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Effect of free-stream turbulence on large structure in turbulent mixing layers

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Flow-visualization investigations and correlation measurements show that the essentially two-dimensional structures which dominated the turbulent mixing layer of Brown & Roshko (1974) are formed only if the free-stream turbulence is low. If free-stream disturbances are significant, as is likely in most practical cases, including a mixing layer entraining 'still air' from the surroundings, three-dimensionality develops at an early stage in transition. Other recent experiments strongly suggest that the Brown–Roshko structure will not form if the initial mixing layer is turbulent or subject to instability modes other than spanwise vortices. Therefore the Brown–Roshko structure will be rare in practice. The alternative large structure in a mixing layer, found by several workers, is intense, but fully three-dimensional and thus less orderly than the Brown–Roshko structure.

The balance of evidence suggests that if the Brown–Roshko structure does appear it will eventually relax into the alternative fully three-dimensional form: the Kármán vortex street behind a bluff body provides a precedent for slow development of three-dimensionality. However the Brown–Roshko structure, if formed, may well relax so slowly as to be identifiable for the full length of a practical flow.

1. Introduction

The flow visualizations of a two-stream mixing layer produced by Brown & Roshko in 1971 (see Brown & Roshko 1974) showed that the two-dimensional 'vortex roll' disturbances which are the eigenmodes of instability of a laminar mixing layer persisted down the length of the test rig. Pairing of vortex rolls occurred at intervals, so that the wavelength was on the average proportional to the shear-layer thickness. Some smaller-scale three-dimensional fluctuations were evident, but most of the fluctuation energy appeared to reside in the two-dimensional structures. Since mean velocity profiles were closely self-preserving and the spreading rate was normal, Brown & Roshko suggested that this was the unique fully developed form of a turbulent mixing layer. Below, we refer to this form as the Brown–Roshko structure. Winant & Browand (1974), again using a two-stream mixing layer, showed that approximate self-preservation could persist through many stages of vortex pairing at low Reynolds numbers, without complete breakdown to the fully three-dimensional flow which is characteristic of turbulence in other types of shear layer. Dimotakis & Brown (1976)

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found some evidence for the Brown–Roshko type of structure in another two-stream mixing layer at high Reynolds number. Oster, Wygnanski & Fiedler (1977) measured velocity correlations with spanwise separation in a two-stream mixing layer, and found very large integral scales compatible with the presence of two-dimensional disturbances, albeit only in the irrotational region outside the shear layer.

Previously, Crow & Champagne (1971) had demonstrated the variety and long streamwise persistence of vortex-ring disturbances in circular jets. Here, fairly rapid changes with Reynolds number were observed and the disturbance wavelength was strongly influenced by the jet diameter, so that the vortex-ring structure was evidently a mixture of columnar oscillations and shear-layer transition modes rather than a self-preserving mode like Brown & Roshko's. Since jet columns are known to be subject to various forms of instability, Crow & Champagne's work was not universally accepted as evidence for anomalous behaviour of the turbulence itself.

The received view of mixing-layer transition and turbulence previous to the above-mentioned work was that the mixing layer became unstable, at a very low value of the Reynolds number based on local thickness, to two-dimensional (or axisymmetric) disturbances; that these disturbances then grew, and paired once or more before appreciable three-dimensionality appeared (Wille 1963); that, perhaps after a considerable time (Bradshaw 1966), the flow reached a self-preserving, fully turbulent state independent of the Reynolds number based on local thickness; and that the large eddies in the fully turbulent mixing layer, although very strong compared with those in a boundary layer, were fully three-dimensional, with correlation integral scales of the same order of magnitude in all three directions. Bradshaw, Ferriss & Johnson (1964), whose correlation measurements were confirmed by Weber (1974), described these large eddies as 'mixing jets' in the sense used by Grant (1958). The question of three-dimensionality is highly important, because three-dimensionality is a prerequisite for the development of a vortex-stretching energy 'cascade', and distinguishes turbulence from various quasi-two-dimensional random flows such as large-scale motion in the atmosphere.

In the present paper we seek to reconcile this received view of classical, fully three-dimensional turbulence with the more recent observations, and to show that the two-dimensional Brown–Roshko structure is rare. Our results show that the vortex-pairing process is sensitive to small three-dimensional disturbances, such as free-stream turbulence, in the early stages when the vortex-roll amplitude is itself small. In Brown & Roshko's experiments, but few others, these disturbances were so small that the laminar instability modes remained two-dimensional and grew to a very large intensity. However, the sensitivity to three-dimensional disturbances is unlikely to disappear completely, and it seems probable that the associated small-scale turbulence will eventually cause the two-dimensional Brown–Roshko structure to break up. If this is so, there is only one truly self-preserving state,† which is fully three-dimensional in accord with the classical view of turbulence. If not, there are *two* self-preserving

† The ratio of the velocity of the low-speed stream, U_2, to that of the high-speed stream, U_1, will affect the asymptotic turbulence structure quantitatively but not qualitatively. Even the quantitative effect is likely to be small if the velocity difference $U_1 - U_2$ is used as a normalizing scale; in particular, $U_2 = 0$ (the mixing layer in still air) is not a singular case, because the most relevant parameter is the ratio of $U_1 - U_2$ to the average velocity $\frac{1}{2}(U_1 + U_2)$, rather than U_2/U_1 itself.

states, of which the three-dimensional one is probably much the more common in engineering practice. Other recent investigations have revealed cases in which the Brown–Roshko structure does not develop. Pui & Gartshore (1977), in measurements in a mixing layer between two streams of nearly equal velocities, find that, if transition first occurs within the wake of the splitter plate rather than in a fully formed mixing layer, the Brown–Roshko structure does not appear and the spanwise coherence lengths (integral scales) are small. Yule (1977) finds that in a circular jet in still air the 'vortex-ring' instability patterns develop circumferential periodicity and break down quite suddenly into fully three-dimensional turbulence. Finally, the balance of evidence discussed below suggests that the Brown–Roshko structure does not form at all if the nozzle-exit boundary layer is fully turbulent.

