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COHERENT STRUCTURES IN TURBULENT FLOWS

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Abstract—Coherent structures—loosely defined as regions of concentrated vorticity, characteristic and flow-specific organization, recurrence, appreciable lifetime and scale—have been the foremost object of scientific curiosity and dispute in turbulence research for more than ten years past. The concept, based on visual observations, that turbulence, hitherto viewed as a purely random phenomenon, appears to contain a constituent of clearly organized structure promised an alternative to the frustrating verdict that turbulence can only be understood and tackled on statistical grounds. After a first period of enthusiasm, which was then nourished by a few supportive survey papers, the concept was challenged and criticism as to the uniqueness, the ubiquity and finally the importance of those structures was put forward.

Although a great number of turbulent flow configurations—essentially all of 'classical' flows—have to some extent been investigated and scrutinized for their content of structural organization, many questions remain open and the dispute is by no means settled. In this review we shall restrict ourselves to trying to summarize a few of the more important results and issues without trying to settle this argument. At the same time some open questions will be discussed.

Meanwhile an abundance of knowledge has been collected on some free flows, in particular the mixing layer, the wake and—to a lesser extent—the turbulent far jet. All free flows undergo at least one transformation before they become self-similar and unique (do they indeed become unique?). Thus, the mixing layer is the eventual outcome of the transformation of the boundary layer flow from the nozzle. Jets and wakes in their early stages go through intermediate mixing-layer manifestations. Little wonder that also in those cases we often find more than one characteristic structure.

Different structural developments appear to be related to different behaviours of the basic flow: The more complex structures, characterized by three-dimensional (Reynolds number and/or lifetime-dependent) agglomerations of hairpin, ring and spiral vortices as in a spot or a puff, are found in those flows which are primarily frictionally unstable (wall flows). Particularly in the boundary layer, we observe a whole zoo of structures, some of which (e.g. the wall streaks) clearly violate the obviously too limiting 'classical' definition of coherent structures being exclusively 'large scale' events. Consequently, as much as these findings undoubtedly add to our understanding of turbulent processes, the concept of coherent structures forfeits some of its original meaning for a more refined picture, the larger the structural multitude becomes.

In those flows where inviscid (inflection-point) instability dominates, we find comparatively simpler structures of large scales like single line or ring vortices as in mixing-layer, jet and wake flows, with three-dimensionalities following secondary instabilities. But also there we find the corresponding 'small scale structures', longitudinal vortices along the interconnecting braids between the large-scale structures. The common aspect then for all shear flows seems to be the existence of at least two coherent scales, the small one with longitudinal (stretched) vortices being responsible for turbulence-energy production, while the large scale takes care of part of the diffusion. An independent aspect is introduced by the consideration of spiral turbulence as being an intrinsic feature of turbulence eventually leading to the formation of coherent structures in all three-dimensional flows. Formation of coherent structures, as we observe it, touches on a phenomenon of greater generality and significance: spontaneous formation of organized structures from a state of relative disorder is found in organic as well as in inorganic nature. This process is known as Synergetic, and chaos theory is but one of the theoretical tools of this discipline.

It is evident that organized structures could not be observed or educed by methods applying any indiscriminate averaging scheme such as Reynolds-averaging. As a consequence, after existence of those structures was evident from visualization, adequate techniques had to be developed to educe repetitive flow events of a certain similarity. The true fraction of coherent energy in the overall turbulent energy can, however, not possibly be assessed with any claim to accuracy. Estimates (their reliability supported by the fact that different methods give similar numbers) show the coherent structures to be responsible for between 10% and 25% of the turbulent energy in most of the flows considered (contrary to Townsend's "big eddies" whose energy content was assumed to be essentially negligible). This figure emphasizes the importance of coherent structures in correctly modelling turbulent flows and, even more so, as a medium to manipulate turbulence (by mechanical, acoustical or chemical means) and thereby influence its most notable technical consequences: noise, mixing, combustion and drag.

CONTENTS

1. INTRODUCTION

Since its earliest conscious observation turbulence has been described and visualized as a chaotic motion. Visualization studies suggested its randomness and the macroscopic analogy to Brownian motion offered itself as a handy model. To the human way of thinking the acceptance of natural phenomena being fully random seems, however, difficult to accept in view of the omnipotent and perfectly obvious law of causality. And does not perfect randomness in a world of clear physical relations seem to contradict the notion of stochasticity altogether? Indeed the idea of 'weak causality' was born only much later, being the basis of the modern theory of chaos.

Little wonder, therefore, that everyone working on problems of turbulence has been searching for traces of order in the apparent chaos for better understanding, as well as for the ultimate goal of handling and managing this particular kind of recalcitrant motion. And there was always an abundance of evidence for the existence of order, i.e. a certain measure of organization in what seemed at first glance to be random: some of the most obvious examples being the clouds in the sky. They exhibit a profusion of variations, yet they can be systematically 'labelled' to belong to only a few distinctly different types.

The concept of coherent structures in turbulent flows became popular only about 15 years ago beginning with Brown and Roshko's (1971) often quoted investigation of the plane mixing layer. The conscious observation of such structures was, however, by no means new: While the 'forefathers' like Boussinesq and Reynolds do not seem to have tried to picture turbulent motion in structural details, it was only a few decades later that Prandtl (1925) tried to improve the description of turbulent motion by introducing concepts arrived at from experimentally studying the characteristics of motion. The outcome of this study was the mixing length hypothesis based on the postulation of "Flüssigkeitsballen", which were considered responsible for the transport (i.e. the mixing) of momentum across the flow. In fact these "Ballen" appear to be the first coherent structures we find in the history of turbulence. No particular characterization or definition of those structures was ventured (or considered desirable) by Prandtl, and it was only much later that Bradshaw (1974) tried to explain and Landahl (1984) tried to justify his concept. Around 1950 we find an increasing interest in visualization of turbulence. More important observations and ideas of those and later years were:

(1) Townsend's (1956) "big eddy hypothesis", postulating the existence of a double structure: big eddies being in energetic equilibrium and the stochastic (sub-)structure, which essentially contains the turbulent energy. Townsend's idea of the big structures is based on the concept of Eulerean correlations. Its apparent lack of clearly defined organization is generally considered its main distinction and shortcoming as compared to the structures of modern thought. [See also Gartshore (1966).] The often emphasized 'substantial' difference between Townsend's model and our modern structural ideas may best be clarified by viewing a coherent structure in the Lagrangian system, i.e. in a frame moving with the celerity of the structure. As a typical example we examine a turbulent spot in a laminar boundary layer as shown in Fig. 1 [after Wygnanski (1981), Falco (1978)].

Although a large-scale unity from an overall point of view, it is actually a well organized agglomeration of small-scale (hairpin) vortices characteristic of this particular kind of flow. Calling the spot a large-scale event or a 'big eddy' is thus in fact telling less than half of the whole story. This is, however, what (in most cases) it would look like after signal filtering, and the so called 'footprint'of a coherent event in the bordering outer, e.g. potential, region of a turbulent flow is just that: a low-pass filtered image of the real event which, when used as a basis of analysis, may lead to over-simplifying conclusions. This low-frequency footprint is, however, successfully employed as a trigger for all kinds of pattern eduction schemes as will be outlined below. Not all cases may offer such a clear distinction and in a general way it seems well justified to consider our modern concept rather a refinement than a replacement of the big eddy.

(2) Some ten years after Townsend's idea was first published, Kline *et al.* (1967) reported observations of longitudinal streaks in the immediate wall-proximity of a turbulent boundary layer. These findings, which had some less-noticed predecessors [Hama (1957), Ruetenik (1954)], initiated a renaissance of interest in boundary layer structures, in particular the structural events and correlations with regard to energy production mechanisms, which is believed to be closely connected with the streaky structure [see also Còrino and Brodkey (1969), Eckelmann (1970)].

Why then did it take so long until the already perceived phenomenon achieved adequate recognition? Clearly our preconditioned view of turbulence as being a purely stochastic phenomenon [Taylor (1935, 1936)] provided a serious obstacle for this kind of concept. Changing a traditional way of thinking is always a lengthy and cumbersome process and the specific tools used to describe turbulence in the classical sense, namely the Reynolds equation and, in this context, the Reynolds-averaging procedure, which indiscriminately irons out all structural peculiarities and characteristics, were not helpful for discovering anything beyond the stochastic.

Historically the notion of coherence was reserved for wave phenomena of optical, acoustic or electro-dynamic physics, meaning (according to *Funk and Wagnalls Standard Dictionary*, 1970): " . . . that relation of coincidence between two sets of waves, which will produce interference phenomena . . . ". In the present context the notion of coherence is used, in contradistinction to its classical meaning, in a more colloquial sense. Thus a coherent structure is a flow structure with discernible correlation, i.e. an element of turbulent motion which is set off against the stochastic background and which by its repetitive specific properties characterizes a specific flow. Figure 2 shows a collection of characteristic flow structures as they are observed in turbulent flows as well as in regions of laminar/turbulent transition. [For a plentiful source of flow visualizations the reader is referred to Van Dyke's *An Album of Fluid Motion* (1982).] All these photographs show laboratory situations. This invites critical scepticism, at least with respect to the 'fully' turbulent structures, as was primarily put forward by Bradshaw and collaborators [Chandrsuda *et al.* (1978)]:

> All photographs show 'young' flows of relatively small Reynolds numbers and (possibly) not yet fully developed structures. One must ask therefore whether then the clearly visible (coherent) structures are true reflections of the turbulent flow or possibly just relics of the characteristic structures of laminar/turbulent transition, which they indeed resemble so closely?

Observation of natural phenomena provides the answer: meteorological structures [e.g. the vortex street in the lee of the island of Madeira, see Berger and Wille (1972)], well known examples of oil-wakes in the lee of damaged tanker ships and, as an extreme case, even Jupiters great red spot [Gleick (1985)], are all characterized by Reynolds numbers orders of magnitudes larger ($\mathrm{Re} > 10^7$) than those attained in laboratory experiments, yet they are manifestations of great similarity to what we find in the latter. Figure 3 gives some examples.

Another argument supporting our belief in the true nature of coherent structures is their spontaneous reformation out of the randomized flow after their deliberate destruction, as was clearly shown for example in the experiments by Breidenthal (1978), and by Wygnanski *et al.* (1979). The photographs shown in Figs 2 and 3 may serve as a basis for a definition.

