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AN EXPERIMENTAL STUDY OF FORCED STREAMWISE VORTICAL STRUCTURES IN A PLANE MIXING LAYER

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ABSTRACT

Streamwise structures have been shown to ride among the primary spanwise vortices in past flow visualization investigations of plane mixing layers. More recently, quantitative measurements were obtained which showed the origin and evolution of streamwise vortices within a mixing layer. In the present study, the effects of perturbing the mixing layer using two different mechanisms are investigated. A serration on the splitter plate trailing edge was found to have a relatively small effect, confined to the near-field development of the streamwise structures. The installation of cylinderical pegs in the high-speed side boundary layer, however, not only generated a regular array of vortex pairs, but also affected the mean development of the mixing layer far downstream. In both cases, the mean streamwise vorticity was found to decay rapidly with increasing downstream distance.

INTRODUCTION

Experimental studies have shown that the near-field development of plane mixing layers is largely influenced by the formation and interaction of large-scale spanwise vortices (Brown and Roshko 1974). Many of the earlier studies which first determined the important role played by the spanwise vortices also showed the existence of organized and persistent *streamwise* structures (Bernal and Roshko 1986). The origin and near-field evolution was later studied in flow-visualization experiments at low Reynolds numbers which showed that the streamwise structures were in fact rows of streamwise vortices (Lasheras *et al.* 1986 and Lasheras & Choi 1988).

The presence and role of "naturally occuring" streamwise structures in a mixing layer were recently investigated by Bell & Mehta (1989). A plane, two-stream mixing layer was generated, with a fixed velocity ratio of 0.6 and the initial boundary layers laminar and nominally two-dimensional. The results indicated that small disturbances in the flow were initially amplified just downstream of the first spanwise roll-up, leading to the formation of streamwise vortices. The streamwise vortices first appeared in clusters containing vorticity of both signs, but further downstream, the vortices re-organized to form counter-rotating pairs. The vortex structure was found to grow in size, scaling approximately with the mixing layer vorticity thickness, and weaken, the maximum vorticity diffusing as approximately $1/X^{1.5}$. The streamwise vorticity was found to be strongly correlated in position, strength and scale with the secondary shear stress ($\overline{u'w'}$). The $\overline{u'w'}$ data suggested that the streamwise structures persisted through to the self-similar region, although they were very weak by this point and the mixing layer appeared to be nominally two-dimensional.

The main objective of the present study was to investigate the three-dimensionality of the mixing layer in more detail by triggering the streamwise structures in a systematic manner. In addition, the effects of the perturbations on the global properties of the mixing layer, such as growth rate and development to self-similarity, were also to be investigated. Two types of spanwise forcing mechanisms were studied and their results are compared to the "undisturbed" case.

EXPERIMENTAL PROCEDURE

The experiments were conducted in a newly designed *Mixing Layer Wind Tunnel* which consists of two separate, independently driven, legs. The two streams are allowed to merge at the sharp edge of a slowly tapering splitter plate in the test section of dimensions 36 X 91 X 366 cm. The flexible side-wall was adjusted to give a nominally zero streamwise pressure gradient. For the present experiments, the leg driven by the bigger blower was operated at a free-stream velocity of 15 m/s whereas the other leg was run at 9 m/s, thus giving a mixing layer with a velocity ratio (U_2/U_1) of 0.6. Both initial (undisturbed) boundary layers were laminar.

The first perturbation mechanism was a sinusoidal serration in the trailing edge of the splitter plate in the xz-plane. The intention was that the serration would introduce a spanwise variation in the mixing layer origin, which would in turn induce the formation of streamwise vortices. The serration wavelength of 2.0 cm was chosen to be approximately equal to the initial Kelvin-Helmholtz wavelength of the spanwise rollers. The serration amplitude of 0.4 cm was chosen to be equivalent to 50% of the combined boundary layer thicknesses, so as to impose only a small perturbation on the flow.

The second perturbation mechanism consisted of a single row of small pegs placed upright at 2 cm intervals on the high-speed side of the splitter plate 2 cm upstream of the trailing edge. Each brass peg was cylindrical, 0.3 cm in diameter, and 1.3 cm long. The pegs protruded through the high-speed side boundary layer (δ_{99} = 0.37 cm) and each peg produced a momentum deficit and, by skewing the incoming boundary layer, a horse-shoe vortex which wrapped around the peg. The two horse-shoe vortex legs (with common flow towards the surface) are then injected into the mixing layer, in counter-rotating pairs with a regular spacing of 2 cm.

