PROSPECTS FOR USEFUL RESEARCH ON COHERENT STRUCTURE IN TURBULENT SHEAR FLOW.

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1.0 ABSTRACT

Six different flows involving coherent structures are discussed with varying amounts of detail. These are the puff in a pipe, the turbulent spot, the spiral turbulence, the vortex ring, the vortex street, and the mixing layer. One central theme is that non-steady similarity arguments and topology are of the essence of coherent structure. Another is that the Reynolds equations, which are sterile when applied to a structureless mean flow, may be quite productive when applied to a single structure. A third theme is the prospect for at least partial control of technically important flows by exploiting the concept of coherent structure.

2.0 INTRODUCTION

This paper is not intended to be either a report of my own research in progress or a review of recent contributions to the concept of coherent structure. It is a personal manifesto which sets out my view about useful strategies for formulating experiments and for modeling of turbulence.

In the phrase "coherent structure", the word "coherent" means having an orderly and logical arrangement of parts such as to assist in comprehension or recognition. The meaning of the word "structure" is less transparent. At one level, coherent structure can be any feature which attracts attention in photographs of a flow. Flow visualization is always a powerful tool, and never so powerful as when it leads to new discoveries. Examples include the discovery by Kline and co-workers (1967) that the sublayer of a turbulent boundary layer is full of streamwise vortices, and the discovery by Brown and Roshko (1971) that the mixing layer is not the featureless wedge of turbulence which it had been thought for many years to be.

At another level, coherent structure can be any flow pattern which survives the phase reference. The mark of real commitment to the concept of Reynolds averaging in the traditional or global sense. Instead, phase information is retained, at least at the largest local scale of the flow, and a celerity, or phase velocity, is sought which will make the mean flow stationary or nearly stationary in some suitable moving frame. In practise, the question of celerity is often approached initially in terms of interface geometry and eventually in terms of topology, which is to say in terms of particle paths both outside and inside the structure. I should say that I was first persuaded of the power of this topological approach in its full generality by Brian Cantwell, who was persuaded by Tony Perry, who was persuaded by I know not whom.

Among flow configurations which qualify as coherent structures, some of the best-known examples occur in isolation in the regime of transition from laminar to turbulent flow. These include

the puff in a pipe,
the spot in a boundary layer, and
the spiral in circular Couette flow.

Two other flows which belong in this group but about which not much is known are the puff in a channel and the spot in a free-

convection boundary layer. Other structures which occur in isolation but not as part of a transition process, because they appear in laminar as well as turbulent versions, include the line vortex, the thermal in two or three dimensions, the vortex pair, and

the vortex ring.

Finally, there are a number of cases in which laminar or turbulent structures occur naturally in train. The best-known examples are

the vortex street and
the mixing layer.

In this paper I will discuss, at rather uneven levels of detail, the six coherent structures which are singled out in the last paragraph. My premise is that each structure is defined for practical purposes by its characterstic pattern of centers and saddles in an appropriate coordinate system. The most appropriate coordinate system is assumed to be one in which both the boundary of the structure and the particle paths are as nearly steady as they can be made.

The centers are points of concentration or accumulation of mean vorticity. The saddles are often points of large mean rate of strain, either in shear or in extension. Thus the saddle are likely to be associated with large rates of turbulence production, although the evidence on this point is at present mostly circumstantial.

The concept of celerity needs careful definition. Topology and celerity go together, because the pattern of instantaneous mean stream-lines or particle paths is very sensitive to the speed of the observer. A coherent structure may not grow (puff, spiral); or it may grow according to certain essentially inviscid similarity laws (vortex street, mixing layer, possibly spot) which limits the value of similarity arguments. However, each part of the average structure, including its boundary, presumably moves at a well-defined speed. A case in point is the mixing layer, for which x-t diagrams have been constructed by various observers (Damms and Kuchemann, 1972; Brown and Roshko, 1974; Acton, 1980). Each of these observers chose a particular local feature (not necessarily the same feature) in order to assign a value to the variable x, and to the celerity dx/dt, and each was successful in exposing the phenomenon of coalescence in the mixing layer. The topological approach can also help to clarify the problem of celerity in cases where this problem does not have a trivial solution, as in the case of the turbulent spot. If particle paths are not known, celerity can sometimes be defined by following points of peak vorticity or centroids of vorticity, as in the case of the vortex street. In my opinion, direct measurements of phase velocity are very unreliable for this purpose (for a typical struggle with the case of vortex evolution in the near wake of a cylinder, see Simmons, 1974), as are indirect measurements in terms of time-space correlations. It does not follow that early experimenters who used these techniques were in any doubt about the meaning of their work, as is evident from the fact that Favre and Kovasznay chose the French word "celerite" to describe their findings qualitively, rather than the more conventional word "vitesse".

In this paper I will take up three different but related aspects of each flow to the extent that I have so far been able to digest the available experimental evidence. One aspect is the topology of the standard structure. Another is the effect of off-design conditions; i.e., the response of the structure to strain imposed by a change in the governing parameters or by the presence of neighbouring structures. The third aspect is the possible role played by the structure in the corresponding technical flow. Two of my six topological sketches (for the puff and the spot) have special elegance and authority because they are based directly on measured data, and thus represent nature. The other four sketches are of lesser quality because they are based at least in part on combinations of flow visualization and conjecture.

