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EXTENSION OF PATTERN RECOGNITION ANALYSIS TECHNIQUES TO DISTORTED AND MANIPULATED FLOWS

A.M. SAVILL[1] and J.A. FERRE[2]

[1]Engineering Department, University of Cambridge
Cambridge CB2 1PZ, ENGLAND

2Department d'Enginyeria Quimica i Bioquimica
Diviso VII, Universitat de Barcelona, 43005, Tarragona, Catalunya, SPAIN

ABSTRACT

Pattern recognition techniques for the analysis of multi-point hot-wire anemometry data, previously tested only on plane wake and jet flows, have now been applied to a highly curved wake and to both plane and manipulated boundary layers. The results compliment and extend earlier single and two-point measurements for such fully developed flows.

INTRODUCTION AND EXPERIMENTAL ARRANGEMENTS

The present work makes use of a Pattern Recognition Analysis (PRA) routine developed as part of a continuing collaboration between groups at the Universities of Barcelona and Cambridge. This combines the best features of the techniques developed at Cambridge; originally by Savill (1979), on the basis of earlier pattern detection work by Townsend (1979), but later greatly refined by Mumford (1982,1983); and the more advanced computational procedures, based on this approach, which have been developed in Tarragona by Ferre & Giralt (1989a,b). The resulting PRA code, with the addition of a new fine-scale intermittency detector, has already been used by Ferre, Mumford, Savill & Giralt (1989) to deduce the full three-dimensional large-eddy structure of a plane wake, and its relation to smaller scales, solely from multi-point experimental data on streamwise velocity (u') and temperature fluctuations.

Both the present wake and boundary layer experiments have been described in detail previously by Savill (1979,1982), and by Savill & Mumford (1988) respectively. In each case streamwise velocity fluctuations were sampled simultaneously by a rake of eight u-wires aligned perpendicular to the flow direction, either across the whole width of the flow (δ) in the shear (xy-plane), or at various vertical positions (at the two maximum shear stress positions in the case of the wake or at intervals of 0.125δ from the wall in the boundary layer) in the spanwise (xz-plane). The curved wake data was recorded at a position 200 diameters (d) downstream of the circular, generating cylinder; by which point the flow had turned through 30°, the shear stress ($\overline{uv}$) had collapsed in the stablised half of the wake, and the unstable side was starting to dominate the whole flow. This was compared with results previously obtained 178d downstream in the equivalent plane flow (Red=6500). The boundary layer data was sampled x=1.6m downstream of the initial trip (Rex=1.3×10^6) and at locations ξ =x/d=4.5, 17.5 & 33.5δ behind a single flat plate manipulator of thickness t=1mm=0.025δ, and length l=1.8δ, mounted at h=0.5δ; close to the optimum for a single device the Reθ=3500 of the experiments.

All of the analysis was performed on the University IBM 3083/4 using continuous records, of 64s (wake) or 128s (boundary layer) length, sampled at 1KHz. The results are presented as iso-level contours of u' fluctuations at ±10%,25%,50% and 75% of the peak signal intensity (only those which were statistically significant are shown solid) in either the xy or xz plane; both axes being normalised (by Lo: the velocity half-width of the wake or the boundary layer integral scale respectively), and the x-ordinate being determined from the product of the convection velocity (at y=Lo in the wake or in the outer region of the boundary layer) with time, T. The appearance of ten rather than eight cross-stream locations results from allowance for a degree of transverse re-alignment.