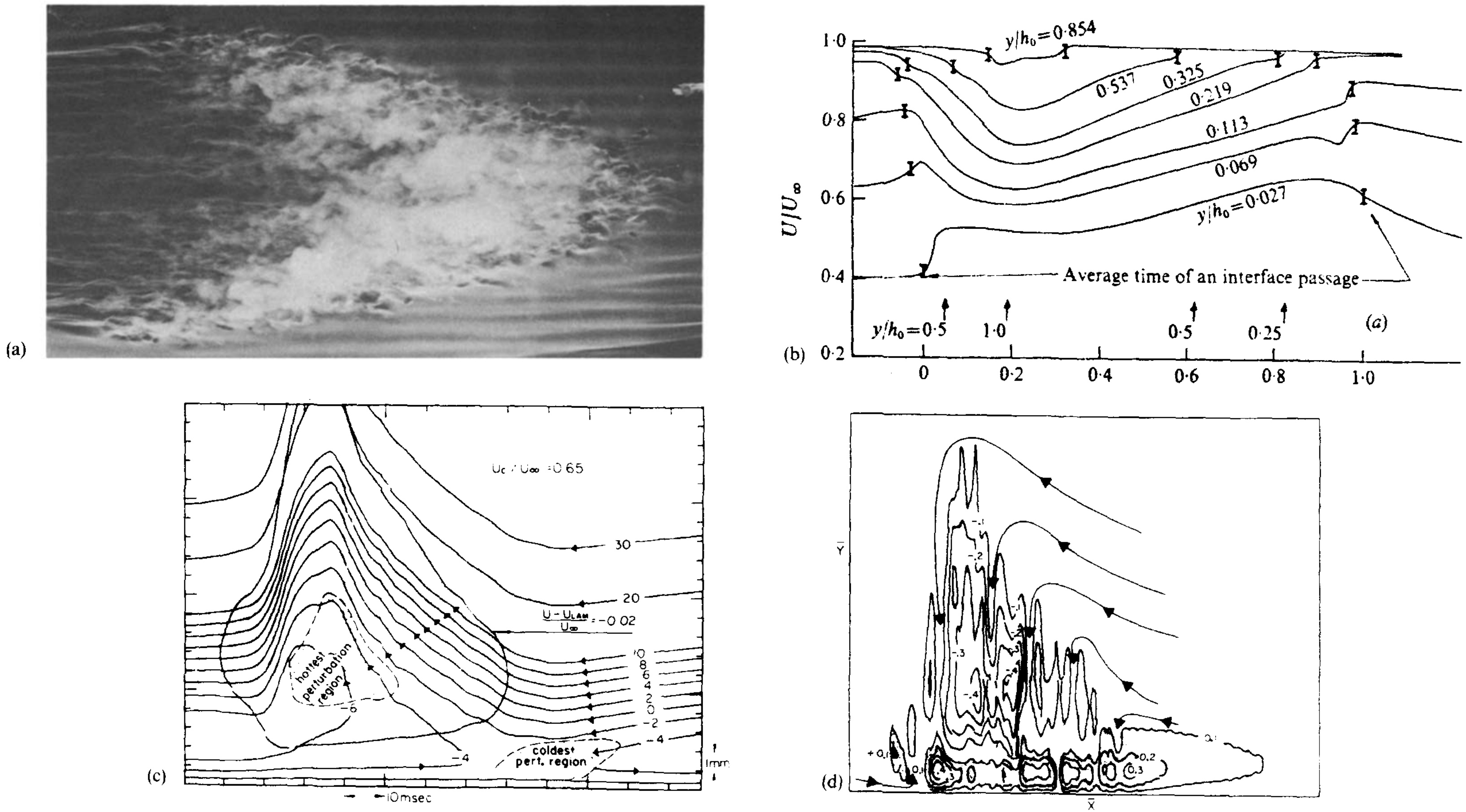


FIG. 1. The turbulent spot in a laminar boundary layer—an example of a coherent structure: (a) smoke photograph (by Falco, 1978), (b) hot wire signals at a spot's passage—different vertical positions (Wygnanski *et al.* (1976)), (c) streamline pattern as seen by an observer moving with the convection velocity U_c, (d) velocity perturbation contours for single event. (c) and (d) from Wygnanski (1981).

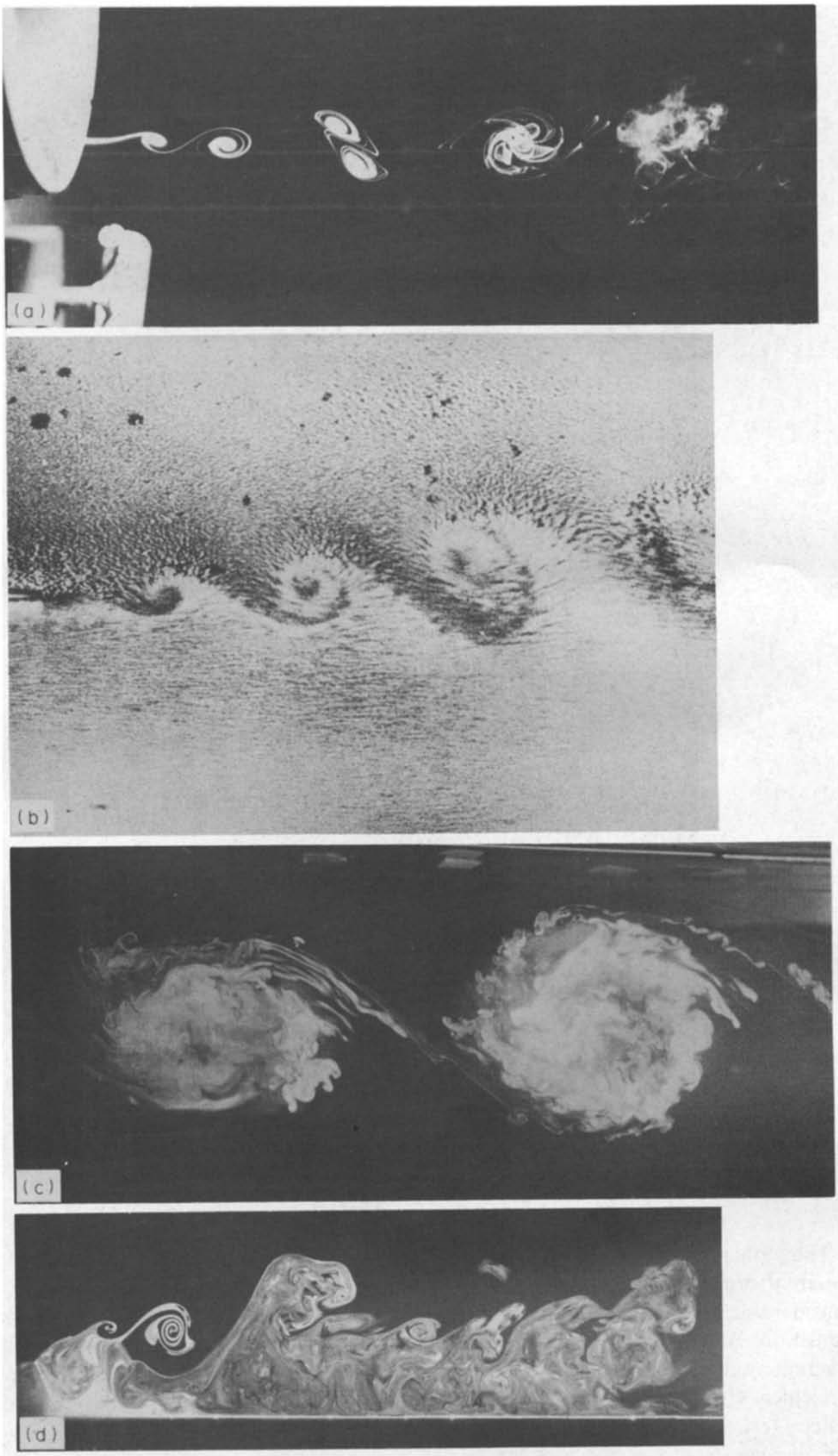


FIG. 2. Coherent structures in laboratory visualizations (Re $\leqslant 10^5$): (a) mixing layer: laminar/turbulent transition [Freymuth (1966)], (b) plane turbulent mixing layer [Michel (1932)], (c) excited accelerated mixing layer [Boettcher and Fiedler], (d) reattaching shear layer [Ruderich and Fernholz (1986)].

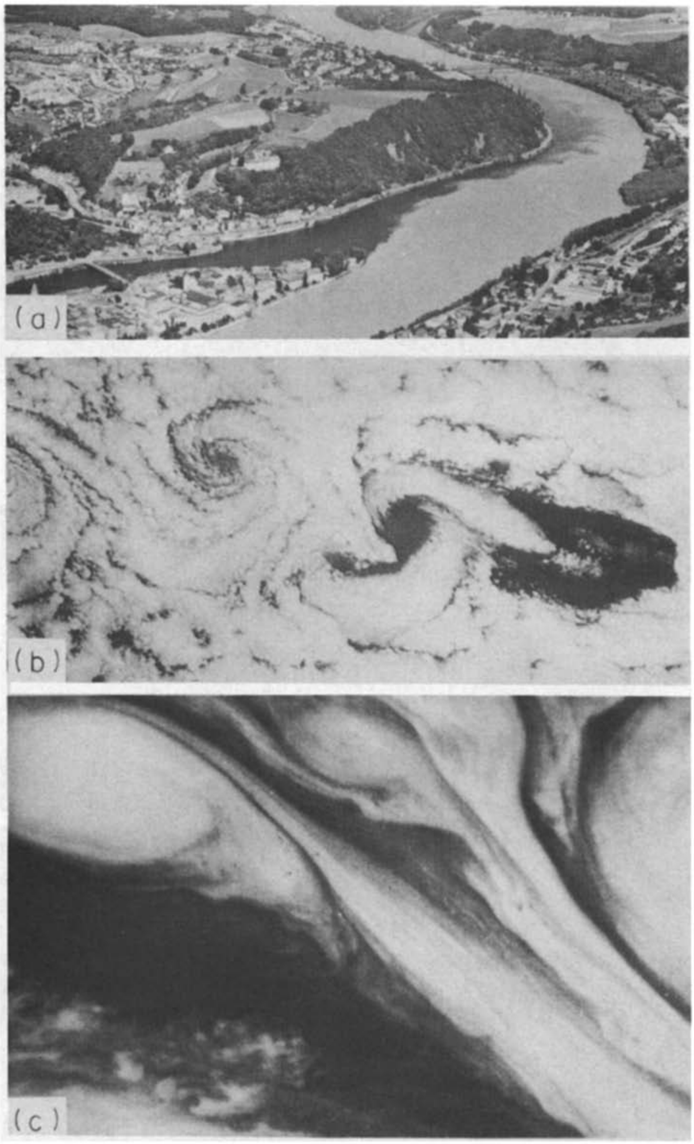


FIG. 3. Coherent structures in nature (Re $\geqslant 10^6$): (a) mixing interface between two merging rivers [Danube and Inn at Passau (Germany)], Re $\sim 10^7$, (b) meteorological structure (wake behind island), Re $\sim 10^{10}$, (c) 'planetary' structure (detail from Jupiter's atmosphere), Re $\sim 10^{14}$.