3.0 THE PUFF IN PIPE FLOW

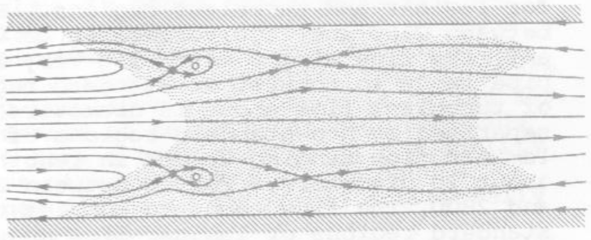

Fig. 1 Mean streamlines in a puff, after Wygnaski, Sokolov, and Friedan (1975). The presentation uses coordinates (z-ct, r), where the celerity c is close to the mean velocity U measured over the pipe cross section. The ratio of the vertical/horizontal scales is about 2.5/1.

Although laminar pipe flow is stable to disturbances, a well-defined transition regime is known to exist when the entrance flow is highly disturbed and the pipe is sufficiently long. For Reynolds numbers $Re = Ud/\nu$ between about 2000 and 2800 (U = mean velocity, d = diameter), the disturbed flow eventually relaxes far downstream to a satistically steady state of intermittent turbulence. The dimensionless

frequency fd/U (f = frequency of passage of turbulent regions) was first measured by Rotta (1956), using an ingenious mechanical method, and by Lindgren (1957), using an optical method. The concensus of these and later measurements by Vallerani (1964) and by Wygnanski and Champagne(1973) is that the frequency fd/U has a maximum value of about 0.025 at about Re = 2450, where the celerity is about 0.9 U. The average interval between turbulent regions is thus about 35 diameters. Given an intermittency of 0.45, this interval can be divided into lengths of about 20 d and 15 d, respectively, for laminar and turbulent regions. For Re between 2100 and 2400, according to Vallerani, the flow at the exit of a very long pipe tends to consist of standard regions of turbulent flow about 15 diameters long, separated by non-standard regions of laminar flow ranging upward in length from about 20 diameters. For Re between 2600
IIIII and 2800, the flow tends to consist of
11111 standard regions of laminar flow about 10
11111 diameters long, separated by non-standard regions of turbulent flow ranging upward in length from about 10 diameters. In all these estimates, the most uncertain quantity is intermittency, because the leading interface is not well defined in the lower transition region, and in any event the interfaces are not plane. The term "length" is therefore used very loosely.

A few measurements of celerity have been made in flow with disturbed entry by Lindgren (1957), Stern (1970), and Wygnanski and Champagne (1973). Below the divide at Re = 2450, turbulent regions have approximately constant length and therefore essentially a single celerity, which is most easily measured at the trailing interface. Above the divide, the leading interface moves faster than the trailing one if space is available, as first noted by

Lindgren. Hence celerity at these higher Reynolds numbers is usually measured in a different mode. Laminar flow is set up in a pipe with smooth entry, and the time interval is measured (for example) between a local artificial disturbance and the associated response at one or more downstream stations. Most such measurements suffer from deficiencies which raise the question of reproducibility among the various experiments. In some cases (Vallerani, 1974; Meseth, 1974), the response was observed at only one downstream station, so that the formation process for the turbulent region was not excluded from the measured time intervals. In other cases (Gilbrech and Hale, 1965; Sarpkaya, 1966), the duration of the disturbance was probably too long, at least in the lower transition region, where a sharp impulsive disturbance is called for. Measurements of celerity at high Reynolds numbers have a particularly <u>ad hoc</u> quality in short pipes when transition occurs IIIII
spontaneously or is triggered artificially 11111
in the developing laminar boundary layer 11111
(Lindgren, 1957; Wygnanski, 1970; Wygnanski and Champagne, 1973). In such cases it is relevant that the boundary layer in the pipe has a thickness $\delta \sim (\nu x/u_\infty)^{1/2}$, from which $x/\delta \sim u_\infty\delta/\nu$. To assure a parabolic laminar profile, the condition to be met is $x/d \sim Ud/\nu$. Detailed caluclations and/or measurements (Reshotko, 1958; Wygnanski and Champagne, 1973), give the constant of proportionality as about 0.1. When this condition is not met, the shape of the laminar-turbulent interface will imitate the shape of the laminar profile, and will depend on x/d (Wygnanski, 1970; Wygnanski and Champagne, 1973; cf. Tietgen, 1975). Moreover, the proper reference velocity for celerity is no longer the theoretical maximum velocity 2U for the parabolic profile, but rather the actual maximum velocity at the station in question

(Wygnanski and Champagne, 1973). In a short pipe, this velocity may be closer to U than to 2U, and may vary over the observation distance.

Finally, it is clear that close attention must be paid to flow regulation. If the mean velocity is not regulated by the experimenter (say by use of a sonic orifice, a positive-displacement pump, or a massive upstream flow restriction), it will be regulated by the experiment, and will vary with the relative fractions of laminar and turbulent flow at each instant. This transient effect is probably less important for intermittent flow with disturbed entry than for intermittent flow at higher Reynolds numbers. In cases where enough information is available to judge the matter, flow regulation has often been poor. Lindgren, for example, recognized that his flow circuit was unstable, and that the limit cycle described by Prandtl and Tietjens (1934) could occur in his apparatus.