PATTERN RECOGNITION ANALYSIS

Curved Wake

Stable side: Initial analysis of xz-plane data, using a test pattern typical of the double-roller circulation found at the maximum shear stress location in the plane wake (Fig.1), extracted a weaker structure more similar to that found at the centre-line of the latter (Fig.2). However subsequent trials with a single-roller template revealed little evidence for this weak double-roller organisation. Instead the iterating pattern retained a compact single eddy structure as illustrated by Fig.3, with approximately 500 such patterns being recorded in each sample of data (as compared to ~300 double-roller patterns detected in similar data sets taken from the plane wake). This indicated that the flow was predominantly composed of single rather than double rollers; detection of approximately equal numbers of opposite sign circulation eddies accounting for the pattern shown in Fig.2. As a check an alternative type of trial pattern, consisting simply of a localised velocity 'front' (fast-to-slow or slow-to-fast) was introduced. This generated a pattern indicative of two contra-rotating single rollers following one another in the stream-direction. Further iteration with trial patterns representative of this arrangement and its double-roller equivalent, also produced a compact single streamwise pair pattern(Fig.4), with either rotational sense, and in each case the number of detected patterns rose to ~750 so it would appear this was the prefered configuration. A further test using just an isolated positive velocity region as initial trial resulted in the detection of a single weak negative cross-stream correlation, again indicative of only single rollers, but this was accompanied by a more intense localised positive excess. Subsequent analysis of the xy-plane data using the same positive peak pattern, centred on the stable side of the flow, revealed (Fig.5) that such high-speed regions (which occured at least twice as frequently as any low-speed counterparts, with up to 800 detected in each data set) were associated with a localised cross-flow from the unstable side of the flow; where the convection velocity (Uc) was higher due to an additional acceleration introduced by the