Measurements were made on cross-sectional grids using a cross-wire probe held on a 3-D traverse and linked to a fully automated data acquisition and reduction system

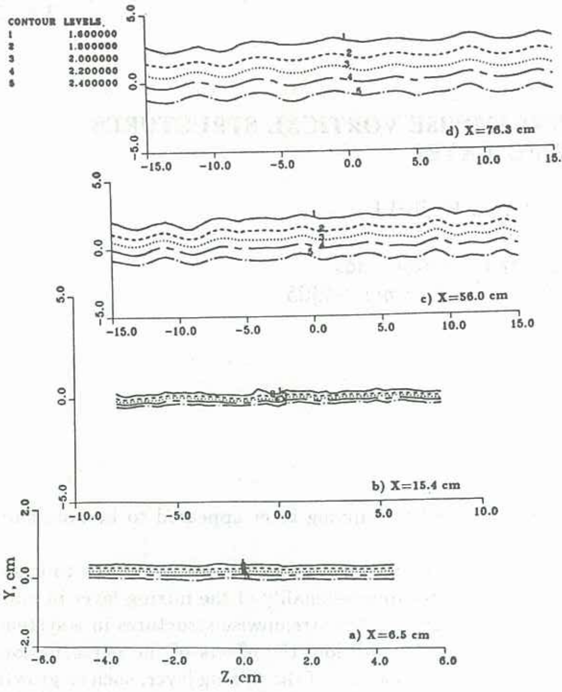

Fig. 1. Velocity Contours (U/U_0) - Serration.

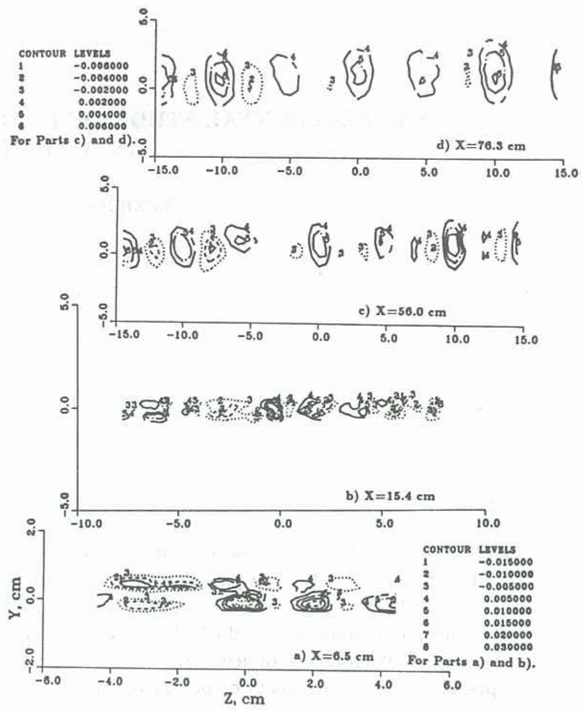

Fig. 3. Shear Stress Contours ($\overline{u'w'}/{U_0}^2$) - Serration.

controlled by a MicroVax II computer. Data were obtained in two planes (uv and uw) by rotating the cross-wire probe about its own axis.

RESULTS AND DISCUSSION

The results for the case with the serration are presented in Figs. 1 - 3. The mean velocity contours (Fig. 1) appear similar to the ones measured for the undisturbed case — some random kinks are noted at the first station (X = 6.5 cm) which turn into a periodic, regular wave by the fourth station (X = 76.3 cm), with the disturbance spreading across the entire mixing layer. The streamwise vorticity contours (Fig. 2) do not exhibit the expected correlation with the serration. In fact, the vorticity distribution is similar to the undisturbed case, except at the first station, where the vortices appear at irregular intervals and not in clusters. The initial vorticity levels are also lower in this case by about 30%, and the number of vortices per unit span is greater. Reorganisation of the vortices into a regular array of counter-rotating vortices and a reduction in vortex strength occurs further downstream, as evidenced in the $\overline{u'w'}$ results (Fig. 3) — the strong correlation between vorticity and the secondary shear stress is maintained in this case. By the fourth measurement station at X = 76.3 cm, almost all the measured quantities for this case were found to be identical to those measured in the undisturbed case. The main reason for this minimal effect was that, at these relatively high Reynolds numbers, the perturbation produced by the serration could not be adequately amplified since it was found to "wash-out" before it reached the first spanwise roll-up.