Experiments with controlled disturbances provide direct access to the phenomenon of splitting discovered by Lindgren, a phenomenon which introduces complications in any study of celerity. In the lower transition regime, one turbulent region can become two, three, four... regions as the structures moves downstream, provided again that space is available. Different observers do not agree about the site at this splitting; Lindgren (1957) seems to place the site at the front, while Wygnanski et al. (1975) seem to place it at the rear. Quantitative information about splitting is rare and inconsistent. Wygnanski et al. report up to four turbulent regions in train at a station 450 d downstream from a single disturbance. Vallerani reports the same number at a station almost an order of magnitude farther downstream in an apparatus

having a better-developed laminar profile but having very poor flow regulation. Vallerani also noted substantial changes in the length of laminar regions created by splitting, depending on Reynolds number and on the number of turbulent regions in train. There are evidently several important unresolved issues involving the mechanisms which promote splitting and prevent coalescence of turbulent regions in pipe transition.

Wygnanski and Champagne (1973) refer to the turbulent structure within the transition range as a puff, and to the structure above the transition range as a slug. They make the distinction strictly in terms of origin; disturbed entry for the puff, boundary-layer instability for the slug. A distinction is certainly desirable, but I do not think it ought to involve the conditions of origin. I prefer a distinction in terms of operational properties of the structures, based on the well-documented change in behaviour near Re=2450. The only new feature at higher Reynolds numbers is the disappearance of laminar regions at about Re = 2800, a disappearance which occurs gradually and may mean only that relatively quiet regions are being classified as turbulent rather than laminar. In this paper the term "puff" always means the structure which is at home in the range of Reynolds numbers from 2000 to 2450.

The puff is a logical candidate for standard coherent structure in pipe flow. Mean streamlines have been measured by Wygnanski et al. (1975) for an ensemble of artificially generated puffs at Re = 2230 (a value chosen to avoid splitting), as shown in Fig. 1. The mean flow should be steady in a coordinate system moving with a celerity of about 0.90 U to 0.95 U; the value used to construct the figure is not stated, but may be U itself. The puff has a long, vaguely defined nose of decaying low-frequency turbulence at the right which is visible in photographs (lindgren,1959, Mattioli and Zito, 1960; Yellin, 1966, Wygnanski and Champagne, 1973) but is missing in the present figure because the interface is represented by the locus of a relatively high fluctuation level ($q'/U=0.10$ in figure 12d of Wygnanski et al., 1975).

Figure 1 shows that the puff as coherent structure is a vortex ring, a property which I missed completely in my contribution to the 1961 colloquium in Marseilles. The term "vortex" implies here (as it does in the case of the Hill spherical vortex) only the existence of closed mean Stream - lines in a moving coordinate system, and not necessarily the existence of a local peak in mean vorticity. Given the present view, an explanation immediately presents itself for the strong stabilizing effect of curvature
IIIII noted by Taylor (1929). Puffs survive in a
11111 stright pipe for Re greater than about
11111 2000; but puffs survive in a pipe coiled to a diameter of 100 d, say, only for Re greater than about 5000. In a puff the vortex ring must be the engine which makes the structure run.The secondary flow in the pipe presumably disables this engine by destroying the geometric and dynamic equilibrium between the puff and its environment.

Bits and pieces of circumstantial evidence can be found to suggest that the vortex ring is (or is not) the prototype large eddy in fully developed turbulent pipe flow. Lindgren (1969) thought he recognized puffs in flow at Reynolds numbers near 6000. Champagne (private communication) has verified the emergence of puff when an initially turbulent flow was reduced in Reynolds number from 11300 to 2260 in a long diffuser, but no hard

numbers are available. Rubin et al. (1980) suggested that the length of a slug might be quantized in multiples of 25 d, but their evidence is not completely persuasive.

Several investigators have reported dimensionless frequencies associated with coherent events in fully developed pipe flow at quite high Reynolds numbers, far above the transition range. In the dimensionless form TU/d (T = mean period between events), these frequencies can be roughly interpreted as spacing in diameters, given the celerity of 1.0 U to 1.1 U implied by time-space correlations in figure 20 of Sabot and Comte-Bellot (1976) or figure 8 of Hassan et al. (1980). This quantity TU/d tends to fall in the range from 10 to 20 if it is defined by a weak maximum in the autocorrelation of u(t) (Mizushina et al, 1973) or by intervals between bursts according to Blackwelder's burst-detection
scheme (van Maanen, 1980). On the other IIIII
hand, the quantity TU/d tends to fall in 11111
the range from 1 to 2 if it is defined by 11111
a quadrant analysis of u'v' (Sabot and Comte-Bellot, 1976) or by bursts of high-frequency fluctations in $\partial u/\partial r$ (Heidrick et al., 1977). The smaller values for TU/d suggest that structural details are being observed on a scale one order of magnitude smaller than the scale of the main structure. If so, corresponding structural details should also be encountered in other flows, and this may be so. However, the implication that a structural hierarchy may develop at high Reynolds numbers is far beyond the range of the present paper. In the case of pipe flow, a serious further difficulty is the finding by Sabot and Comte-Bellot (1976) that large excursions in u'v' in both directions are common on the pipe axis. This finding is not consistent with a vision of coherent structure in fully developed pipe

flow as an irregular train of vortex rings. The matter needs clarification, perhaps by use of conditions requiring simultaneous large-scale maxima in local wall shearing stress and/or local pressure gradient at several points along and around the pipe.