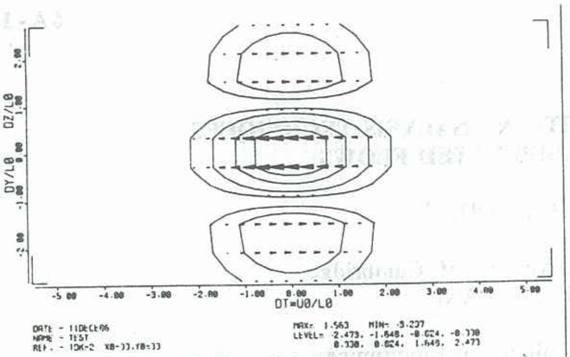


Figure 1 Double-Roller Trial Pattern

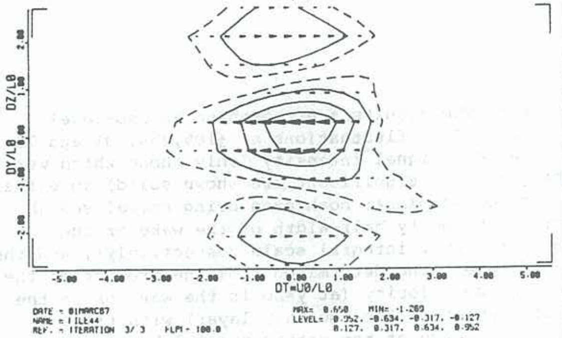


Figure 2 Extracted Pattern in Stable Side

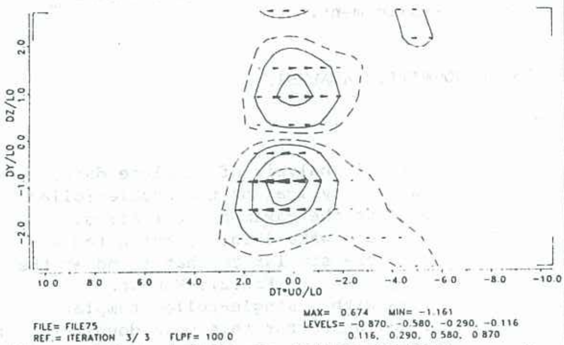


Figure 3 Detected Single-Roller Pattern

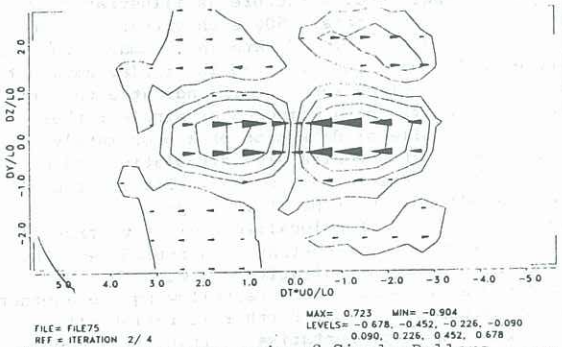


Figure 4 Streamwise pair of Single-Rollers

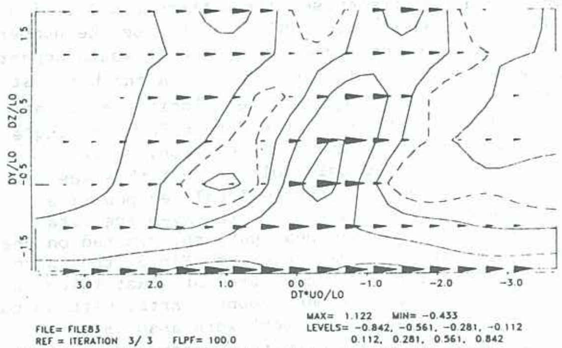


Figure 5 Inter-penetrating flow in xy plane

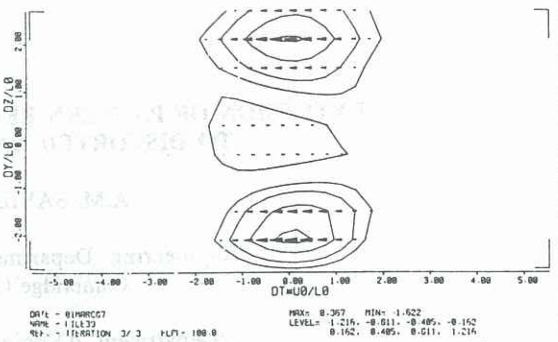


Figure 6 Extracted Pattern on Unstable Side

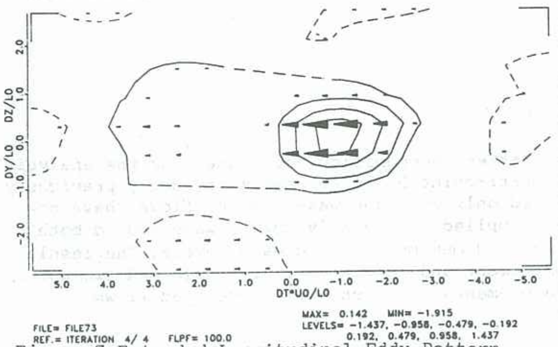


Figure 7 Extended Longitudinal Eddy Pattern

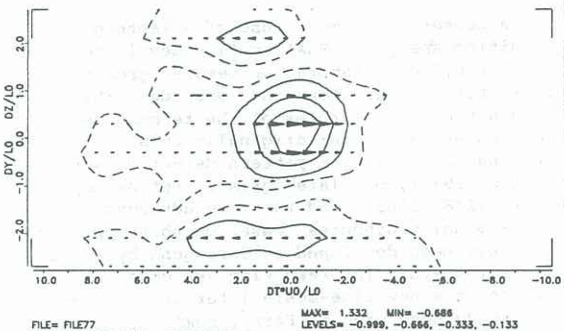


Figure 8 Weaker Double/Single Roller Pattern

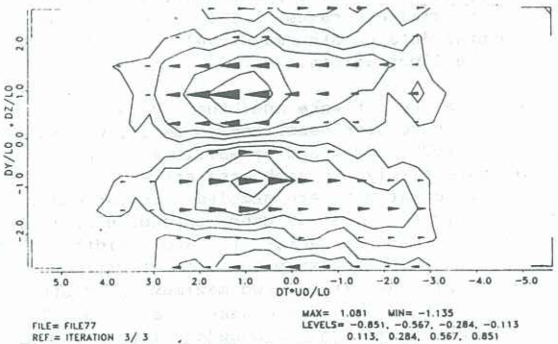


Figure 9 Extended Single-Roller Pattern

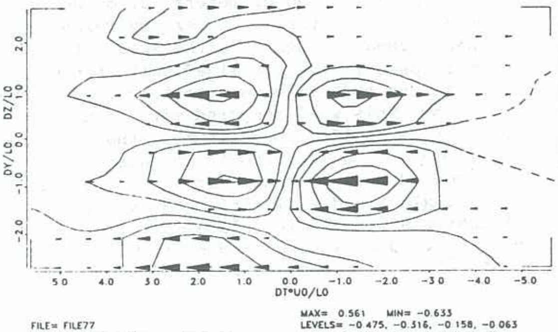


Figure 10 Triple-Roller Organisation

experimental set-up.

Unstable side: Here the initial double-roller template generated a pattern dominated by the two positive lobes only (Fig.6). Such positive cross-stream correlation has previously been attributed (Savill 1982) to the presence of longitudinal eddies, with circulation predominantly in the yz-plane, masking the normal xz-plane roller circulation. Separate trials with 'front' templates extracted a pattern consisting just of an extended velocity excess, or defect (Fig.7), again indicative of turbulent longitudinal vortices not evident from earlier mean flow or single point turbulence data. In both cases the contributing structures were detected with a frequency of occurence approximately twice that of the double-roller eddies found in the plane wake. Tests using a compact isolated low-speed region template also selected out a rather broader pattern, and re-analysis of the xy-plane data, with a similar negative velocity region template centred in the unstable half of the flow, produced essentially the same 'fingering' pattern as Fig.4, but showed that the 'return flow' from the stable side (lower Uc) was weaker, more diffuse, and occured less frequently.