2. DEFINITION

Thus coherent turbulent structures in a turbulent flow are first of all regions or motions of apparent order, as observed from flow visualization which, at least in a loose way, show considerable similarity to the instability waves observed in the range of laminar–turbulent transition. At closer inspection we may characterize them as connected non-stationary dynamic systems 'connected' in the sense of a (correlated and concentrated) dynamic quality, for which Hussain (1983, 1986) suggested vorticity ($\boldsymbol{\Omega}$); others, not quite convincingly, helicity ($\mathbf{c} \cdot \boldsymbol{\Omega}$), where $\mathbf{c}$ = velocity vector (vectors are represented by bold symbols).

Coherent structures are 'non-stationary' systems since one ought to exclude all those structures which are, as a primary consequence of flow geometry, trapped in a certain flow region (e.g. corner vortices and the like). From the flow pictures we may derive some criteria for coherent structures which may serve to provide a definition. Thus they can be said to be:

(a) Typically of composite scales, their largest comparable to the lateral flow dimension.
(b) They appear to be flow-specific in shape and composition, i.e. indirectly related to boundary conditions.
(c) They are, and this is their very essence, as a pattern recurrent, having a life-span typically at least the average passage time of a structure.
(d) They exhibit a high degree of organization in their structure as well as in their dynamics. Their appearance on the other hand is at best quasi-periodic (typically stochastically intermittent).
(e) They show strong similarities with corresponding structures of the (preceding) laminar–turbulent transition.

These criteria are relatively limiting and other concepts are not uncommon. Thus one finds occasionally stationary flow patterns like corner vortices etc. labelled as coherent structures. Tennekes (1985) for example claims the existence of a large number of coherent structures in one and the same flow (the planetary boundary layer), a notion which of course renders the whole idea questionable as to its usefulness.

In fact, in view of the multitude of structural manifestations observed, it seems reasonable, at least our present state of knowledge, to refrain from trying to find a complete definition of coherent structures and rather leave it at a concise characterization. An excellent survey on organized structures in turbulent flows was given by Cantwell (1981). In the following we consider their origins and causes.

3. ORIGINS AND CAUSES

This problem touches on a phenomenon of greater generality and significance. Spontaneous formation of organized structures out of the chaotic is observed in inorganic as well as in organic nature. This phenomenon, which has received strong attention during the last, say ten years, is known as synergetics; a scientific discipline of theoretical physics [see Haken (1983)]. It provides a basis for understanding and a theoretical description of coherent structures as a phenomenon of self-organization. A specific mathematical tool of synergetics is 'Chaos Theory', which only recently has attained some popularity as a possible basis for the description of flow turbulence [Miles (1984)]. Thus a coherent structure might be interpreted as a physical manifestation of a strange attractor, a recurrent iteration cycle of a system of higher dimension [say, $D_F \approx 2.5$ according to Sreenivasan and Maneveau (1986), where D_F = fractal dimension].

Whether this concept will, for the time being, further our understanding is as yet undecided. To go into further details of this approach would certainly exceed the scope of this article. The interested reader is therefore referred to the numerous papers dedicated to this subject.

Encouraged by the strong similarity of transitional and turbulent structures, formation of the latter has largely been considered a phenomenon of flow-instability, where the mean flow is treated like a laminar one [e.g. Fiedler *et al.* (1981), Gaster *et al.* (1985), Ho and Huerre (1984)]. Consequently coherent structures may be viewed as instability modes of the basic flow. The ambiguity of this procedure is obvious: mean profiles in a turbulent flow, to which inviscid stability theory is applied, have no physical reality. Still the results seem to justify the method. For example, for the plane mixing layer, one obtains line vortices which largely correspond to the observed turbulent structures and which also exhibit the characteristic pairing behaviour.

Those line vortices are on the other hand unstable along their axes, as we again know from visualizations. They develop secondary instabilities in a similar way as do ring vortices in a round jet (see Fig. 4), as was shown by Glezer (1984), Schneider (1980), and Widnall and Sullivan (1973).

There is further the phenomenon of feedback which may also have bearing on the formation and in particular the quasi-periodic recurrence of the structures, and we have finally to mention the influence of resonance as treated by Ho (1981), Laufer and Monkewitz (1980), Koch (1985) etc.

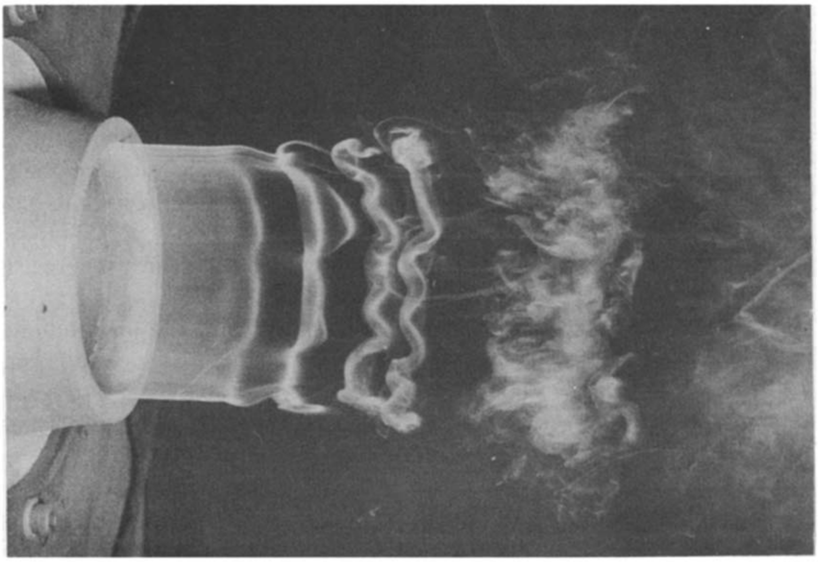


FIG. 4. Axial instability of a vortex: smoke photograph of periodically excited ring-vortices in laminar–turbulent transition regime of circular jet (axisymmetric shear layer). Photograph by R. Wille and A. Michalke showing circumferential undulations of growing amplitudes in the ringvortices followed by transition.

Arguments for helicity being intrinsic for three-dimensional turbulence and as such a basic element of coherent structures have been presented by Levich and Tsinober (1983), Tsinober and Levich (1983) and by Sagdeev *et al.* (1984). While it is understood that helicity is vital for turbulence it seems, however, (to this author) to be neither necessary nor sufficient for creation of coherence.

4. 1ST. DESCRIPTION: MORPHOLOGY/TOPOLOGY

For a morphological system, coherent structures, as identified in the so-called simple flows, can be reduced to (combinations of) a small number of elements, namely (Fig. 5)

Line vortex
Ring vortex
Hairpin vortex
Helical vortex

Perry and Fairly (1984) introduced the theory of critical points [based on Poincare (1879)] as a powerful tool for topological description of coherent structures [see also Coles (1985), Perry and Chong (1984), Ruderich and Fernholz (1986)]. Structures are characterized by Nodes, Saddles and Foci, while all other observed forms can be understood as combinations of the above elements. An example is shown in Fig. 5.

While observing a high degree of organization in the structures themselves we find their temporal sequence to be random. A particular aspect of this phenomenon is the intermittent change between dominantly coherent and stochastic flow, which we call structural intermittency. At least two explanations may be given. Lesieur (1984) visualizes the phenomenon as the result of a three-dimensional breakdown of the quasi-two-dimensional primary coherent structures following their secondary instability, and their subsequent spontaneous reformation out of the stochastic motion as a consequence of the instability of the mean velocity distribution. While this may be a perfectly valid model, we have strong evidence from numerical investigations recently pursued in the author's laboratory for the observed phenomenon to be essentially a feedback effect, and as such to a considerable extent facility dependent. Figure 6 (together with Fig. 27) may provide some insight: the discrete vortex simulation shown in Fig. 27 is a strictly two-dimensional computation yet it

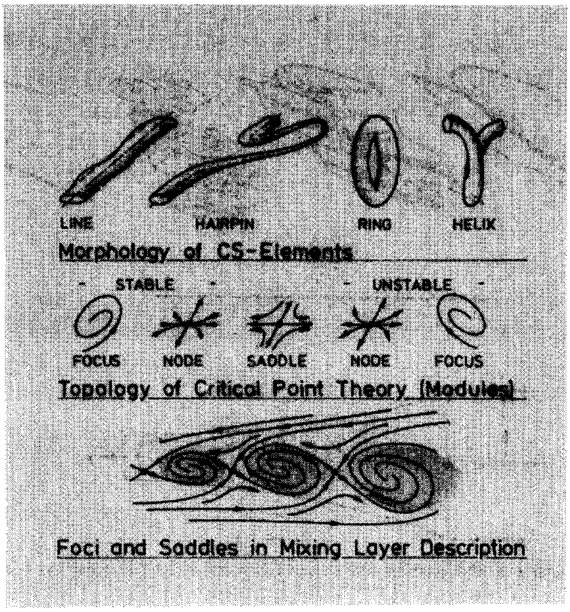


FIG. 5. Morphological and topological elements for description of coherent structures: (a) four basic morphological elements, (b) five basic topological elements, (c) topological description of a mixing layer flow.

clearly shows a kind of structural intermittency, thus offering an alternative to Lesieur's model.

5. METHODS OF EXPERIMENTAL ANALYSIS: METHODOLOGY/ANATOMY

To obtain useful information about structural characteristics in a turbulent flow, methods of analysis have to be employed which are made to fit the object: Contrary to the non-descriminating Reynolds-averaging over a given time, one has to compare and to sample recurrent events of certain similarity and eventually compute ensemble averages, which then represent the 'typical' (however not necessarily 'realistic') structure.