4.0 THE TURBULENT SPOT IN A LAMINAR BOUNDARY LAYER

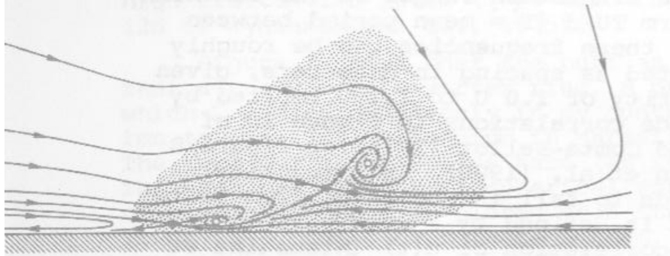

Fig. 2 Mean particle paths in the plane of symmetry of a turbulent spot, after Cantwell, Coles, and Dimotakis (1978). The presentation uses non-steady similarity coordinates ($x/u_\infty t$, $y/u_\infty t$). The ratio of the vertical/horizontal scales is about 14/1.

If it was ever supposed that boundary-layer transition might involve a contenous range of states from laminar to turbulent, this supposition should not have survived Dryden's observations of intermittency (1936). A plausible but wrong explanation of these observations might have been that a contineous interface exists between laminar and turbulent regions and moves erratically back and forth like the interface between shore and ocean at a beach. Some experiments in another context, and a powerful stroke of intuition, led Emmons (1951) to the correct explanation in terms of turbulent spots, and this explanation was promptly verified by Schubauer and Klebanoff (1955).

Except for one paper by Dhawan and Narasimha (1958) on the connection between spot formation and growth and boundary-layer transition, one paper by Elder (1960) on the question of spot origin, and some unpublished flow-visualization movies by Head, interest in the turbulent spot languished until the rise of the coherent-structure concept. Recent contributions by Coles and Wygnanski and their co-workers (Coles and Barker, 1975; Wygnanski, Sokolov and Friedman, 1976; Cantwell, Coles, and Dimotakis, 1978; Zilberman, Wygnanski, and Kaplan, 1977; Haritonidis, Kaplan, and Wygnanski, 1978; Coles and Savas, 1980) illustrate two quite different points of view toward the problem. Wygnanski invariably emphasize the interaction between spot and ambient flow. For an isolated spot, for example, he consistently measures deviations from an undisturbed state which includes the laminar boundary layer. Coles, on the other hand, thinks in terms of an asymtotic state in which the laminar boundary layer is reduced to a vortex sheet on the surface. Since this sheet has no thickness (no viscous scale), it is permissible to force a conical approximation in order to gain easy access to the powerful machinery of non-steady similarity. These two points of view are not mutually exclusive; they are simply different.

Another difference on the question of structure is more fundamental. Coles and Barker (1975) concluded that the main feature of the spot was a single large Λ-shaped vortex, located under the ridge of maximum thickness. This conclusion was originally based on weak evidence for instantaneous mean streamlines and on the correctness of a plausible guess as to the characterstic celerity of the vortex in the plane of symmetry. Wygnanski et al. (1976)

did not endorse either the guess or the conclusion, although their own more extensive measurements, particularly of the mean velocity normal to the wall, might suggest to some the presence of just such a vortex and give some information about its spanwise strength and extent. Support for the large-vortex view is also provided by measurements by Handa (1976). Cantwell et al. (1978) again made the point about the vortex, using the method of non-steady similarity, and proposed a celerity of 0.77 u_∞ in the plane of symmetry (subject to the influence of a small negative pressure gradient). Their main topological result is reproduced in Fig. 2. They also concluded that most of the entrainment in a spot occurs along the trailing interface as the spot is overtaken by faster-moving free-stream fluid. Much of this work was aimed at relatively primitive issues, and none of it includes enough detailed data about fluctuations (or about
IIIII mean particle paths in three dimensions) to
11111 allow a complete quantitative analysis of
11111 structure. The spot therefore represents a formidable piece of unfinished business. In fact, the prospect of having to establish experimentally the effects of pressure gradient, longitudinal curvature, mass transfer, compressibility, etc., is more than formidable; it is mind-boggling.

One property attributed to the spot, for example by Schubauer and Klebanoff (1955), is that it can grow in size only if the Reynolds number in the ambient laminar boundary layer is large enough to support amplification of Tollmien-Schlichting waves. I have some reservations about this property, because two other structures, the puff and the spiral, occur in laminar flows which are confidently believed to be stable to infinitesimal disturbances. Although the puff and the spiral have fixed volumes, they both entrain (and de-entrain) fluid

along part of their bounding interfaces, and must therefore share with the spot the property that they provoke some kind of strong local instability in the vorticity-bearing ambient flow.