2. Measurements in a single-stream mixing layer

Figure 1 (plate 1) shows the side view, and figure 2 (plate 1) the plan view on a reduced scale, of a mixing layer formed on the 75 cm side of a 75×12 cm air stream emerging into 'still air' in a room about $10 \times 7 \times 5$ m, free of draughts from other sources. The rig was a blower wind tunnel, without a diffuser or a working-section roof, so that the floor and walls of the working section minimized bodily oscillations (and three-dimensionality) of the mixing layer formed in the plane normally occupied by the roof. The walls extended well above the roof position and thus acted as end plates. The Reynolds number of the exit boundary layer, based on momentum thickness, was about 50, well below the Blasius instability value of about 200. The turbulence level of the tunnel stream was less than 0·1 % at 20 m s^{-1}, and while the level may have been somewhat higher at the speed of about 0·5 m s^{-1} used in the present tests it was certainly within the range typical of good laboratory test rigs. Kerosene-droplet 'smoke' was injected into the entrainment flow at the contraction exit. The streaks in figure 2 were caused by spacers in the injector slot, and their persistence shows that the smoke introduced no significant turbulence. However the second of the spanwise vortex cores in figure 2 shows spanwise non-uniformity on a larger scale than the local shear-layer thickness; this is also the explanation of the multiple streaks seen in the side view (figure 1), the whole spanwise extent of the smoke being illuminated. The third and fourth vortex cores in figure 2 are in the process of pairing, in a three-dimensional (helical) fashion. The last core, evidently the remains of a pair, is virtually turbulent in the conventional sense, with a fully three-dimensional small-scale structure.

Further visual observations showed that vortex pairing in the presence of naturally occurring three-dimensional disturbances led to a double-helix pattern like that seen in figure 3 (plate 2), and conventional turbulence soon ensued. Occasionally two-dimensionality would persist through two or three stages of pairing but helical pairing and breakdown always occurred eventually. These observations do not contradict the linear theory of Jiminez (1975) that adjacent co-rotating vortices of small amplitude are stable: transitional disturbances in a mixing layer can attain large amplitudes, the maximum Reynolds shear stress attained being as much as 1·5 times that in the fully turbulent flow (Bradshaw 1966). An incipient double-helix pattern can be seen in figure 2 of Rockwell (1977), which shows a low-Reynolds-number mixing layer of finite span in a simulated fluidic device. A very clear sequence of movie frames by