Centre-line: Here the initial double-roller trial pattern extracted an apparently stronger, double structure. However using a local excess velocity template produced a far weaker double-roller pattern (Fig.8). A pattern of similar form, but greatly extended in the stream direction was obtained with a single-roller eddy as trial (see Fig.9) suggesting that such structures are either more highly sheared or tend to follow one another closely in this region. Despite the strong influence of the unstable side, the flow structure on the centre-line was therefore more similar to that in the stable side and not greatly altered from that found at the centre-line of a plane wake, being composed of both single and paired rollers. Further PRA to investigate the longer-range ordering of the rollers revealed that a template representing a counter-rotating streamwise pair extracted a more complex triple-roller organisation from the data (Fig.10), similar to the arrangement detected in a plane jet, while tests with fronts as trial patterns resulted in an alternative three-eddy grouping consisting of a single-roller ahead of a double-roller. In each case up to 750 such patterns were detected per data set compared to only ~250 single or double rollers. It would thus appear that the flow structure at this position in the flow was made up of groups of two or three roller eddies with different senses of rotation and a degree of order intermediate beween that of the stable part of the curved wake and the plane wake, where the double-rollers occur in close streamwise-aligned groups of 3-5 such structures.

Plane Boundary Layer

Simple single-roller and velocity-front trial patterns (see insets to Fig.11 & 12) proved sufficient to analyse the most significant details of the flow structure. Indeed, within only one iteration, a template of the latter type centred within the flow extracted the extended, inclined, shear plane correlation typical of hairpin eddy structure (Fig.11). Locating the front at the outer edge of the flow picked out this inclined correlation, spreading towards the wall, equally rapidly and also identified an associated entrainment circulation; indicating that the latter was positively correlated with the near wall region. When the analysis was repeated using a single positive circulation pattern as template the same roller and entraining motion flow patterns were again extracted together, although the apparent correlation with wall-events was weaker. In each case approximately 1800 patterns were detected from the longer data records, a frequency of occurence at least twice that of the double-roller eddies found in the far wake (which occupy ~40% of the flow and contain ~40% of the turbulence energy), indicating that such structures completely dominate the boundary layer. Applying PRA to the xz-plane data (see Figs.12-14) using the same single eddy template resulted in the detection at the centre of the layer of a flow pattern similar to that associated with the wake double-roller stucture, but again twice as frequent and rather more extended into the stream-direction, with an extra positive spanwise lobe (Fig.13). This suggested that in comparison to the wake the flow was composed of approximately equal numbers of more-highly sheared eddies with opposite senses of rotation; although these might be either symmetric pairs of vortices (other data suggests that such paired double-roller structures as do exist in the flow are linked at their tops to form a closed-loop hairpin or horse-shoe vortices as found also in the wake by Ferre et al.(1989)) or assymetric single vortices. However a similar test analysis of the outer part of the flow ($y=0.875\delta$) showed only weak evidence for any double-roller organisation (Fig.12), indicating instead that the structure there was composed predominantly of single roller structures (again 1800 being detected per data set), while in the inner region ($y=0.125\delta$) the extracted flow pattern (Fig.14) was stronger, more symmetric, and elongated in the stream direction; reflecting a larger contribution from rather more highly sheared vortex loops, with both sense of rotation, and perhaps also the influence of streaky structure of a similar transverse scale. The PRA thus suggested that few of the hairpin loops (either positive or negative) seen near the wall remained intact further out in the flow, with the result that the outer layer was predominantly composed of asymmetric isolated hairpin legs, normally with attached 'heads'; a conclusion supported by the recent Stanford assessment of NASA Ames Direct Numerical Simulation data bases, conducted by Robinson, Kline & Spalart (1988).