A related and quite remarkable phenomenon reported by Wygnanski, Haritonidis, and Kaplan (1979) is the appearance of regular wave packets, bearing a strong family resemblance to Tollmien-Schlichting waves, near the wing tips of a spot. If these wave packets can break down into new turbulence, as they apparently do, it should be possible for the volume of a turbulent spot to change essentially discontinuously. However, there is no direct evidence of such behavior in any of the availble flow visualization. The phenomenon of eddy transposition reported for certain spot arrays by Coles and Savas (1980) is probably closely related to Wygnanski's discovery, and further suggests the
possibility that the normal processes of IIIII
entrainment and energy transfer can be modi- 11111
fied when downstream structures are shielded 11111
by upstream ones.

Flow-visualization photographs of spots have been published by several investigators (Elder, 1960; Cantwell et al., 1978; Falco, 1979; Gad-el-Hak et al., 1980; Matsui, 1980). When dye or smoke is used as a passive contaminant and is properly placed in the flow, the large -vortex prompely materializes as a locus of accumulation for the contaminant. Heat has also been used as a passive contaminant, with a similar result, by Van Atta and Helland (1980). Other flow visualization using dye by Coles (see Cantwell et al., 1978) and by Gad-el- Hak et al. (1980) leaves no doubt that turbulent wedges and regions or turbulent transverse contamination contain spot-like structures. Some experiments on spots in train by Coles (unpublished) and by

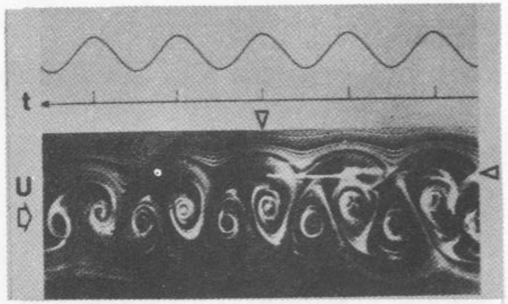

Fig. 4. Flow pattern by multi-exposure at Re = 140.

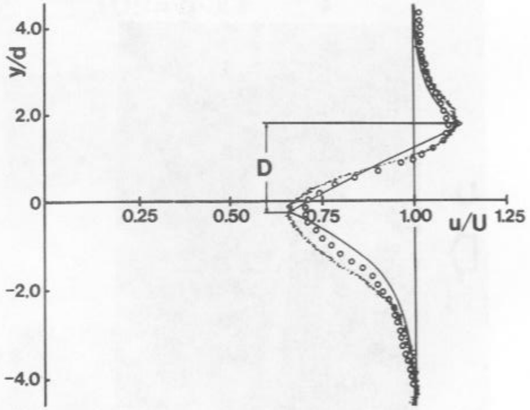

Fig. 5. Velocity distribution through the center of a vortex in the upper row at x/d = 20.

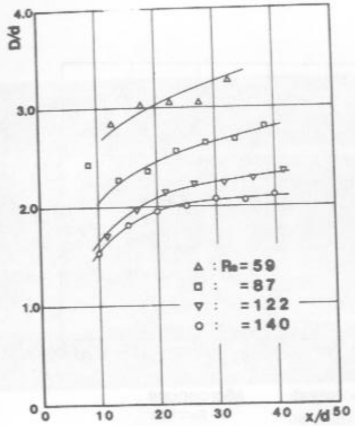

Fig. 6. Downstream growth of vortex cores.

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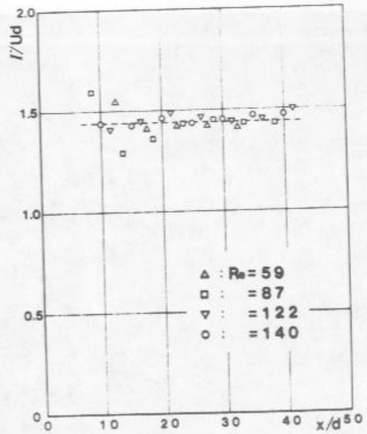

Fig. 7. Circulation of vortices in a vortex street.

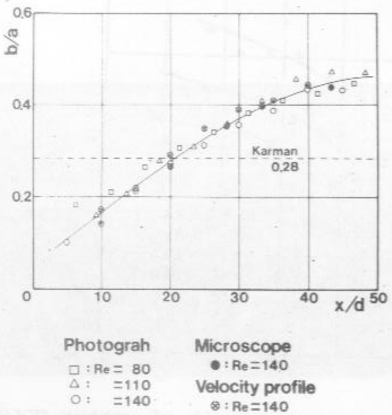

Fig. 8. Downstream variation of the ratio b/a.

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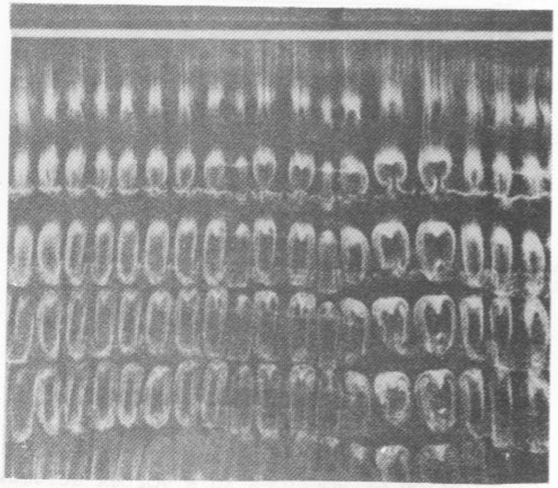

Fig. 9. Wake of a circular cylinder rotating in a uniform flow, d = 10 mm, U = 2.78 cm/s, U_p/U = 2.4 and Re = 214.