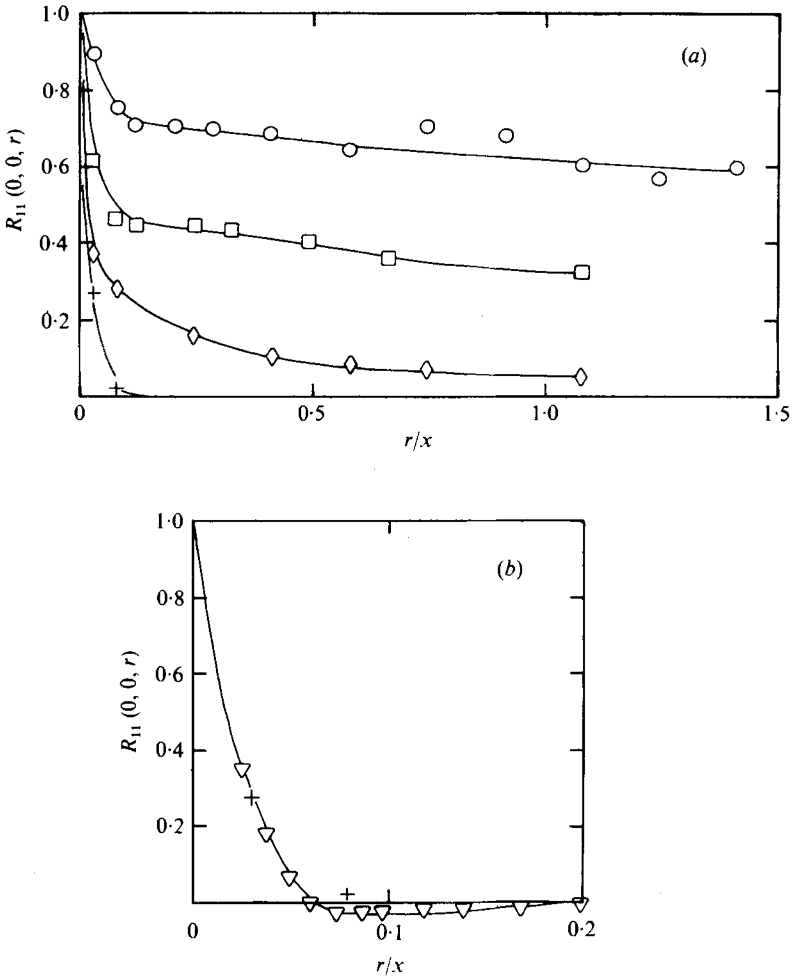

FIGURE 4. Spanwise correlations of longitudinal-component velocity fluctuations in mixing layer in 'still air', $\eta = -0{\cdot}056$. (*a*) $x = 12{\cdot}2$ cm. Jet speed U_1(m s^{-1}) and Reynolds number $U_1 x/\nu$: ○, 3·1, $2{\cdot}6 \times 10^4$; □, 5·5, $4{\cdot}6 \times 10^4$; ◇, 8·8, $7{\cdot}7 \times 10^4$; +, 15·3, $1{\cdot}3 \times 10^5$. (*b*) Fully turbulent region. +, $x = 12{\cdot}2$ cm, $U_1 = 15{\cdot}3$ ms^{-1}, $U_1 x/\nu = 1{\cdot}3 \times 10^5$; ▽, Bradshaw *et al.* (circular jet, circumferential traverse at $\eta = -0{\cdot}05$, $U_1 x/\nu = 7 \times 10^5$).

Lam Kit (1977) shows strongly three-dimensional pairing in a confined two-dimensional jet, effectively a mixing layer over a backward-facing step. Helical pairing of steady co-rotating trailing vortices from a wing with flaps is often observed (e.g. Bilanin *et al.* 1976). The rapid onset of three-dimensionality in our experiments was in marked contrast to the persistence of two-dimensionality in Brown & Roshko's work. This phase of our work was reported briefly by Bradshaw (1975): a more detailed description of work on the 75×12 cm rig, and of previous work on mixing-layer transition, is given by Chandrsuda & Bradshaw (1975), but their discussion is superseded by the present one.

To check the flow-visualization result that two-dimensionality rapidly disappeared, measurements of $R_{11}(0, 0, r)$, the correlation of the longitudinal components of velocity fluctuations with separation in the spanwise direction, were made over a range of speeds in the same mixing layer. The results are shown in figure 4 (*a*). At small values of $U_1 x/\nu$, i.e. in the transition region, large value of R_{11} are found at large r, indicating a strong tendency to two-dimensionality. At higher $U_1 x/\nu$ the spanwise scale decreases, which is consistent with the conventional development of three-dimensionality in the later stages of transition as shown in figure 3. At the highest speed, where transition is complete at the traverse position, the lateral integral scale is very roughly $0{\cdot}03x$, or $0{\cdot}15\delta_\omega$, where δ_ω is the 'inflexion thickness' or 'vorticity thickness' $\Delta U/(\partial U/\partial y)_{max}$, introduced by Bradshaw *et al.* (1964). The values of $R_{11}(0,0,r)$ measured by the latter authors at $\eta = 0{\cdot}05$, $x/d = 2$ in a circular jet with $U_1 x/\nu = 7 \times 10^5$ are in agreement with the present measurements at the highest speed (figure 4*b*): figure 1 (*c*) of Bradshaw *et al.* shows that their flow was undoubtedly turbulent at this x/d. Jones, Planchon & Hammersley (1973) and Wygnanski (private communication) find lateral integral scales of order $0{\cdot}03x$ within two-stream mixing layers, but $0{\cdot}2$–$0{\cdot}3x$ in the irrotational flow on either side (see also Oster *et al.*). The reason is not clear, but the strong two-dimensional structure seen in Brown & Roshko's photographs would surely have produced large scales *within* the shear as well.

An incidental finding of our correlation measurements was that the long tail in $R_{11}(0,0,r)$ at $\eta \simeq -0{\cdot}05$ reappeared at large downstream distances, R_{11} asymptoting to as much as $0{\cdot}2$. This was found to be due to the proximity of the mixing layer to the floor of the test rig, the spanwise influence presumably being propagated via the irrotational fluctuations. When the working-section height was reduced, the long tail reappeared at a value of x giving nearly the same ratio of shear-layer thickness to working-section height. The correlation curves for $r/x < 0{\cdot}05$ agreed quite closely with the data of figure 4 (*b*). The large effect of a nearby solid surface on a mixing layer was pointed out by Castro & Bradshaw (1976); the present measurements were made during a study of this effect by Mr D. H. Wood, which will be reported separately by him. Clearly, the proximity of a solid surface can lead to unsound conclusions about two-dimensionality of large structure, and may have been *partly* responsible for the long tail in the above-mentioned correlations in the irrational flow.

The correlation measurements were not sensitive to the height of the tunnel side walls nor to the insertion of a vertical plate above the exit so that the jet emerged from a 'semi-infinite' wall. This suggests that the present single-stream mixing layer is a representative one and not subject, for instance, to unusually large external disturbances. Rodi (1975) cites the data for a plane mixing layer of Castro & Bradshaw (1976), obtained in the same rig at a speed of about $30\,\mathrm{m\,s^{-1}}$, as among the most reliable: their spreading rate agrees closely with the measurements of Liepmann & Laufer (1947).