Manipulated Layer

Immediately behind device ($\xi=4.5\delta$): PRA was first conducted of the xy-plane data with a front template. Positioning this in the centre-of the flow generated the pattern shown in Fig.15 where the location of the manipulator plate is indicated by the solid line. Several features are evident: the inclined correlation typical of the plane boundary layer can be seen extending both above and below the level of the plate; but above the structure is more sheared over and below the negative boundary layer structure correlation is cut, presumably by opposite sign and inclination corelation associated with the lower-wake roller structure (since plane wake roller eddies are typically positively correlated across the centre-line); and superimposed on this is the influence of the xy-plane circulation associated with the upper wake entrainimg motions (more clearly seen using a template representing such circulation). Using a front template located either close to the wall or in the outermost region extracted similar details to those seen in the plane layer occuring as frequently, but the inclined contours reprenting the remaining boundary layer eddies were cut off at the manipulator height and there was little evidence of any correlation between entrainment and wall events. The subsequent analysis of xz-plane data taken directly in the wake of the manipulator, using a single eddy template, detected a compact double-roller pattern typical of a wake, (although more frequent due to the proximity of the generating manipulator) jitter explaining the wider spread of the less significant contours on (Fig.16). By comparison similar analysis of data recorded in the inner and outermost regions produced patterns very similar to those found at the same locations in the un-manipulated flow showing that the immediate

