.J., Hanratty, T.J. 1996 A study of streaky structures in a turbulent channel flow with particle image velocimetry, *Int. Symp. on the application of laser technology to fluid mechanics*, Lisbon.

(21) Kim, J. 1985 Turbulence structures associated with bursting events, *Phys. Fluids* 28, 52.