3. Measurements in a two-stream mixing layer

It seemed likely that the transitional disturbances in the two-stream mixing layers of Brown & Roshko and other workers kept their two-dimensionality, while ours did not, because the turbulence in each stream of the two-stream test rigs was much lower than that of the 'still air' in our single-stream rig (the latter turbulence level being no higher than in other typical single-stream rigs and at least one order of magnitude less than that of the mixing layer). This hypothesis was tested in another rig. A $1\cdot2 \times 0\cdot6$ m suck-down smoke tunnel, which had no contraction but whose intake was fitted with a honeycomb and four screens giving a turbulence level of about $0\cdot2$ %, was converted into a two-stream mixing-layer rig. The streams were separated by a $1\cdot2$ m wide partition extending all the way from the room wall, which was perpendicular to the tunnel axis, to the last screen. The velocity ratio was altered by fitting layers of cloth, or a solid baffle, over one half of the honeycomb, at which station a sheet of smoke was injected tangential to the partition and parallel to the flow. The faster stream velocity was typically 1 m s^{-1}, so that the Reynolds number was of the same order as in our blower-tunnel tests.

Various combinations of velocity ratio and free-stream turbulence showed that the strength and persistence of the two-dimensional pattern increased as the velocity ratio departed from unity and decreased as the turbulence intensity in the low-velocity stream increased. The most spectacular change (figures 5 and 6, plate 3) occurred when the velocity of the low-speed stream was reduced from a few per cent of the mainstream velocity – just sufficient to supply the entrainment required by a mixing layer in still air – to zero. When the entrained air was delivered via the screens and honeycomb the turbulence level was low, and the two-dimensional structure in the shear layer was at least as strong as in Brown & Roshko's pictures. When the secondary stream was shut off, the flow became that over a backward-facing step, the entrained air was deflected upstream from the reattachment line and was thus highly turbulent, and the transitional oscillations became strongly three-dimensional almost as soon as they appeared. Similar results were obtained with a turbulence grid in the secondary stream, but the photographs are not so clear because smoke diffused into the reversed flow behind the grid bars and filled most of the high-speed stream. Even with the secondary stream shut off, the turbulence level in the entrained air is very much less than in the mixing layer itself: the mechanism is the distortion of weak oscillations in the transition region, not the disruption of fully developed turbulence structure by free-stream turbulence of the same order.

Figures 5 and 6 are photographs of thin illuminated longitudinal sections of a smoke-filled flow: this gives less clear results than the shadowgraph technique, which yields a spanwise average and therefore accentuates tendencies to two-dimensionality. It should be emphasized that even in the conditions of figure 6 the large-eddy structure is still very strong, so that in longitudinal sections we observe a fairly regular large-scale structure, having a spatial distribution which is not radically different from the later stages of the Brown–Roshko flow. The difference in the smaller-scale structure is easily seen in the figures, however, and of course results from the three-dimensionality of the larger eddies, as evidenced by the correlation measurements in the single-stream rig.

Even when two-dimensionality was normally absent, one strong and long-lived travelling vortex roll could be induced by thumping the test rig or suddenly altering the setting of the inlet baffle. Evidently the well-known sensitivity of free-shear-layer transition to mechanical or acoustic excitation implies a corresponding sensitivity of the Brown–Roshko structure. This could provide an explanation of many forms of resonance in jets.

4. Discussion

The above results show that, in the presence of free-stream turbulence of an intensity typical of many test rigs or engineering situations, the spanwise-vortex mode of mixing-layer instability can break down, via helical pairing, into fully three-dimensional turbulence with a spanwise integral scale of a fraction of the shear-layer thickness. The contrast between our flow-visualization results and those of Brown & Roshko and the contrast between our correlation measurements and those of Oster *et al.* leave little doubt that the Brown–Roshko structure did not persist in our experiments except for the case of the two-stream mixing layer with low turbulence in each stream. The large eddies that appear in our mixing layers are clearly of the conventional three-dimensional 'mixing jet' type, found in annular mixing layers by Bradshaw *et al.* (1964) and also found in other common types of shear layer. Equally clearly, Brown & Roshko's results indicate a quasi-two-dimensional pattern persisting for the full length of their test rig, and the free-stream turbulence level in their rig was undoubtedly lower than in the 'still air' surrounding our single-stream mixing layer. Before discussing the persistence of the Brown & Roshko pattern once it has formed, we review recent experiments which reveal more mechanisms for suppressing the Brown–Roshko pattern. We also attempt to distinguish the question of Brown–Roshko structure from questions about the effect of transition trips on the spreading rate.

Brown & Roshko stated that placing wire transition trips just upstream of the trailing edge of the splitter plate did not disrupt the large structure. However Hill, Jenkins & Gilbert (1976) present schlieren flow-visualization photographs of a plane jet, at rather low Reynolds number, which show a transitional/Brown–Roshko structure when the exit boundary layer is laminar and small-scale (presumably three-dimensional) structure when the exit boundary layer is turbulent. Both Bradshaw (1966) and Yule (1977) show that the turbulence intensity on, say, the line $\eta = 0$ in a circular jet rises monotonically with x to its self-preserving value if the exit boundary layer is turbulent but has a pronounced peak when the exit boundary layer is laminar, which suggests that the structure in the initial region is markedly different in the two cases. The trip used by Champagne, Pao & Wygnanski (1976) did not produce a fully turbulent boundary layer at the nozzle exit. The function of a trip wire is to cause separation, and thus produce an inflexionally unstable *mixing-layer* velocity profile; unless the shear layer reattaches some distance upstream of the exit, the transition process will be typical of a mixing layer rather than a boundary layer, i.e. it will be qualitatively the same as if the trip wire were not there. Batt (1975) and Oster *et al.* (1976) found that the spreading rate of a plane mixing layer could be increased by putting a trip wire near the nozzle exit. The trip wire of Oster *et al.* was 1·6 mm in diameter and only 10 mm (six diameters) upstream of the exit, and the shear layer can barely have reattached at all. Indeed the most plausible explanation for the increased spreading rate is intermittent reattachment leading to flapping of the mixing layer, perhaps involving a feedback mechanism. In this case the spreading rate would eventually return to normal. Birch (1977*a*, *b*) presents data for a mixing layer whose initial boundary layer was undoubtedly fully turbulent and, in agreement with Bradshaw (1966), finds closely the same asymptotic spreading rate as when the exit boundary layer is laminar although large differences occur in the initial region.