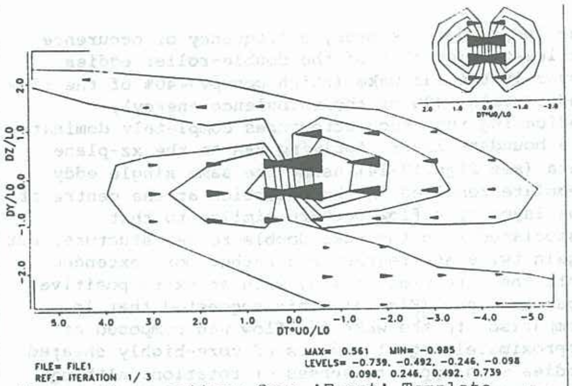


Figure 11 xy pattern from 'Front' Template

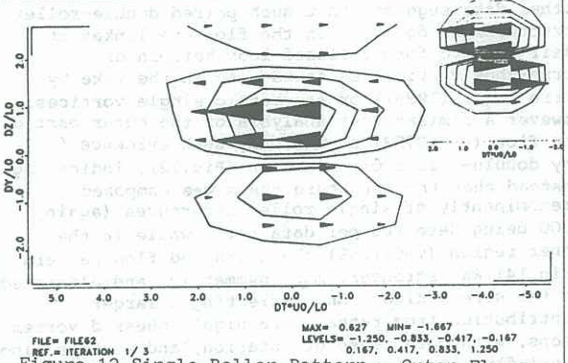


Figure 12 Single-Roller Pattern - Outer Flow

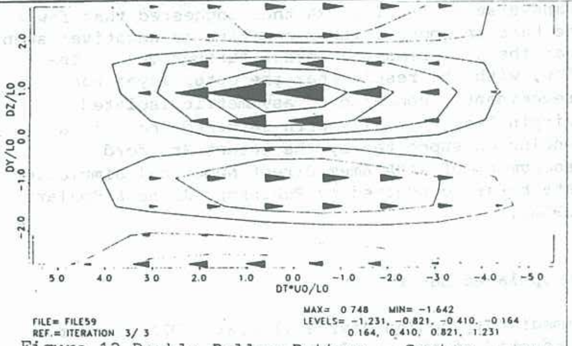


Figure 13 Double-Roller Pattern - Centre

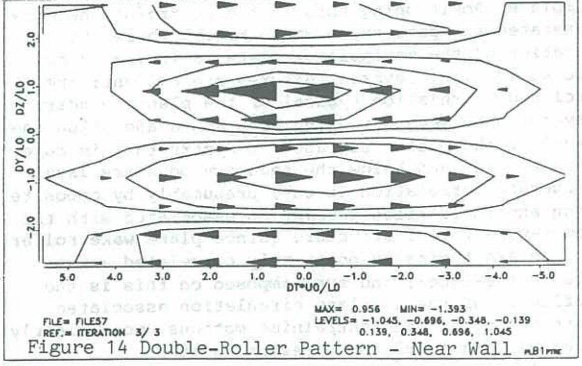


Figure 14 Double-Roller Pattern - Near Wall

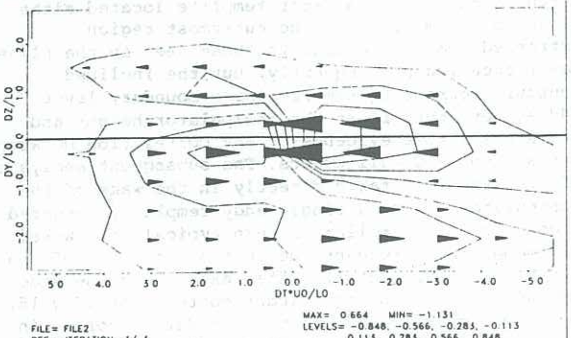


Figure 15 xy pattern - Manipulated Layer

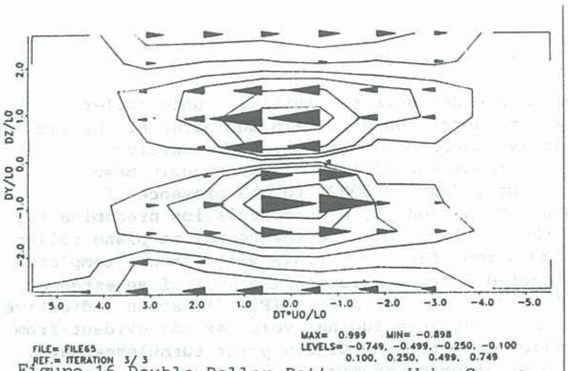


Figure 16 Double-Roller Pattern on Wake C_L

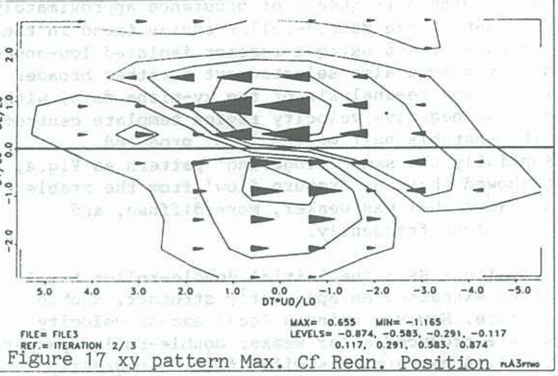
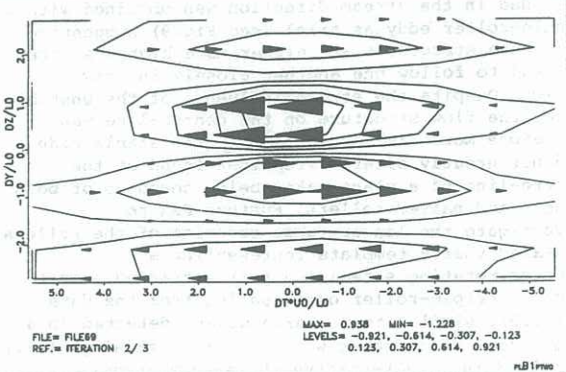


Figure 17 xy pattern Max. Cf Redn. Position



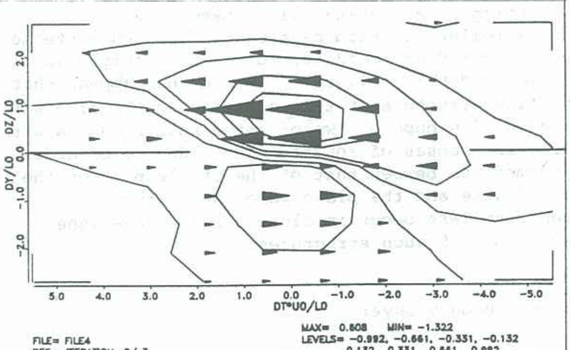


Figure 19 xy pattern in Recovery Region

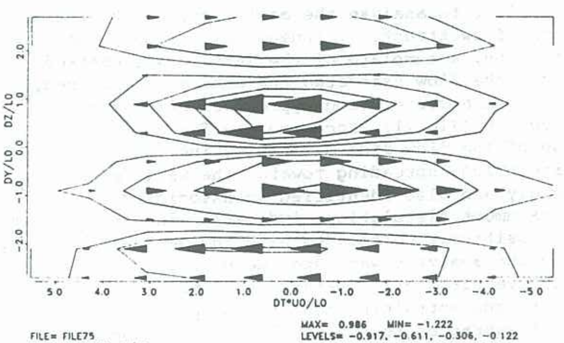


Figure 20 Stronger Near Wall Recovery Flow

effect of the device on these two remaining sections of boundary layer structure was otherwise slight.