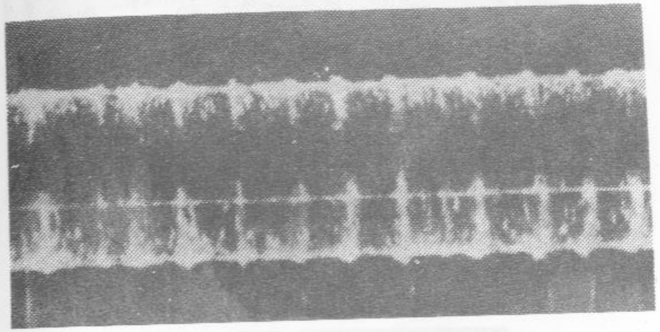

Fig. 10. Taylor vortices in the circulating layer. d = 10 mm, U = 3.1 cm/s, U_p/U = 2.2, Re = 238.

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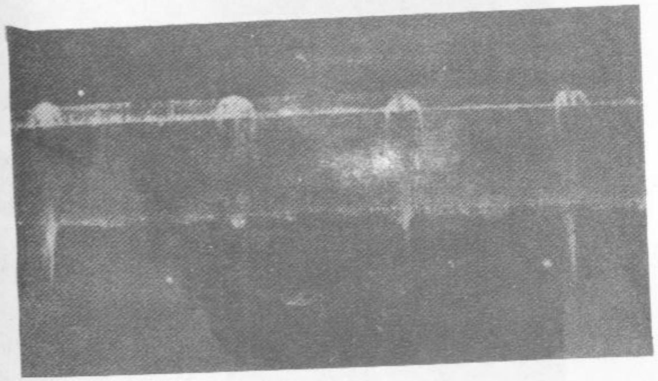

Fig. 11. Görtler vortices in the outer layer. d= 10 mm, U = 3.1 cm/s, U_p/U = 2.2, Re = 238.

been fully exploited, nor have sufficient experimental data been obtained to resolve important structural questions about entrainment and turbulence production. Even given suitable non-intrusive instrumentation, it is a major difficulty that the trajectory of successive rings is subject to considerable dispersion, so that statistical quantities are likely to be even less precisely defined than is usually the case in work on coherent structure.

The sketch in Fig. 4 is my present conjecture as to probable mean particle paths in non-steady similarity coordinates for a turbulent vortex ring with a thin core. However, the structure in the sketch is not a likely candidate for prototype large eddy for the circular jet. The growth rate is much too slow. In this respect the vortex ring is very like the line vortex in a mixing layer, and very unlike the spot in a boundary layer. Coalescence, if it occurs, must be a very complex phenomenon. Several fascinating studies of the behavior of non-circular rings and of multiple-ring interactions have domenstrated the occurrence of ringing, fusion, fission, and various other processes which can be roughly described as excitations or as collisions (Kambe and Takao, 1971; Oshima, 1972; Viets and Sforza, 1972; Fohl and Turner, 1975; Oshima and Asaka, 1975,1976, 1977a, 1977b).

Another large part of the literature on vortex rings deals with effects of buoyant forces. A thermal, whose momentum is continuously changing, is not the same as a vortex ring, whose momentum is fixed when it is formed. Nevertheless, these two motions are often considered together, and similarity arguments are in fact quite advanced for buoyant flows. The term puff is commonly used in this literature to denote a structure whose vorticity is

distributed rather than concentrated in a thin core. Such distributed vorticity can be realized experimentally as use of a screen or other resistance at the nozzle exit, or analytically by use of an eddy viscocity. The structure which is obtained is turbulent by definition and intent, and in the absence of buoyant forces is completely consistent with the similarity variables already defined. The puff, because it has a growth rate very much larger than the growth rate for a vortex ring, may in fact be the proper prototype large eddy for the turbulent jet.

7.0 THE TURBULENT VORTEX STREET

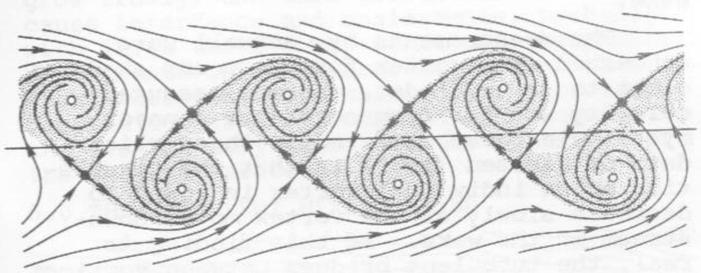

Fig. 5 Conjecture for approximate mean particle paths in a turbulent vortex street, mostly after Cantwell (1975 and private communication). The presentation assumes quasi-steady flow in coordinates (x -ct,y), where the celerity c is close to the mean of the centerline and free-stream velocities. There is no appreciable distortion of scale.