The spreading rate measured by Brown & Roshko (without a trip wire) agreed well with previous measurements at similar values of U_2/U_1 and, when extrapolated to $U_2/U_1 = 0$, agreed equally well with the consensus value of Liepmann & Laufer (1947), Birch and others, $d\delta_\omega/dx \simeq 0{\cdot}16$ in Brown & Roshko's notation. The most likely conclusions are

(i) that the Brown–Roshko structure does not appear when the initial boundary layer is fully turbulent (Hill *et al.*);

(ii) that the asymptotic spreading rate is independent of the state of the initial boundary layer (Birch) at least in the case $U_2/U_1 = 0$;

(iii) that the spreading rate found in the presence of Brown–Roshko structure is consistent with that mentioned in (ii); and, consequently,

(iv) that the questions of an anomalous spreading rate and of the existence of Brown–Roshko structure are not directly related.

Pui & Gartshore, in measurements in a two-stream mixing layer with

$$0{\cdot}65 < U_2/U_1 < 0{\cdot}83,$$

find that if the splitter-plate wake is strong enough for transition to occur via a vortex street (with contra-rotating vortices) the Brown–Roshko structure of co-rotating vortices does not appear. The flow-visualization results of Sabin (1963, figure 16) seem to show the same effect. Pui & Gartshore also show that free-stream turbulence increases the growth rate, but this is qualitatively expected and does not necessarily provide evidence about the Brown–Roshko structure. Pui & Gartshore's results suggest, again, that the Brown–Roshko structure will not appear if forestalled by transition.

Yule has recently studied the transition process in a circular jet (annular mixing layer) in 'still air'. As in the present experiment, the laminar flow instability pattern (in this case annular vortices rather than two-dimensional ones) breaks down rapidly into conventional turbulence: ring vortices are not observable in this turbulent region, no harmonics or subharmonics are seen in the frequency spectra, and although large eddies can be identified by flow visualization of the turbulent region they are not circumferentially coherent and their movements are more disorganized than those of the traditional vortex rings. However, three-dimensionality seems to appear in a different way from that found in our plane mixing layer: Yule's flow-visualization pictures, at Reynolds numbers based on jet diameter of order 10^4, show that a regular spanwise (i.e. circumferential) periodicity appears at an early stage, and after it has grown sufficiently a final pairing or entanglement of distorted vortices results in turbulent flow. The circumferential periodicity in the transition region was observed by Bradshaw *et al.* (1964; see the left-hand sides of figures 1 *b*, *c*), who attributed it to the Lin–Benney mechanism (Benney 1961). As pointed out by Yule, the vortex-ring instability theory of Widnall & Sullivan (1973) is more relevant. The numerical results of Widnall & Sullivan show that the number of circumferential wavelengths is about 1·5 times the ratio of ring radius to vortex-core radius (i.e. wavelength $\sim 4 \times$ core radius). In figure 1 (*b*) of Bradshaw *et al.* (1964), with a flow speed of $12\,\mathrm{m\,s^{-1}}$, there are about 18 wavelengths around the circumference while in figure 1 (*c*), at $85\,\mathrm{m\,s^{-1}}$, there are about 50. This agrees quite well with the expectation that the thickness of the laminar shear layer (which forms the core) will vary as $Re^{-\frac{1}{2}}$: $(\frac{85}{12})^{\frac{1}{2}} = 2{\cdot}66$; $\frac{50}{18} = 2{\cdot}78$. The observed radius of the rolled-up vortex sheet (the equivalent core) at the onset of

Authors	Situation	Breakdown mechanism
Bradshaw (1966) Hill *et al.* (1976) Yule (1977)	Circular jet, turbulent boundary layer	Existing turbulence
Bradshaw *et al* (1964) Yule (1977)	Circular jet, laminar boundary layer	Circumferential periodicity (Widnall–Sullivan)
Sabin (1963)	Two-stream mixing layer	Wake (vortex street) instability
Pui & Gartshore (1977)	Two-stream mixing layer, strong splitter-plate wake	Wake (vortex street) instability
Present	One-stream and two-stream mixing layer, high 'free-stream' turbulence	Helical pairing
Brown & Roshko (1974) Winant & Browand (1974) Oster *et al.* (1976)	Two-stream mixing layer, low free-stream turbulence	