Techniques of the kind necessary for such a task are of almost unlimited complexity and expenditure. One of the basic requirements therefore is the digital computer, the leading role of which is unquestioned in modern experimental turbulence research. Apart from the again popular visualization methods, which in spite of their well known ambiguities, are advantageously used in combination with synchronized hot-wire measurements [e.g. Head and Bandyopadhyay (1981), Zaric *et al.* (1984)], basically two principles to obtain hard data are employed:

1. Conditional averaging, and
2. Pattern recognition

In addition there are a number of special methods of signal filtering (manipulation), by which a coherent signal content is amplified against the stochastic background [e.g. adaptive filtering; Nieberle (1985)], and the minimum entropy method [Corke and Guezenne (1986)]. Introduction of passive scalar tracers (e.g. temperature) is useful to identify coherent structures as was shown by, among others, Fiedler (1974) and is demonstrated in Fig. 7. Purely statistical methods like correlation techniques appear to be unsuited or at least extravagant for problems of this kind [e.g. Lumley (1981)]. A useful technique on the other hand is mode analysis, as introduced by Michalke and Fuchs (1975) [see also Fuchs *et al.* (1979)]. Its statistical results serve ideally for spatial interpretation of the structures for which (in most cases) the above procedures give but a two-dimensional cross section.

Having mentioned the important tool of visualization a few remarks seem in order:

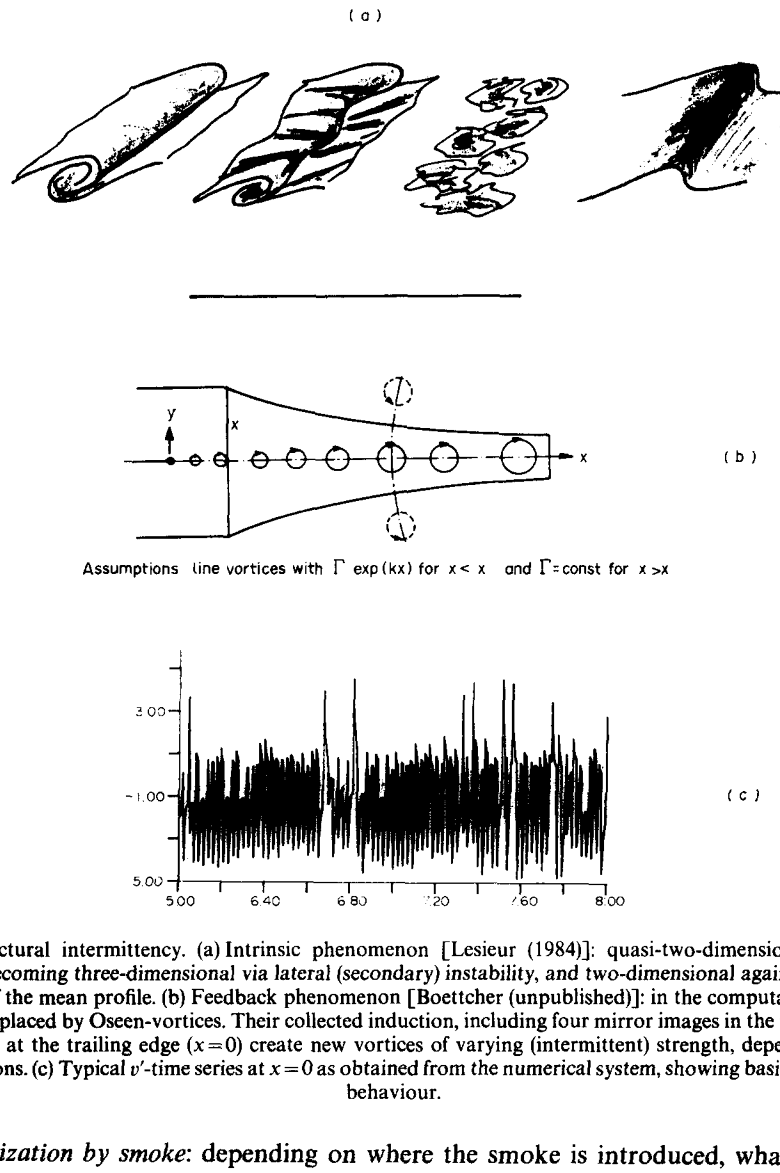


FIG. 6. Structural intermittency. (a) Intrinsic phenomenon [Lesieur (1984)]: quasi-two-dimensional coherent structures becoming three-dimensional via lateral (secondary) instability, and two-dimensional again via primary instability of the mean profile. (b) Feedback phenomenon [Boettcher (unpublished)]: in the computational model the flow is replaced by Oseen-vortices. Their collected induction, including four mirror images in the walls for each 'real' vortex, at the trailing edge ($x=0$) create new vortices of varying (intermittent) strength, depending on the phase positions. (c) Typical v'-time series at $x=0$ as obtained from the numerical system, showing basic intermittent behaviour.

(1) *Visualization by smoke*: depending on where the smoke is introduced, what is seen is essentially a streakline picture, the connection of which with the velocity field is complex. Interpretation of smoke pictures is therefore fallible and may be grossly misleading, as was discussed by Hama (1962). This is particularly true if the structures to be studied undergo significant dynamic changes. On the other hand there exists a clear analogy between lines of constant vorticity (isovorts) and streaklines, as long as the viscosity of the fluid remains negligible. This has been discussed by Michalke (1965), who indeed showed perfect identity of streaklines and isovorts in the transition region of a laminar mixing layer (see Fig. 8).

(2) *Visualization by Schlieren (or shadow) method* offers, on the other hand, a more direct insight, since the visible contrast is a linear function of the *local* density derivative and thus a function of the *local* velocity field.

Another distinction of importance is provided by the different illumination methods used in both cases discussed: smoke visualization typically employs illumination of a thin two-dimensional section of the flow (light sheet technique–scanning laser beam), thereby giving particularly detailed information about local *small scale* events. Schlieren visualization on the other hand integrates over the flow depth (unless sophisticated tomographic methods are employed), thereby essentially blotting out the small scale structure and emphasizing the (in the direction of the light beam) two-dimensional *large scale* structure, as is demonstrated by

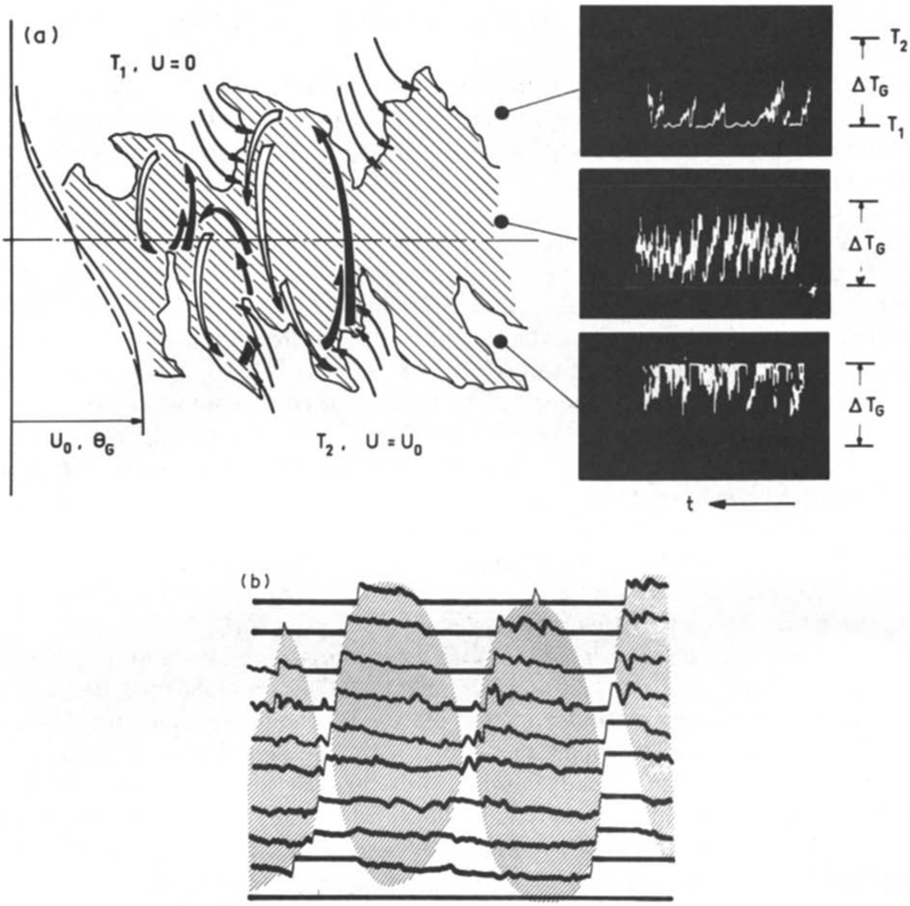


FIG. 7. Temperature field disclosing coherent structures: (a) conceptual sketch of structure in the mixing layer with typical ramp-shaped temperature signals, (b) series of temperature signals at different y-positions showing large scale structures (single events).

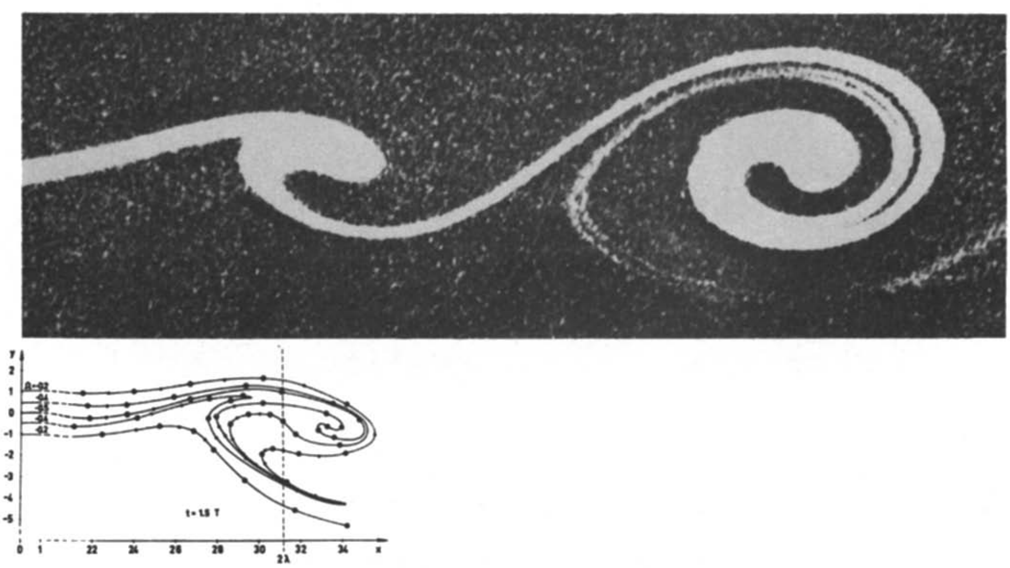


FIG. 8. Comparison of streakline pattern and isovorts; instability-rollup of laminar shear layer, smoke-photographs and appropriate isovorts [computed from linear stability theory by Michalke (1965)].

the well known shadow pictures shown by Brown and Roshko (1974), as compared to smoke pictures taken in a similar flow.