The vortex street is a train of two-dimensional vortex structures which are very closely linked. Excellent flow-visualization studies of the laminar case have been made, for example, by Taneda (1959), Zdravkovich (1969), Corke et al. (1977), and Matsui and Okude (1980). Each vortex entrains fluid and grows in size. Vortex coalescence and doubling of scale are known to occur, but only after a distance of many tens or hundreds of body diameters (Taneda, Matsui and Okude). The turbulent case is not qualitatively different from the laminar one, and I believe that the sketch in Fig. 5, which is based on experiments by Cantwell (1975 and unpublished) and Owen and Johnson (1980) and on flow visualization by Ryan (1951) and Thomann (1959), is topologically sound. In particular, the saddle points in the sketch are real and are properly placed. Each vortex entrains fluids mainly along its upstream-facing interface, and this fluid comes mainly from the opposite side of the wake.

The measurements by Cantwell were concerned with vortex formation and shedding close to the cylinder, and the measured celerity was far from constant. A major mystery in these data and in the earlier
IIIII data of Nielsen (1970) is that the circula-
11111 tion of an individual vortex is found to
11111 decrease slowly as the vortex moves downstream in the wake. If this finding is real, the turbulent bridges between vortices must constitute very weak upstream jets which continuously transport small amounts of mean vorticity between vortices of opposite sign.

An important feature in Fig. 5 is the set of saddle points, near which there is a substantial strain field. It is almost certain that the rate of turbulence production is large near these saddles, and that this turbulence is subsequently transported into the main vortex structures where it accounts for the observed peaks in turbulent energy.

The real structure of a turbulent far wake is not known, although estimates of scale have been made by Barsoum et al. (1978). My own conjecture, in view of the

fact that vorticity of both signs is present in the flow, is that the characteristic structure is probably a vortex loop closed across the wake. Some evidence on this point can be found in work on tapered cylinders, or cylinders having discountinuities in diameter, or uniform cylinders in shear flow, although I will not present the evidence here. It is characteristic of vortex shedding in the high subcritical range of Reynolds numbers that there is considerable dispersion in the strength and trajectory of successive turbulent vortices. No method was found in Cantwell's experiment to reduce this dispersion. The vortices grow slowly, and this growth must eventually cause interfence and coalescence, probably with large three-dimensional effects. Future experiments on the turbulent vortex street might well take advantage of the fact that oscillation of a cylindrical body normal to
the flow greatly increases the coherence of IIIII
the shedding process. 11111
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8.0 THE TURBULENT MIXING LAYER

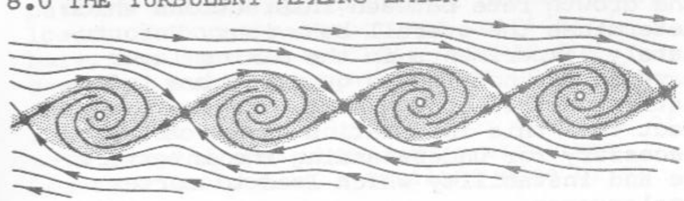

Fig. 6 Conjecture for approximate mean particle paths in a turbulent mixing layer, mostly after Brown and Roshko (1971) and various numerical studies. The presentation uses coordinates (x - ct, y), where the celerity c is close to the mean of the two stream velocities. There is no appreciable destortion of scale.

A seminal event in the development of coherent-structure concepts was the presentation of a paper on the turbulent mixing layer has by Brown and Roshko at an AGARD conference in London in 1971. The problem of the mixing layer has by now generated a very large literature, which I regret that I have not had time to examine with the care it deserves.

A part of this literature deals with the transition process, particularly the appearance of three-dimensional small-scale motions. Another part deals with eddy coalescence and its control. Numerical as well as experimental studies have contributed to both of these areas. One important result of this research certainly must be mentioned. Analysis by Hernan and Jimenez (1979) of motion pictures from CIT apparatus, as well as numerical simulations by Takaki (1979), suggest that the total volume of turbulent fluid is nearly constant during coalescence in the mixing layer. An immediate implication (which may be valid for other flows also) is that it is only the growth rate between interactions which determines the overall behaviour. Unfortunately, experiments in the mixing layer have so far not led to quantitative information on this growth rate, despite the fact that this information may be vitally necessary for understanding the interference and instability which lead to vortex coalescence.

9.0 DISCUSSION

The six structures just described have in common that each involves a recognizable concentration of large-scale mean vorticity in two or three dimensions. To any approximation which leaves out effects of viscosity, these concentrations can be thought of as obeying the usual vortex laws. The vortices must close on themselves or go to infinity. In a viscous fluid, branching may occur.

Classification of these flows into a smaller number of species is an uncertain process. The transition structure- the puff, spot, and spiral - involve walls.Hence vorticity is present in the external environment, and propagation of turbulence may be governed by special rules. The transition structures also have in common that they may be thin enough to call for a boundary-layer approximation. The vortex ring is free to grow indefinitely, but because the vorticity is supplied impulsively the structure must eventually decay. The structures which occur in train - the mixing layer and the vortex street - are not free to grow indefinitely, because interference between adjacent structures must inevitably lead to interactions which change the pattern.

The idea of coherent structures as vortex concentrations obeying the vortex laws has to be taken seriously. One example is the case of vortex shedding from a cylinder in shear flow, where the expected and observed result is a cellular shedding pattern and the appearance of closed vortex loops. Among the structures considered here, the spot is special, because the skeleton vortex presumably ends on a wall and is therefore in contact with its image system. Nothing is known about the fate of this image system when such a structure leaves a surface at a trailing edge or at a corner.