TABLE 1

circumferential periodicity at 12 m s^{-1} does seem to be roughly one-twelfth of the jet radius as required for the 18-wavelength mode, but as the 'core' size grows rapidly the quantitative application of Widnall & Sullivan's mechanism to the annular mixing layer is not straightforward. The application to a *plane* mixing layer is also dubious: nominally the wavelength tends to a constant multiple of the core radius as the vortex-ring radius tends to infinity, but the higher modes of instability are very selective and it appears that the likelihood of excitation decreases as the mode number increases. Brown & Roshko's plan-view shadowgraph (their figure 8*b*) shows longitudinal streaks which are probably due to the Lin–Benney mechanism of longitudinal-vorticity generation: the relation of the latter to the Widnall–Sullivan mechanism is obscure because Widnall & Sullivan do not consider the details of the viscous region at all, but both mechanisms are aspects of self-induced distortion of vortex lines. In Brown & Roshko's figure 8 (*b*) the breakdown of two-dimensionality is – at most – very slow and not rapid as in Yule's experiments, so strong effects of spanwise periodicity are apparently confined to the circular jet. At least in the experiments of Bradshaw *et al.* and of Yule, 'free-stream' turbulence has no significant effect. Probably it would act in the same way as in a plane mixing layer if not forestalled by Widnall–Sullivan instability, but it is possible that vortex rings are more resistant to distortion than straight vortex lines.

The experiments discussed above and summarized in table 1 strongly suggest that the Brown–Roshko structure appears only when not forestalled by three-dimensionality in the transition region or by pre-existing turbulence. It remains to discuss the circumstances in which the Brown–Roshko structure will appear, and to speculate on its persistence.

It seems that the main case in which Brown–Roshko structure (nearly two-dimensional, nearly self-preserving spanwise vortices in the presence of small-scale three-dimensional turbulence) can appear and persist is the plane mixing layer with a low turbulence level in the fluid on either side. Unless special precautions are taken this implies a two-stream mixing layer fed from a high-quality contraction. This is a rather rare type of flow, and seems not to have been the subject of detailed turbulence measurements and flow visualization prior to Brown & Roshko's work. Another group of possible cases are flows with a feedback mechanism or artificial excitation, such as a bluff-body vortex street or the Crow–Champagne oscillations in a circular jet: however this kind of orderly structure is likely to vary too much from case to case to be usefully compared with Brown & Roshko's mixing layer.

At present it is not certain whether or not the Brown–Roshko structure will persist indefinitely, once formed. The instability mechanism in a laminar mixing layer is effectively inviscid at practical Reynolds numbers, the critical Reynolds number based on shear-layer thickness being much less than 100. Therefore if no secondary instabilities occur, the primary instability mode can continue to increase in amplitude in the presence of small-scale turbulence (very crudely speaking, it will grow if the Reynolds number based on the eddy viscosity ν_T is higher than the critical Reynolds number mentioned above, which is the case even in a fully turbulent mixing layer where $\Delta U \delta_\omega / \nu_T \equiv \rho \Delta U^2 / \tau_{\max} \simeq 100$).

The amplitude will presumably self-limit at some fraction of ΔU, the energy input going into an increase in spatial scale (shear-layer growth). Thus energy considerations alone reveal no reason why the Brown–Roshko pattern should not continue indefinitely, and it cannot be dismissed as a laminar-flow instability mode which automatically decays in turbulent flow. Conversely, the lack of influence of viscosity on the original instability implies that the presence of the Brown–Roshko structure at high Reynolds numbers does not *prove* that it is real turbulence rather than a relic of transition. Taylor–Görtler (longitudinal) vortices in a curved or rotating flow provide a precedent for an instability pattern common to laminar and turbulent flow. However the instantaneous vortex pattern in curved or rotating turbulent flows is usually quite unsteady, with random spanwise migration (Johnston, Halleen & Lezius 1972), and a given streamwise vortex cannot be reliably identified for a long axial (streamwise) distance. If the spanwise vortices of the Brown–Roshko pattern start to lose axial (spanwise) coherence it seems inevitable that the pairing process will enhance the three-dimensionality, causing eventual breakdown to fully three-dimensional turbulence. The vortex street behind a two-dimensional bluff body is an example of a structure that can maintain two-dimensionality for a long distance downstream but eventually subsides into conventional turbulence. Our view of Brown & Roshko's shadowgraph pictures is that they do show increasing disorganization and three-dimensionality as the downstream distance increases, to a greater extent than can be explained by the presence of small-scale three-dimensional turbulence cascaded from an essentially two-dimensional large structure. However, the question of indefinite persistence is almost an academic one because, as has been well pointed out by Dimotakis & Brown (1976), the total length of a typical flow is only a few large-eddy life 'times': thus the Brown–Roshko structure, if formed, may very well persist to the end of the flow. The present experiments were not, of course, designed to achieve an asymptotic state.

The above discussion does not constitute a denial of the importance of large eddies (or 'large structure') in turbulent flow. Indeed it is because of their importance that we must be as clear as possible about the degree of orderliness of the large eddies, in particular their spanwise extent (ratio of spanwise integral scale to shear-layer width) and streamwise periodicity (sharpness of peak in longitudinal wavenumber spectrum). The results of the present paper imply that inferences, drawn by other authors from Brown & Roshko's results, about the orderliness (and therefore the tractability) of turbulence may be much too optimistic.

5. Conclusion

The present experiments in plane mixing layers, and the foregoing review of other recent work, suggest that the two-dimensional vortex-roll disturbances found by Brown & Roshko (1974) arise in the transition region, and will appear only in plane mixing layers with laminar boundary layers at the nozzle exit and low turbulence in the external flow. It appears that the turbulence level in the 'still air' on one side of a plane single-stream mixing layer (which is in fact fluid recirculated from the mixing layer itself) is high enough to induce three-dimensionality at an early stage in transition, followed by helical vortex pairing. In a circular jet three-dimensionality appears via a vortex-ring instability (Yule 1977). The Brown–Roshko structure also fails to appear if transition occurs in the wake of the splitter plate of a two-stream mixing layer rather than in the mixing layer itself (Pui & Gartshore 1977); this and other evidence suggests that the Brown–Roshko structure will not appear if the exit boundary layer is turbulent.