The perturbation provided by the pegs is clearly stronger and more effective as shown in Figs. 4 - 7. A very regular distortion is seen in the mean velocity profiles (Fig. 4) at the first station (X = 7.4 cm) which spans across the whole mixing layer width and has the expected wavelength of 2 cm (the spacing between the pegs). The turbulence quantities exhibit a similar behavior, although some of the Reynolds stresses, such as $\overline{u'v'}$ (Fig. 5), also show the presence of local peaks in the near-field region. This initial distortion is caused by the streamwise vortices which are generated by the pegs, as discussed above. The absolute magnitude of the positive and negative vorticity is also the same and very regular, as evidenced in the vorticity (Fig. 6) and secondary shear stress results (Fig. 7). Further downstream, at the second station (X = 16.7 cm), the regular arrangement of the vortices is maintained — a reorganisation of the vortices is of course not necessary in this case. However, the maximum vorticity levels drop rapidly, following a $1/X^{1.8}$ decay. As the mean velocity and

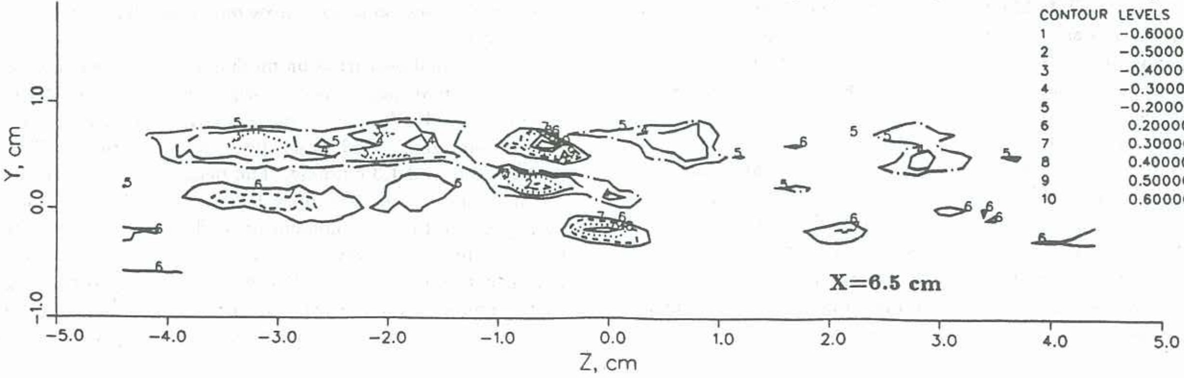

Fig. 2. Streamwise Vorticity Contours ($\Omega_x/U_0, cm^{-1}$) - Serration.

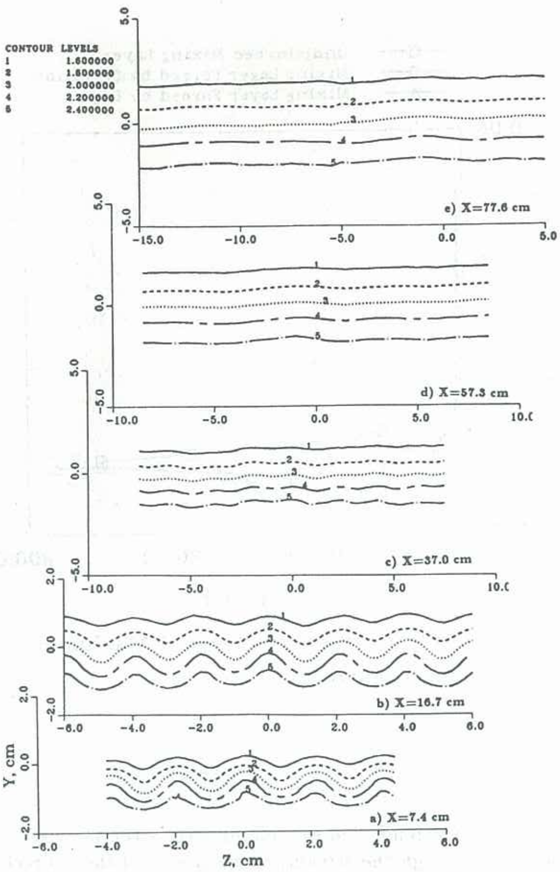

Fig. 4. Velocity Contours (U/U_0) - Pegs.