Conditional averaging depends on the existence of a trigger signal of sufficient stringency by which the ensemble averaging process is activated. In contrast to simple periodic situations difficulties are encountered when applying this method to a fully turbulent case. These are primarily caused by:

(1) Departure from periodicity.
(2) Phase jitter (fluctuation around the mean phase-position).
(3) Varying size and shape of single structure.

To minimize these problems, stabilization of the structures by periodic excitation of the basic flow at natural frequency in the dominant mode has often been applied [e.g. Oster and Wygnanski (1982), Fiedler and Mensing (1985), Hussain *et al.* (1986), Ho and Huerre (1984), Wygnanski and Petersen (1985), Stone and McKinzie (1984)]. It is, however, not always clear as to what extent and detail the thus 'frozen' structures, which are experimentally much easier to assess, represent the natural ones even at minimum excitation level. An answer to this question as obtained for a special flow is provided in Fig. 15. The problem is essentially that in the excited flow secondary modes as well as secondary instabilities are suppressed and therefore the structure obtained is too 'clean'. Low levels of excitation will give structures nearest to the natural ones. A certain level of excitation is, on the other hand, needed to obtain sufficient stabilization.

Comprehensive discussion of problems and their minimization in conditional averaging techniques is given by Antonia (1981), Blackwelder (1977), Yule (1980) and Hussain (1986).

Pattern recognition is in comparison even more extravagant. What makes it principally different from conditional averaging methods is its independence of an external reference signal: Pattern recognition methods consider only the basic signal itself out of which, via certain criteria, the structure of interest is educed. Thus pattern recognition methods are more versatile than conditional averaging schemes since they can be applied also in those cases where no reliable reference can be found. Figure 9 shows as an example the reconstructed vortex in a slightly (passively) heated one-stream mixing layer via a pattern recognition method developed by Rösgen (1979) and applied to temperature signals.

A critical comparison of some better known methods (e.g. the VITA-method (VITA: VARIABLE-INTEGRAL TIME-AVERAGING) introduced by Blackwelder and Kaplan (1976) and further developed by Chambers *et al.* (1983), and the TPAV-method (TPAV:

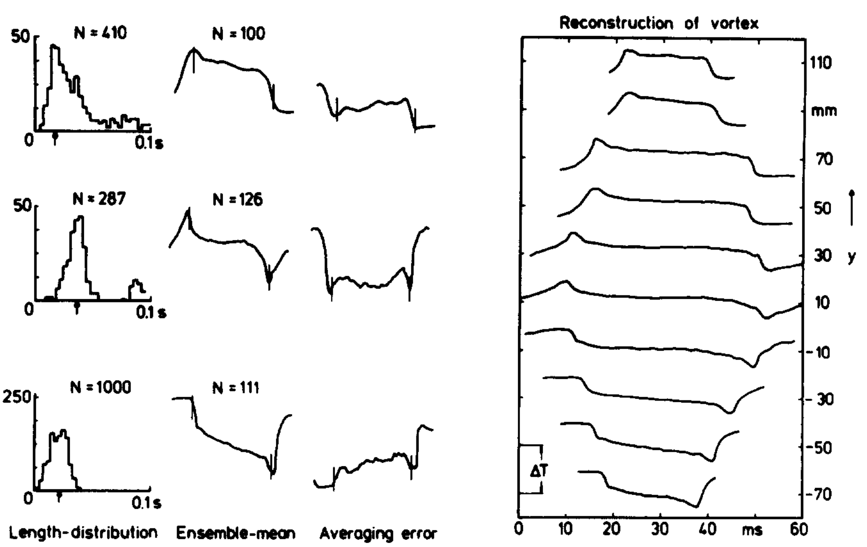


FIG. 9. Reconstruction of a vortex in a turbulent one-stream mixing layer from the temperature field: application of a pattern recognition method on temperature signals in a mixing layer separating a heated stream of air (passive scalar) and ambient air at rest and room temperature [Rösgen (1979)], compare this ensemble averaged vortex structure with the single events shown in Fig. 7.

short time TEMPORAL AVERAGE) by Wallace *et al.* (1977)], is provided by Nieberle (1985) who also presents a new and, in comparison with the above, more versatile method. See also Young (1986) and Kunen (1984) for general information, discussion and critique of pattern recognition methods. For the sake of completeness the quadrant analysis where structural information is drawn from the $u'v'$ signal in a four quadrant $u'v'$ representation [Lu and Willmarth (1973), Wallace *et al.* (1972)], and search strategies for coherent structures by direct signal analysis based on vortex models [Dracos (1984)] are to be mentioned. Both methods have been successfully employed in wall-bounded shear flows.

6. 2ND. DESCRIPTION: DYNAMICS

Refined analysis of a turbulent flow requires more sophisticated description, i.e. decomposition of its constituents as compared to the classical Reynolds description. In the course of an investigation of Taylor–Couette flow, a decomposition of the turbulent shear stress into an organized and a stochastic component was already given by Pai (1943). He wrote:

$$u'v' = u'v'_p + u'v'_s$$

where $_p$ stands for periodic and $_s$ for stochastic.

Similar procedures are customary for all flow parameters in treating and analysing coherent structures. A comprehensive discussion of the two current possibilities of decomposition and their consequences, the different forms of momentum and energy equation as well as some interpretations was given by Hussain (1983, 1986) and shall not be repeated here at length. Essentially two ways of data reduction are commonly used:

The double decomposition: $C_i = C_{c,i} + c_{CD,i} + c_{s,i}$.

The triple decomposition: $C_i = \bar{C}_i + c_{CT,i} + c_{s,i}$,

where $i = 1, 2, 3$ and $C_1 = U$, $C_2 = V$, etc. $C_{c,i}$ = convection velocity of the coherent structures (celerity) and the $\bar{C}_i$ = mean (time averaged) velocity. Indices $_{CD}$ stand for 'coherent, double-decomposed'; $_{CT}$ for 'coherent, triple-decomposed'; and $_s$ for stochastic. In this context we have to bear in mind that, although the stochastic and the coherent fluctuations are uncorrelated, there is often a significant correlation between the coherent signal phase and the stochastic signal amplitude, the latter riding, as it were, on the former. Figure 10 serves for demonstration.

Figure 11 shows two vector plots of a shear layer flow with periodic excitation taken at a certain phase position in juxtaposition to a smoke photograph. The upper picture was obtained by triple-decomposition, while in the centre we see the structure as obtained from double-decomposition (quasi-Lagrangean view).

In double-decomposition the flow field is viewed as from an observer moving with the convection velocity of the structure. The emerging structures are physically real and correspond essentially to what is seen in flow visualization. The primary flow is identical with the flow field induced by the vortices (= structures), that is to say there is no *a priori* flow field and the mean profile is part of the coherent fluctuations themselves. The disadvantage of this view is obviously then the fact that the interesting question of energy input into the vortices (production of coherent energy) becomes meaningless. In this case, triple-decomposition may be advantageous, defining the coherent structures content as (quasi-periodic) parts of departure from the mean values, i.e. coherent and stochastic fluctuations are considered additional motions superimposed on the mean motion. Coherent energy production terms are now easily defined but on the other hand the velocity field representation is unrealistic, showing alternately left- and right-turning vortices with half the basic wave length but of no physical reality. Essentially then this representation corresponds to the picture which would be seen by an observer moving with the average convection velocity and at the same time rotating with the mean vorticity, an unusual point of view indeed!

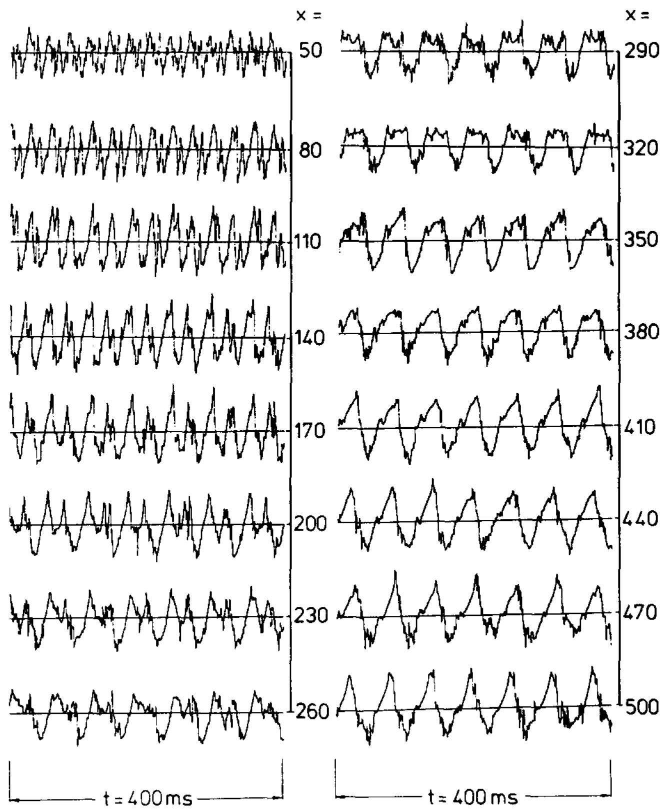


FIG. 10. Velocity signals in excited mixing layer, showing correlation of large scale phase and small scale amplitude [Fiedler and Mensing (1984)].

7. SCENARIOS IN DETAIL

All turbulent flows undergo certain metamorphoses before reaching their final state and every intermediate state is characterized by typical flow structures. While (turbulent) transient states generally lead to a qualitative change in structures it is believed (on the basis of observation) that laminar–turbulent transitional structures are largely similar to the subsequently developing turbulent ones. Examples are the turbulent spot in the boundary layer, the puff in pipe flow, the line vortices (and their amalgamations) in the plane mixing layer and the ring vortex in the round jet. Consequently the more purely and clearly developed and thus easier assessable transitional structures are often taken as models for the coherent structures in the corresponding turbulent flow, some of which are discussed in the following.