Maximum Cf reduction location ($\xi=17.5\delta$): In the shear plane the patterns generated by iterative analysis starting from either a velocity-front or a single circulation template converged towards one-another resulting in a multi-structure averaged pattern similar to that found closer to the device (compare Fig.15 & 17), but now the inclined correlation in the outer part of the flow was stronger and a little more upright probably reflecting the spreading influence of the wake eddy structure. It is also evident, particularly from Fig.17, that the centre-line of the wake was displaced towards the wall, and a weak positive correlation seems to have been re-established between the outer and inner-most regions. However the latter was not seen when either test pattern was located in the entrainment region, and, when these were positioned close to the wall, less than half the number of patterns were detected and the iterative pattern decayed in intensity, presumably because this region was dominated by wake vortices of opposite sign circulation. The xz-plane analysis with single eddy templates revealed a centre-line structure intermediate between that seen close behind the device (Fig.16) and in the boundary layer (Fig.13); more typical of a fully developed wake. Near the wall this structure was more compact and less frequent ($\sim$1500 detected patterns per record), giving the appearance of a wake structure 'footprint' superimposed on a near-wall boundary flow pattern associated with reduced production (Fig.18), while in the outer region there was clearer evidence of double-roller structure from the wake.

In recovery ($\xi=33.5\delta$): Here both front and circulation centre-line templates detected inclined structures extending much further both above and below this location (Fig.19). In addition the same trial patterns placed at the outer edge of the flow extracted a similar combination of entraining and inclined roller motions to that seen in the plane layer, while searching for patterns close to the wall produced an inclined correlation extending to nearly 0.7δ. The xy-plane analysis also produced patterns similar to those found in the plane layer at the centre of the flow and in the outermost regions, where there was evidence that symmetric wake structures were being replaced by predominantly one-sided-loop eddies more typical of the boundary layer. But near the wall the extracted pattern was more symmetric and of greater intensity (Fig.20) suggesting that the growing inner layer structure was somewhat more stable, as indicated by earlier two-point correlation data of Lemay et al.(1987).

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REFERENCES

FERRE, J.A. & GIRALT, F. (1989a) Pattern-recognition analysis of the velocity field in plane turbulent wakes. J. Fluid Mech. 198, pp.27-64.

FERRE, J.A. & GIRALT, F. (1989b) Some topological features of the entrainment process in a heated turbulent wake. J. Fluid Mech. 198, pp.65-78.

FERRE, J.A., MUMFORD, J.C., SAVILL, A.M. & GIRALT, F. (1989) Three-dimensional large-eddy motions and fine-scale activity in a plane turbulent wake. Accepted for J. Fluid Mech.

LEMAY, J., SAVILL, A.M., BONNET, J.-P. & DELVILLE, J. (1987) Some Similarities Between Turbulent Boundary Layers Manipulated by Thin and Thick Flat Plate Manipulators. Proc. TSF6, pp.179-193. Springer-Verlag.

MUMFORD, J.C. (1982) The structure of the large eddies in fully developed turbulent shear flows. Part 1: The plane jet & (1983) Part 2: The plane wake. J. Fluid Mech. 118, pp.241-268 & 137, pp.447-456.

ROBINSON, S.K., KLINE, S.J. & SPALART, P.R. (1988) Quasi-Coherent Structures in the Turbulent Boundary Layer: Parts I & II. Proc. ICHMT Int. Sem. Ser. on Near-Wall Turbulence, Dubrovnik.

SAVILL, A.M. (1979) Effects on turbulence of curved or distorting mean flow. Ph.D. Thesis, University of Cambridge.

SAVILL, A.M. (1982) The Turbulence Structure of a Highly Curved Two-Dimensional Wake. In Structure of Complex Turbulent Shear Flow, ed. R.Dumas & L.Fulachier, pp.185-197. Springer-Verlag.

SAVILL, A.M. & MUMFORD, J.C. (1988) Manipulation of turbulent boundary layers by outer layer devices: skin-friction and flow-visualisation results. J. Fluid Mech. 191, pp.389-418.

TOWNSEND, A.A. (1979) Flow patterns of large eddies in a wake and in a boundary layer. J. Fluid Mech. 95, pp.515-531.