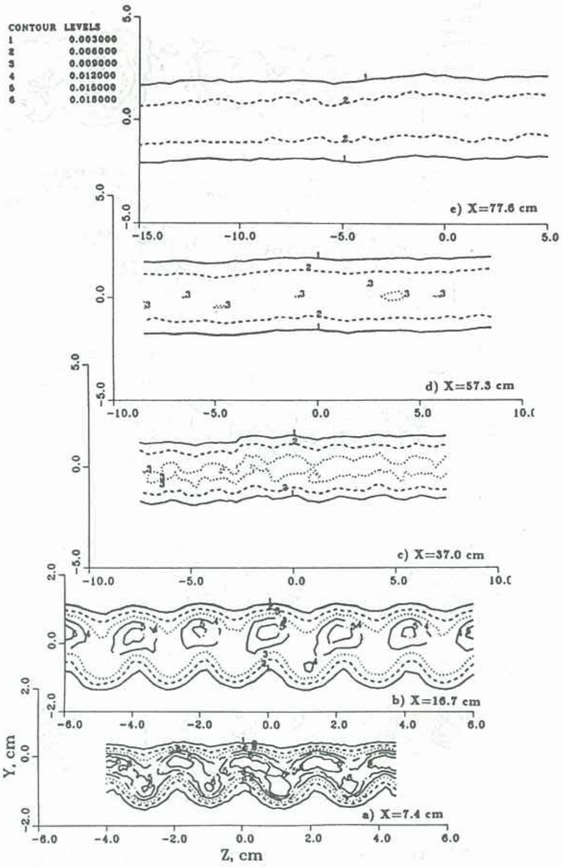

Fig. 5. Shear Stress Contours ($\overline{u'v'}/{U_0}^2$) - Pegs.

primary shear stress contours in Figs. 4 and 5 indicate, by the fifth measurement station at X = 77.6 cm, the vorticity has decayed to the point where the contours appear two-dimensional. So although the pegs produce a very strong and regular perturbation in the mixing layer, the vorticity appears to decay faster. The main reason for this effect is that the pegs, apart from producing the streamwise vorticity, also make the laminar boundary layer transitional. This transitional behavior affects the turbulence anisotropy parameter ($\overline{v'^2}$ - $\overline{w'^2}$) in the near-field, which in turn, affects the decay of the streamwise vorticity within the mixing layer (Bell and Mehta 1989).

The mixing layer growth with the two types of perturbations added are compared to the undisturbed case in Fig. 8. While the serration seems to have an insignificant effect, the pegs clearly change the whole character of the development, whereby the mixing layer is thicker than the undisturbed case initially, but then becomes thinner further downstream. In addition, the mixing layer with pegs does not seem to achieve a linear growth region, even by the most downstream measurement station, thus suggesting that this layer will take even longer to achieve a self-similar state. A more sensitive parameter for self-similarity is provided by the streamwise development of the maximum primary shear stress; the maximum normalized shear stress is expected to achieve a constant value of about 0.011 (Townsend 1976). The development for the present cases is presented in Fig. 9 and it shows some interesting trends. Not surprisingly, the near-field development is different for all three cases. While the distribution for the undisturbed case approaches an approximately constant level beyond $X \sim 100$ cm, that for the peg case exhibits lower values with a slow monotonic increase. The two cases seem to have achieved comparable levels by the end of the test section, suggesting once again that the peg case would eventually reach a self-similar state.

CONCLUSIONS

The effects due to two types of added perturbations on the three-dimensional structure of a plane mixing layer have been investigated. The serrated trailing edge failed to produce a significant lasting effect because the perturbation decayed before reaching the location where amplification occurs. The pegs generated a strong and regular array

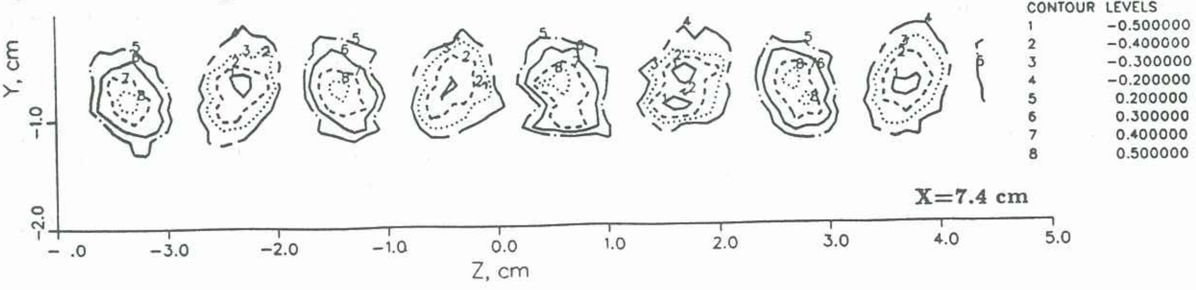

Fig. 6. Streamwise Vorticity Contours ($\Omega_x/U_0, cm^{-1}$) - Pegs.