7.1. FREE FLOWS

7.1.1. *The Mixing Layer Between Parallel Streams*

This particular flow has not only triggered the coherent structure chase [since Brown and Roshko (1974)] but it has also remained probably the most often and most closely investigated 'simple' configuration [see Birch and Eggers (1972), Browand and Ho (1983)].

Much effort has been devoted to establish 'clean' situations regarding static and dynamic boundary conditions for the neutral flow [Fiedler and Mensing (1984), Dziomba and Fiedler (1984), Hussain and Zedan (1978)] as well as to 'purify' the structure to be investigated by acoustical or mechanical stabilization [e.g. Ho and Huerre (1984), Bechert (1982), Oster and Wygnanski (1982), Fiedler *et al.* (1981), Fiedler and Mensing (1984)]. The influence of 'external' conditions on the spread of a mixing layer is demonstrated in Fig. 12. An

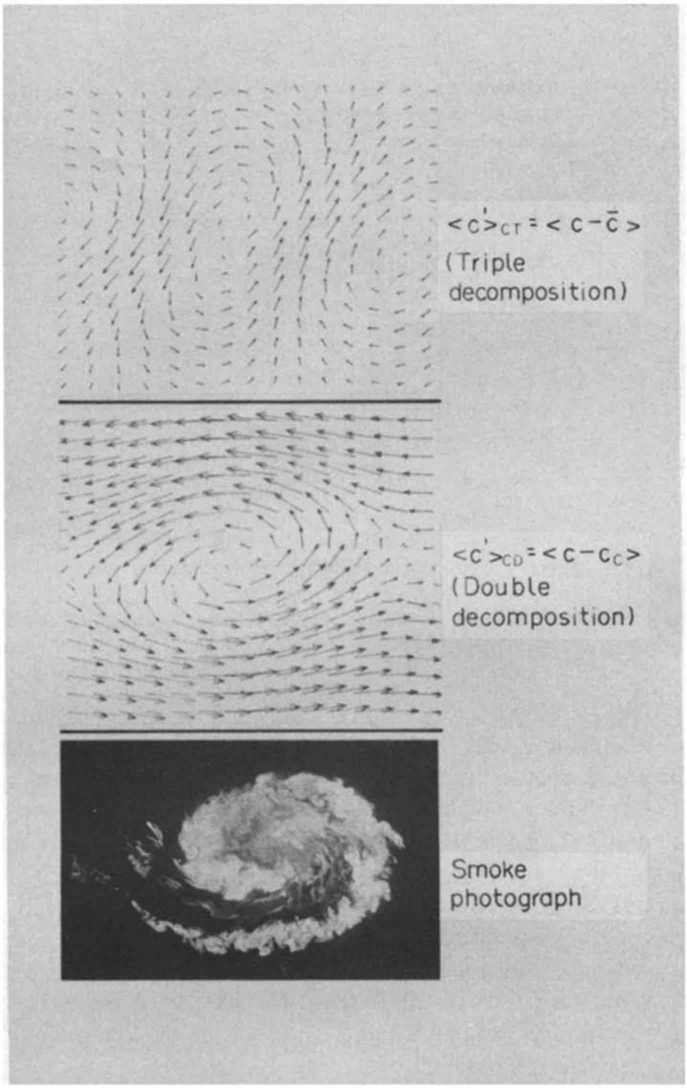


FIG. 11. Demonstration of consequences of double- and triple-decomposition of turbulence signals: juxtaposition of vectorfields in triple- and double-decomposition with smoke-photograph showing conformity of the latter two.

abundance of structure data as obtained by phase averaging techniques was published by Hussain and co-workers [see Hussain (1986)]. Still there remains a notable number of badly understood items, most of which have been discussed in the workshop 'Puzzles in Free Shear Layers' [Ho and Huerre (1974)]. There one of the most controversial issues appeared to be the question of whether pairing is central to spread. Another pending question of significance is concerned with the occurrence of structural intermittency (see below). Preferred modes, most clearly observed in axisymmetric mixing layers (e.g. the core region of a free jet), are again not fully understood [see Michalke (1984)]: in the near jet characteristically two (independent?) frequencies are found to occur simultaneously: a constant frequency f_{PM} with a typical Strouhal Number of $S_{PM} = f_{PM}D/U_0 \simeq 0.45$ which is called the preferred (column) mode and the shear layer mode f_s which is inversely proportional to the distance from the trailing edge, i.e. $S_s = f_s x/U_0 \simeq 1.0$. [Hussain and Zaman (1981), Gutmark and Ho (1983), Ho and Hsiao (1983), Nieberle (1984)]. Here we have used the symbols S = Strouhal Number, f = frequency, U_0 = jet velocity and D = nozzle diameter. The indices $_{PM}$ and $_S$ stand for preferred mode and shear layer respectively. An interesting explanation for this mode is offered by Bejan (1981) on the basis of an analogy between inviscid jets and elastic columns.

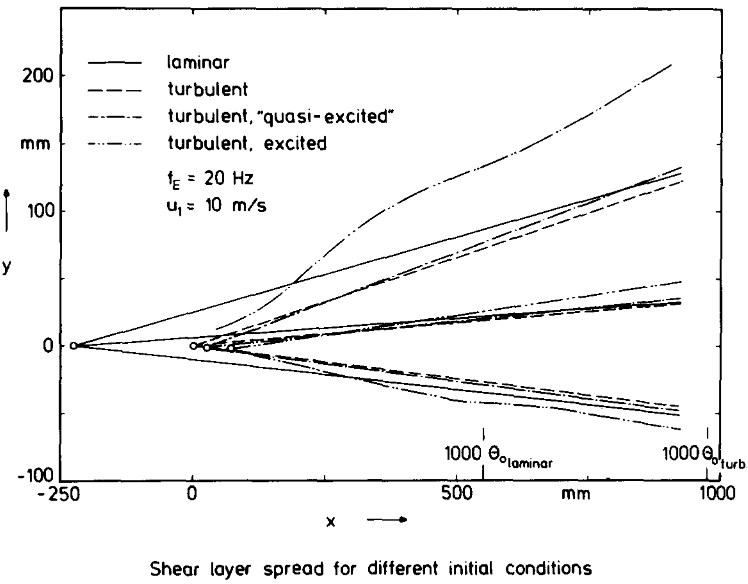


FIG. 12. Mixing layer development (spread) for different conditions: one-stream layer [Fiedler and Mensing (1984)]. Lines of $\bar{u}/u_0 = 0.1$, 0.5, 0.95.

A similar situation is found for the question of coupling of large (coherent) scales and the small or medium (stochastic) scales [see e.g. Liu (1981), Brasseur and Corrsin (1986)].

Another important aspect is mixing and its relation to coherent structure [e.g. Koochesfahani (1984)]. Influence of density differences of the two streams on the strength of the coherent structures have been investigated by Rebollo (1972) and Brown and Roshko (1974) among others. This problem has been taken up again and is revisited in the author's laboratory via numerical and experimental routes (Lummer, Nottmeyer): it is found that stability theory reveals a distinct relationship between density ratio and formation of coherent structures, which is in good agreement with experiments and direct numerical simulation. It turns out that the coherent structures are strengthened (and thereby the spread increased) in a situation where the higher density is on the low velocity side, and vice versa.

Let us now take a look at the structure itself: the basically two-dimensional line vortices, so characteristic for the transitional structure [Freymuth (1966)] but equally so in turbulent flow, soon develop three-dimensionalities, i.e. transverse wavyness (see Fig. 4). In addition longitudinal vortices (helices) of dimension typically an order of magnitude smaller than the primary structures, appear on the interconnecting braids [Lin and Corcos (1984), Lasheras *et al.* (1986), Jimenez *et al.* (1979)]. It is here that turbulence energy is produced [Hussain (1984), Coles (1984)]. The primary structures are seen to either amalgamate via double or multiple pairing, which in itself is generally a three-dimensional (helical) process, or lose their individual coherence by tearing [Saffman (1981)]. According to Wei Zhonglei *et al.* (1983) this process seems to depend to some extent on the turbulence level of the external streams. A conceptual sketch of the transverse and longitudinal vortex structure in a plane shear layer is given in Fig. 13 [after Bernal (1981)].

A unique flow for investigation of coherent structures was described by Fiedler (1984) and sketched in Fig. 14a: a plane mixing layer between two parallel streams of different velocities U_1 and U_2 was subjected to a longitudinal pressure gradient tailored such that the characteristic frequency f_c of the flow remained constant with x (in the parallel mixing layer $f_c \sim 1/x$). This then was tantamount to creating a flow with the utmost structural simplicity, i.e. a quasi-frozen pattern of a certain structural manifestation such that from a kinematic point of view vortex pairing must not occur. Experiments were made in a test section with a specially designed wall contour where the spread of the turbulent mixing zone as well as the propagation velocity of the large scale (coherent) vortices was, in accordance with theory,

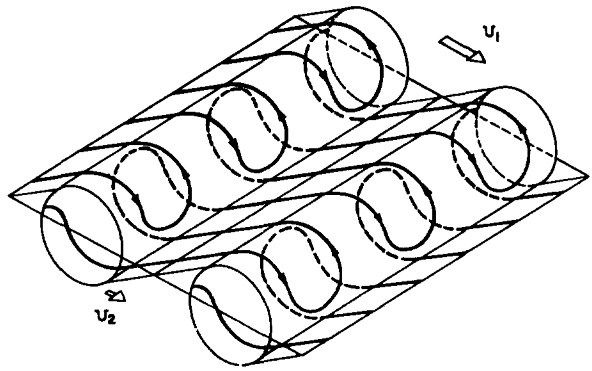


FIG. 13. Principle sketch (idealized picture) of vortex structures (coherent structural pattern) in plane mixing layer, after Bernal (1981).