We conclude that the Brown–Roshko structure is rare in practice, the normal form of large structure in a mixing layer being fully three-dimensional. When the Brown–Roshko structure does appear it may still be identifiable at the downstream end of a typical flow, simply because most flow-rig lengths are not many times a large-eddy life 'time' (Dimotakis & Brown 1976). However the sensitivity of the transitional instability mode to three-dimensionality suggests that the Brown–Roshko structure will slowly succumb to three-dimensionality generated by its associated small-scale turbulence: if this is so, which we are strongly inclined to believe, there is only one asymptotic state of a plane mixing layer and its large structure, though strong and undoubtedly of great importance in determining flow development, is fully three-dimensional and less orderly than the Brown–Roshko structure.

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FIGURE 1. Side view of vortex-roll growth and breakdown in mixing layer in 'still air'. High-velocity stream is on upper side. Reynolds number based on length of photograph approximately 10 000.

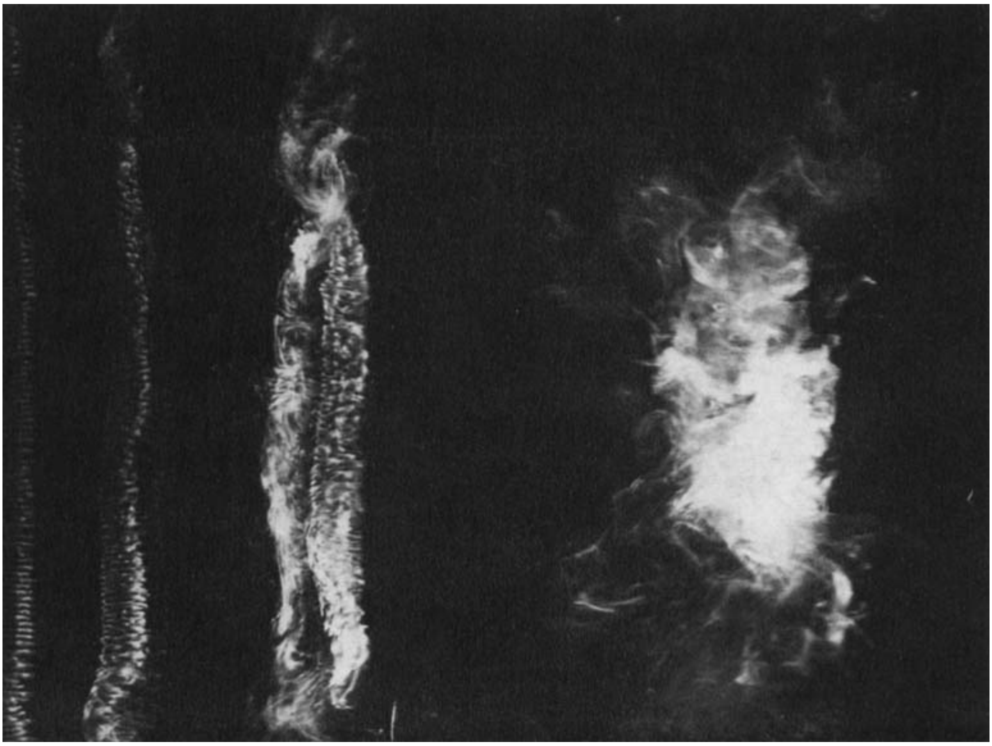

FIGURE 2. Plan view of vortex-roll growth and breakdown in mixing layer in 'still air', viewed from still-air side. Reynolds number based on length of photograph approximately 40 000.