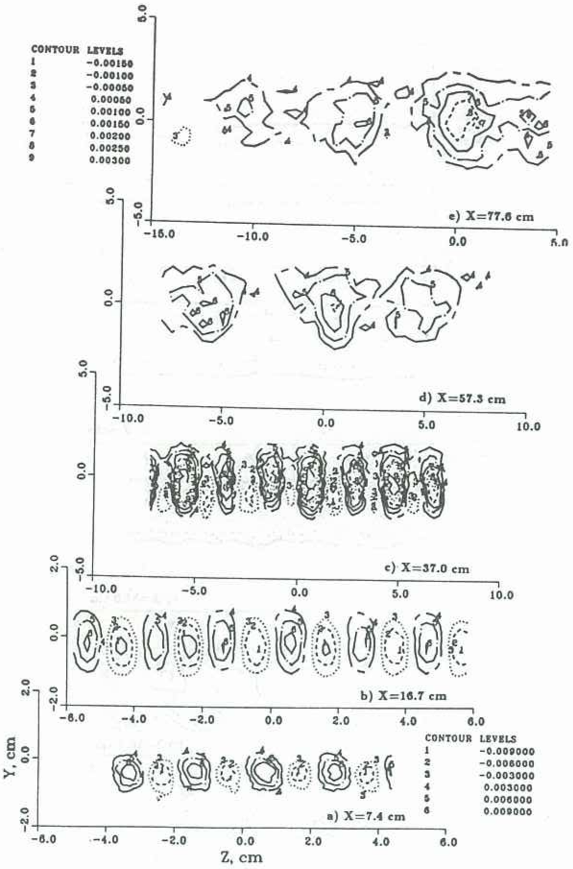

Fig. 7. Shear Stress Contours ($\overline{u'w'}/{U_0}^2$) - Pegs.

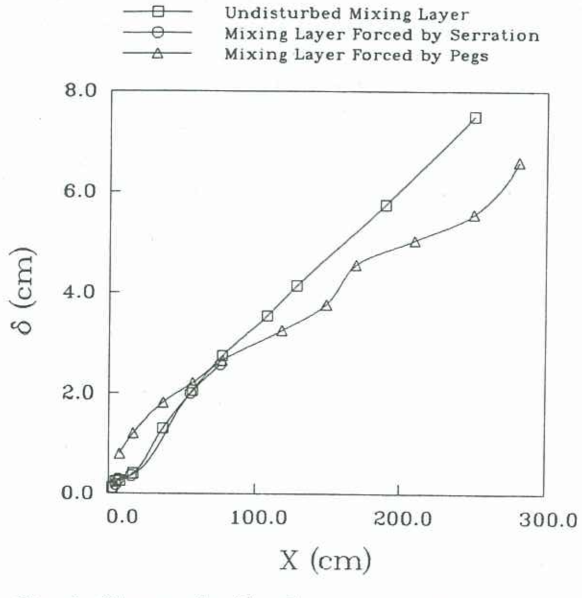

Fig. 8. Streamwise Development of Mixing Layer Thickness.

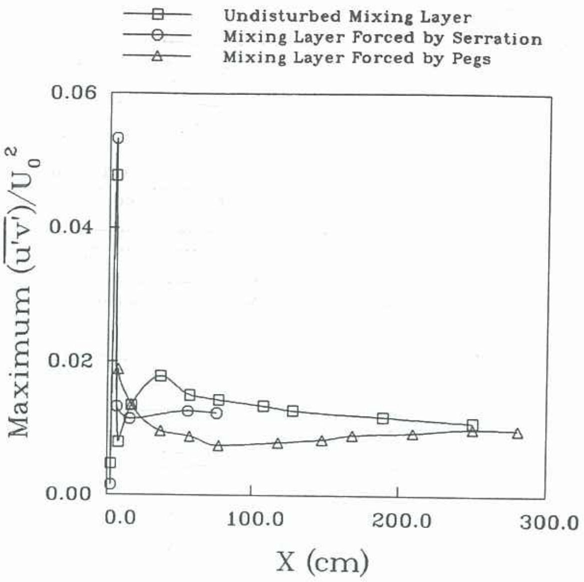

Fig. 9. Streamwise Development of Maximum Shear Stress.

of vortices which affected the mixing layer structure significantly. Although the streamwise vortices and their direct effects decayed rapidly, this perturbation left a lasting effect on the global properties of the mixing layer whereby a self-similar state was not achieved within the measurement domain.

ACKNOWLEDGMENTS

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