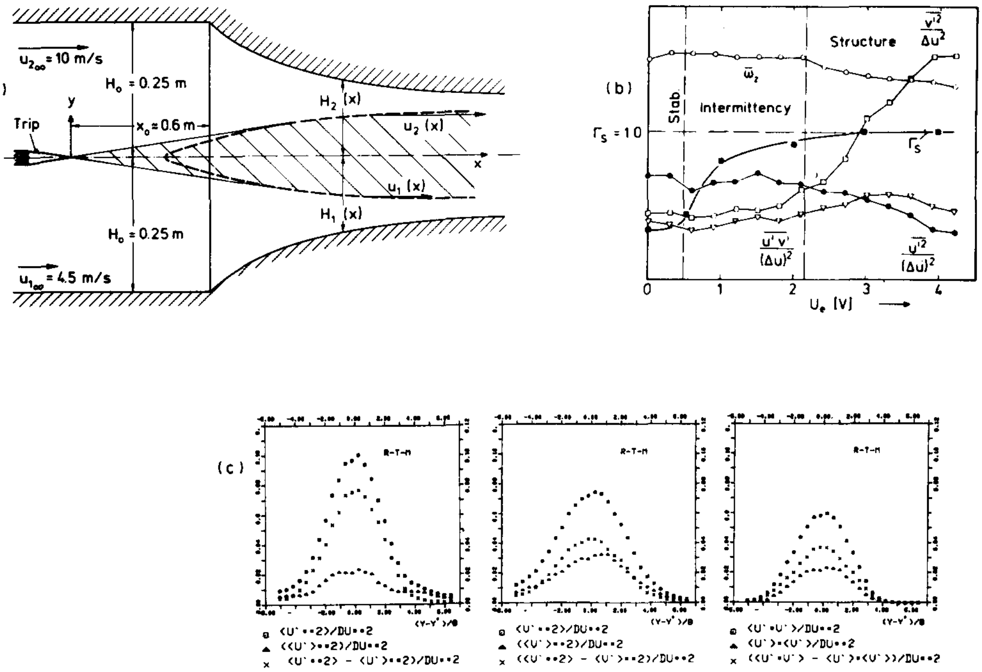


FIG. 14. The accelerated mixing layer: (a) experimental setup and flow geometry, (b) global influence of excitation strength, (c) coherence content in a cross-section.

found to be

$$b \sim U_2 + U_1 \sim (x - x_0)^{1/3} \sim 1/(U_2 - U_1).$$

We further found constant circulation Γ for the individual vortices, which behaved with respect to growth and velocity decay as viscous Oseen-Vortices with $\mathrm{Re}_b = b(=2r_0)(U_2 - U_1)/\nu = 150$ (a typical value for turbulent vortices). In contrast to the 'ordinary' shear layer this flow is therefore, comparable to jets and wakes, a purely decaying flow, where the spread is a consequence of growth of the decaying vortices. One of the most interesting observations was, however, that these vortices indeed never seemed to undergo any pairing or amalgamation (unless this had set in at $x < x_0$), yet they showed even slightly stronger local growth rates than is found for constant velocity mixing layers between streams of comparable speeds. This proved that pairing is not, as was often assumed, the central mechanism for spread.

Another phenomenon of interest was structural intermittency which, at least in this flow, appeared to be caused by vortex feedback (collected induction at the trailing edge of the splitter plates, see Fig. 14a), as was suggested by numerical simulation.

Stabilization of the structures by a loudspeaker-driven membrane in the splitter plate, having an overall widening effect on the flow, produced stabilization of the (otherwise jittering) frequency in the coherent bursts, while full spatial coherence of the flow, characterized by a 'structural' intermittency factor of $\Gamma_s = 1$, was established only at quite large excitation amplitudes. Further increase of excitation power showed severe influence on structure shape and intensity. Figure 14 shows the experimental situation and some characteristic results. In Fig. 15 a series of contour plots as obtained from phase averaging measurements for different excitation amplitudes is presented [Boettcher, Köpp, Kim (unpublished)].

Experiments of this kind are of special interest as they allow specific studies of certain flow characteristics in a tailored ambience. Another pertinent investigation presently under way is concerned with the influence of axial strain on the coherent structures in a plane mixing layer of zero pressure gradient. Figure 16 outlines the situation and shows characteristic results, some of which can be explained by rapid distortion theory. The main aspect is, however, the question of stability (and thus the possibility of manipulation) of a structure under longitudinal strain, which was numerically investigated by Takaki (1975). On the basis of this study we expect stabilization for the expanded vortex and randomization for the compressed one [see also Keffer *et al.* (1978)], which in fact is supported by the smoke photographs shown in Fig. 16 [Schüttpelz (unpublished)].

Finally we must mention the influence of test section geometry, which may lead to unexpected flow behaviour as in the case of a mixing layer in a narrow channel [Fiedler (unpublished)]. There it was found that for certain conditions a long wave periodicity dominated the flow, which in turn exhibited a dramatic increase of lateral spread, the cause of which is still a matter of conjecture.

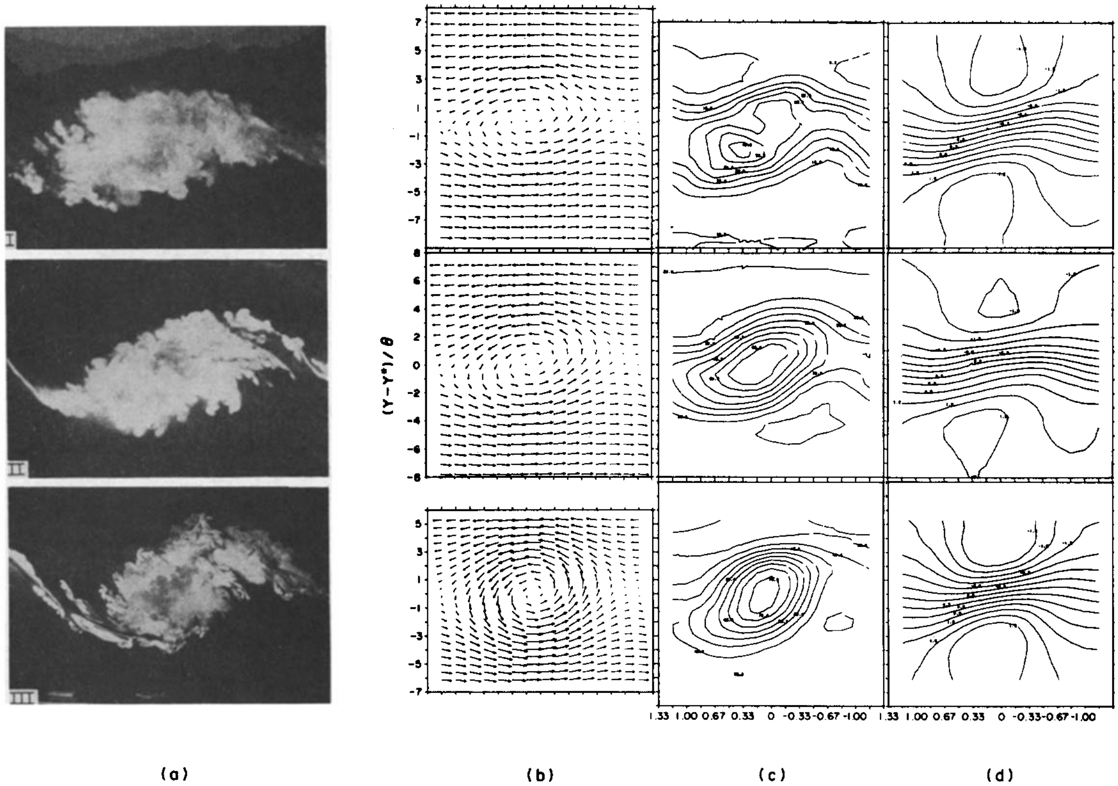
7.1.2. *Free Jets*

Free jets are believed to be structurally related to shear layers in having coherent structures of comparable simplicity. Again the basic modules are line vortices for the two-dimensional configurations and ring or helical vortices in the axially symmetric cases [Schneider (1980), Glezer (1981), Widnall and Sullivan (1983)]. There, as in most axisymmetric flows, mode analysis shows the first three modes: ring, single helix, double helix (Fig. 17); approximately equally distributed. A survey of the round jet is given in Fig. 18. Both configurations have been investigated with regard to coherent structures, although not quite to the extent as the mixing layer. Only few investigations seem to have been carried out in the far region. Two obvious reasons appear to be responsible:

(1) External excitation shows little (if any) effect in the self preserving regime. Thus the convenient vehicle of vortex stabilization does not apply.

(2) Coherent structures in the far region of jets appear to be quite weak and are therefore difficult candidates for an eduction scheme.

The few substantial investigations in the far region of the round jet are probably those by Tso (1984), Tso *et al.* (1980), Kumori and Ueda (1985) and Nieberle (1985). In the latter work an average of approximately 10% coherent energy content (of the u' fluctuation) was evaluated. Tso on the other hand applied mode analysis and found the single helix to be the typical structure in the far jet (characteristic Strouhal number based on maximum velocity and half velocity diameter was approximately $S = fb_{u/2}/U_{\max} \simeq 0.5$, similar to the column mode). The combined results of both investigations might give a better idea of the structure in three dimensions. Here we begin, however, to realize that the usefulness of the concept of coherent structures may become questionable for certain flows. There is obviously no 'single' structure and the ones that we observe display such a multitude of forms and scenarios with remarkably little similarity between individual and successive events that a sensible description must again include statistics to a large extent. This fact is clearly demonstrated by the photograph in Fig. 18 [taken from Dimotakis (1982)], which shows a most confusing structural situation as seen in a longitudinal cross section of a turbulent jet. A word of warning seems in order with regard to further interpretation of this photograph for structural details as well as for the contiguity of the turbulent regime (intermittency). This