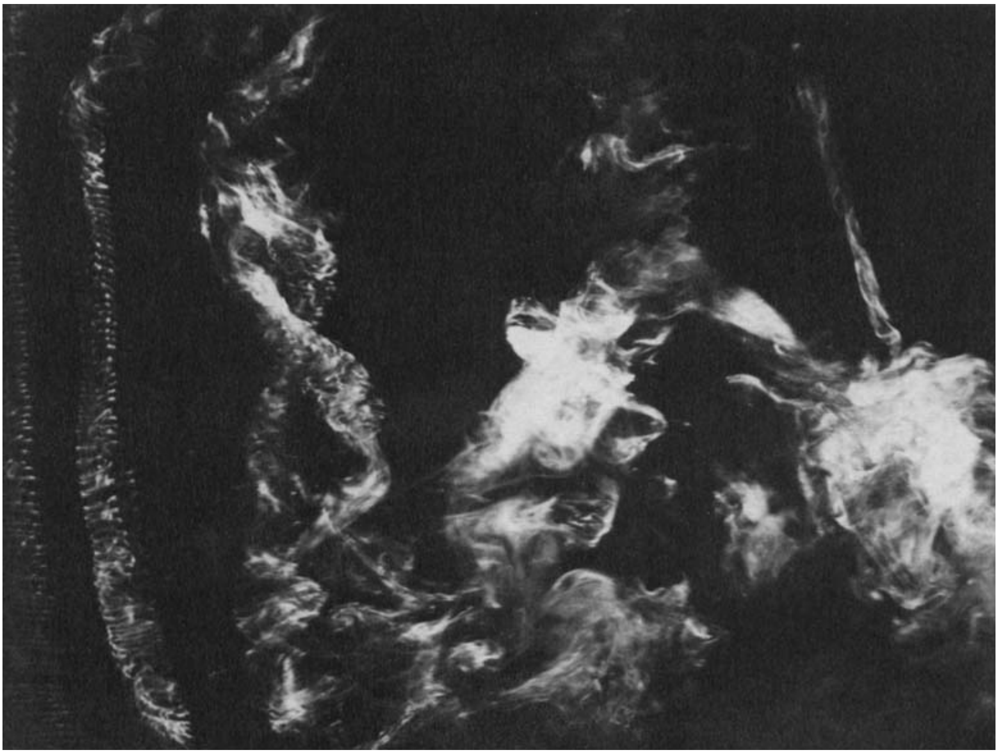

FIGURE 3. Plan view of double-helix vortex pairing. Conditions as in figure 2.

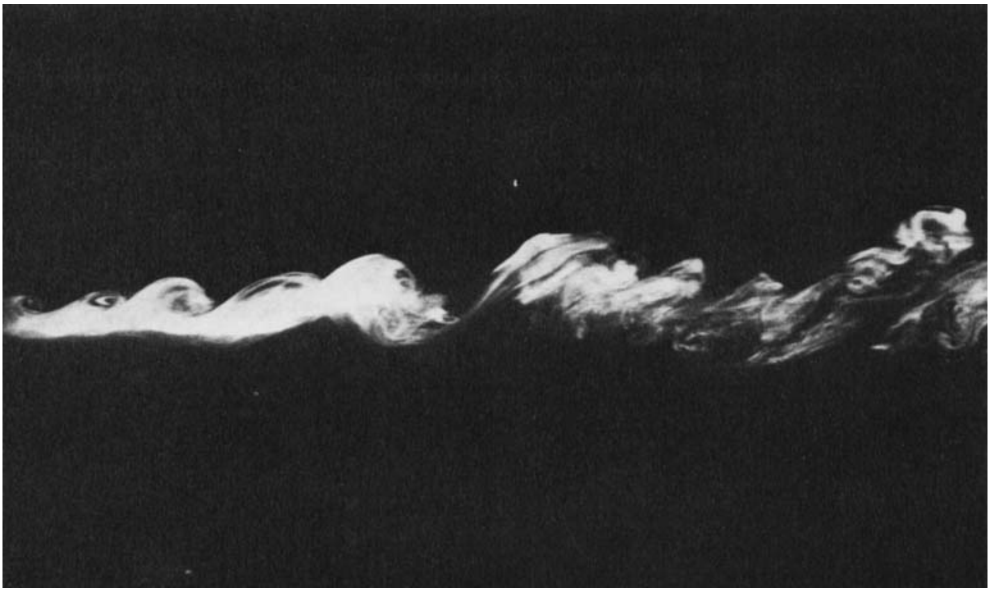

FIGURE 5. Side view of persistent two-dimensional structure in two-stream mixing layer. Stream speed ratio about 30 : 1. Reynolds number based on length of photograph approximately 60 000. Illuminated longitudinal section of smoke-filled flow.

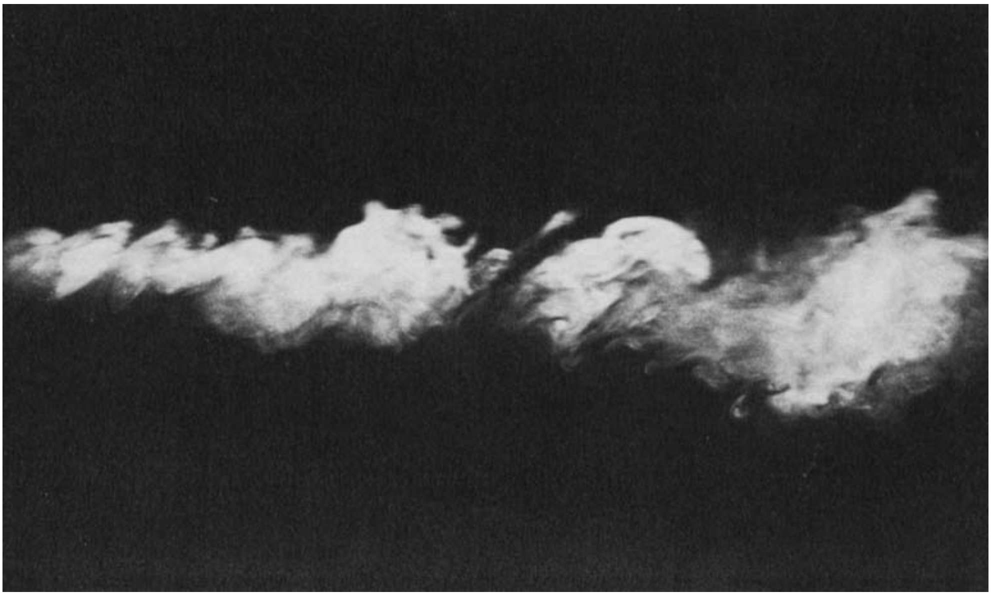

FIGURE 6. Conventional turbulence in two-stream mixing layer. Conditions as in figure 5 except that low-speed stream has been stopped completely and entrainment flow is provided by highly turbulent recirculating air. Again only a longitudinal section is illuminated.