An important element of classification for coherent structures is the mechanism of turbulence production. In the wall-dominated flows, the mechanism is probably shearing strain, perhaps within a boundary-layer approximation. In the free shear flows, the mechanism is probably vortex stretching. The turbulence moves from its source region mainly by transport (both along and across mean particle paths) by motions at intermediate scales. Eventually, there must be an interface. I think it likely that the propagation velocity of this interface can be described by a non-linear diffusion model of a kind first suggested to me by Julian Cole, and proposed independently by Les Kovasznay (see Kline, Morkovin, Sovran, and Cockrell, 1969). In this model the diffusion coefficient is proportional to the turbulent energy, and the propagation velocity is therefore proportional to the gradient of turbulent energy near the interface. That the gradient in question is roughly constant is suggested by some of the data already cited; see for example Coles and Van Atta (1967) or Wygnanski et al. (1975). This non-linear model can perhaps account also for nearly passive interfaces if it is the gradient of the small-scale energy which governs the propagation process.

Several analytical (including numerical) directions of attack suggest themselves for the problem of coherent structure. Various authors have studied numerically the kinematics of discrete vortices, usually stipulating finite cores to avoid singularities. The results often imitate nature, closely, suggesting that a rotational but inviscid model for coherent structure has considerable value. Large-eddy simulation is conceptually closer to an experiment. One advantage is access to more information than can be readily extracted from an experiment, including perhaps the elusive pressure-strain covariance which is not experimentally accessible. A disadvantage is cost, since celerity and structure have to be extracted simultaneously by statistical methods which may require many realizations (or a single realization extending over a long time).

By any standard, the puff in a pipe is an attractive candidate for study by large-eddy simulation, or even by direct solution of the Navier-Strokes equations. The

structure is axisymmetric and occurs naturally in train, thus bounding the numerical domain. Moreover, because of the low Reynolds number, widely different grid intervals in different parts of the flow should not be required. One prospect is that the phenomenon of splitting might be reproduced and something learned about its nature. Another is that a test might be made of the recent conjecture that sublayer vortices are produced and maintained by an instability of Taylor-Görtler type. Such sublayer vortices were in fact observed in pipe flow by Richardson and Beatty (1959) at about the same time that they were first attracting attention in boundary-layer flow.

A more technically oriented but still realistic goal on the analytical side is to lower the application to Reynolds averaging one level, to a description of the coherent structure itself. Details which might themselves qualify as coherent structure under either of the working definitions in the introduction would automatically be averaged out. Several risks are involved in attempts to model an average structure, by which I mean a deterministic average structure, in this way. The problem of a model for diffusion of turbulence near interfaces has already been mentioned. Energy production should be concentrated mainly near saddles, with energy intensity increasing in the direction of mean particle trajectories toward the associated center. The computed distribution of turbulent energy must possess the appropriate spatial gradients so that interfaces with the correct propagation velocity appear in the correct locations. Rates associated with various flow processes of considerable technical importance, possibly including separation, might eventually be describable using estimates of characterstic transit times from saddle to center.

Finally, an exciting prospect, developing rapidly on all sides, is the prospect of control of turbulent shear flows by manipulation of coherent structures. The first demonstration of this technique was the use by Roshko of a splitter plate to inhibit vortex shedding and thus to affect the drag of a bluff body. Examples of diagnostic attacks on various flows using essentially black-box methods include the work on the boundary layer by Stratford (1959), the work in pipe transition by Vallerani (1964), and the work on jets by Crow and Champagne (1971), Olivari (1974), and others. In the case of the boundary layer, operational control of surface friction in liquids using high-molecular weight polymers is commonplace. In a recent survey paper, Bushnell (1979) has described the use of riblets, or small streamwise grooves on a wall, in an effort to interfere with the natural scale of sublayer vortices, and the use of screens or honeycombs, in an effort to modify the outer boundary layer. This research is at an early stage, but the future is bright.

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THREE-DIMENSIONAL ASPECTS OF BOUNDARY-LAYER TRANSITION

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1.0 INTRODUCTION

In the present paper it is intended to discuss only a limited number of subjects concerning the three-dimentional aspects of boundary-layer transition, especially those which are not only essential for affording a correct understanding of the basic feature of transition, but also adequate for systematizing the writer's own thoughts on the problem of transition.

2.0 TRANSITION IN TWO-DIMENTIONAL BOUNDARY LAYERS.

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Transition in Blasius boundary layer and plane Poiseuille flow is preceded by the appearance of two-dimentional waves of the type predicted by linear stability theory (Tollmien-Schlichting Waves), but the effect of finite amplitude presents itself in the form of a nearly periodic variation of wave amplitude in the spanwise direction, with maxima (peaks) and minima (valleys) along certain streets parallel to the stream. This variation of wave amplitude generates a system of streamwise vortices, which in turn redistributes the momentum of the basic flow, in particular, producing an inflexional velocity profile at the peak position. The theory of Benney and Lin (1960, 1961, 1964), centered on the non-linear interaction between a two-dimensional wave and a three-dimensional wave with spanwise periodicity, accounts for the generation of streamwise vortices from an initially