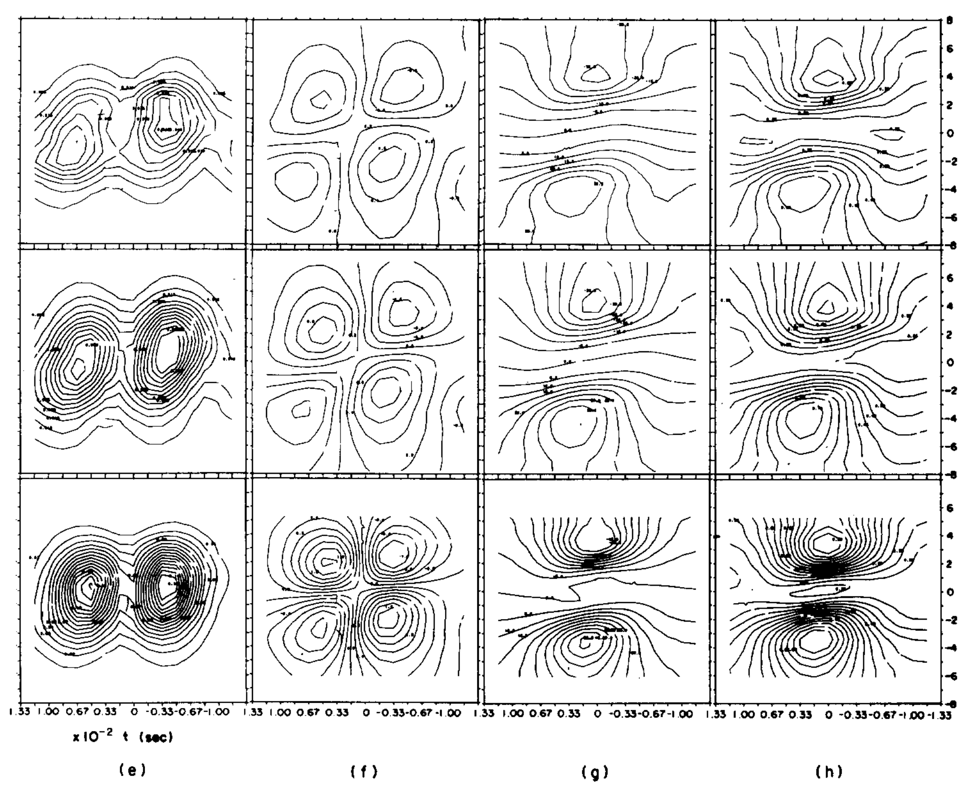


FIG. 15. Contour plots of coherent structure in accelerated mixing layer: I: no excitation; II: weak excitation; III: strong excitation. (a) Smoke (streakline) picture of structure, (b–h) ensemble averaged structure-contours in double decomposition. (b) Velocity vectors, (c) vorticity, (d) overall u'-RMS, (e) overall v'-RMS, (f) overall shear-stress, (g) diffusion, (h) dissipation of coherent energy (double decomposition).

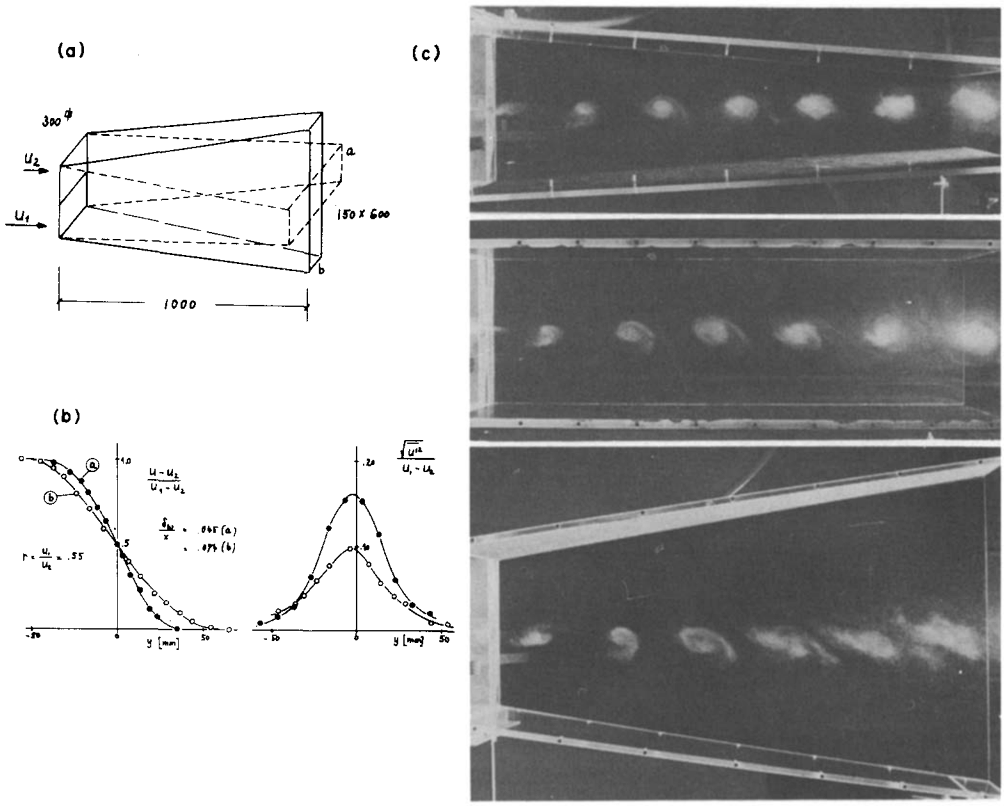


FIG. 16. Distorted mixing layer: (a) test section geometries, (b) mean velocity profiles and turbulence intensities, (c) smoke pictures for two distorted cases and the parallel layer (periodically excited flow), showing distinctly different stability behaviour of structures.

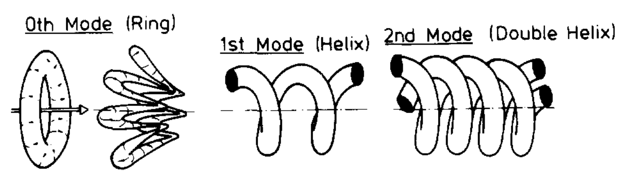
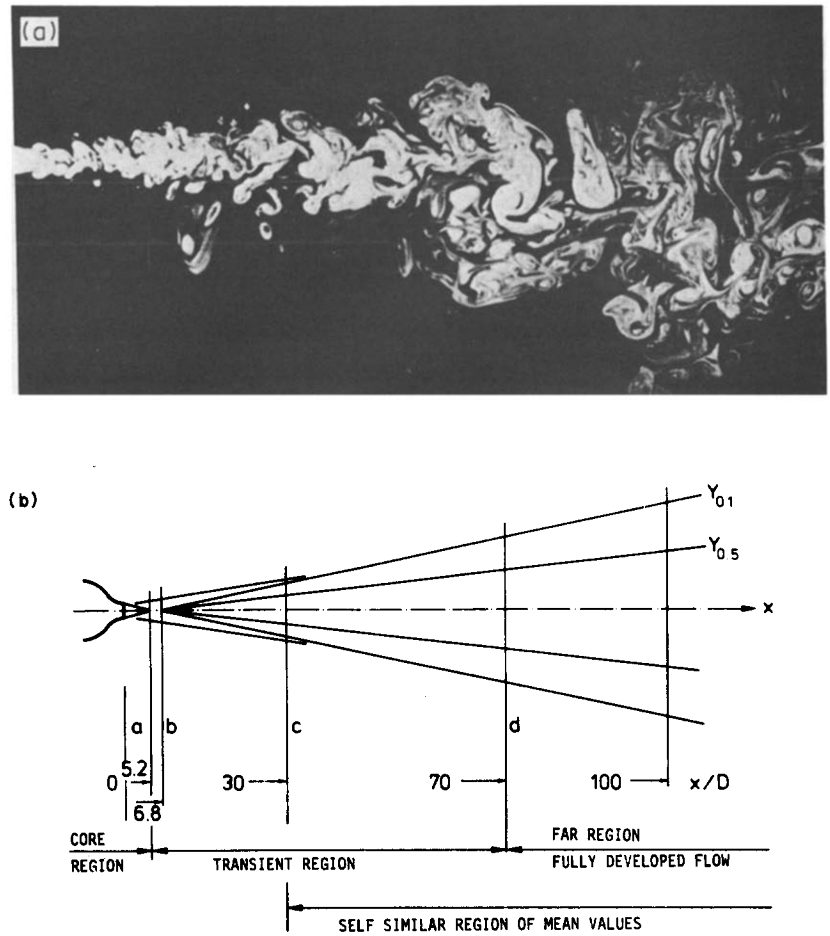


FIG. 17. Dominant vortical and helical modes in axisymmetric jet flow, basic structural modules.

picture shows the streakline pattern as obtained from a dyed jet flow in water. Its use for interpretation of the vorticity distribution appears, in this case, questionable for two reasons. Firstly the amount of dye is limited to what is issued with the nozzle fluid, whereas vorticity is continuously produced. Secondly, the diffusion of matter in aqueous media is orders of magnitude smaller than the diffusion of vorticity, the Schmidt number being of order $> 10^3$. Thus, the observed sharp dye interfaces with the apparent inclusions of original entrainment fluid even in the jet centre, and hence the dye intermittency factor is less than 1 in the jet centre and is not a true reflection of the distribution of vortical fluid.

Beginning with Crow and Champagne's (1971) startling investigation we find, on the other hand, a great number of papers on the intermediate and the near jet of round and plane



Near (core-) region: $0 \leq x/D \leq 5.5$

$Re_D \approx 5.4 \cdot 10^4$

Characteristic frequencies:

preferred mode (PM): $S_{PM} = \frac{f\,D}{u_0} \approx .48$

$(.30 \leq S_{PM} \leq .65)$

shear layer mode (SM): $1.1 \leq S_{SM} = \frac{f\,x}{u_0} \leq 1.5$

Far region: $x/D \geq 75$

$Re_D \approx 6.0 \cdot 10^4$

Characteristic frequency: $S_J = \frac{1\,x}{u_0} \approx 0.13 \div 0.24$

FIG. 18. The axisymmetric jet: (a) black-and-white image of light sheet photograph of dyed jet in water [Dimotakis *et al.* (1982)], (b) regions and characteristics of jet flow. [Nieberle (1986)]

configurations at neutral and excited flow condition [e.g. Fiedler and Korschelt (1979), Bernal and Sarohia (1984), Favre-Marinet *et al.* (1981), Binder and Favre-Marinet (1984), Peterson (1978)]. In the excited round jet the particularly spectacular phenomenon of jet splitting or 'blooming' was observed and investigated by a number of people, e.g. Leonhard (1985), Glezer (1981), Lee and Reynolds (1985). As has been remarked by Glezer, this phenomenon deserves further attention since it may provide a model for understanding the relatively rapid spread in a turbulent jet.

For the plane jet it is particularly the work of Mumford (1982, 1983) that provides an idea about the coherent structure in the far field. Mumford proposes 'strainwise rollers', which he also finds for the far wake.

Interesting structural developments of practical relevance particularly with regard to mixing are found in jets issuing from non-circular nozzles (rectangular, elliptic) as was reported by e.g. Krotapally *et al.* (1981), Ho and Gutmark (1982), Gutmark and Ho (1983), Husain and Hussain (1983) where the elliptical ring vortex with its interesting dynamic evolution [Lugt (1979), Dhanak and De Bernardinis (1981)] or the elliptical helix are the basic structural modules. The observation of double-vortex structures in jet-flames was reported by Eickhoff (1982a, b).

7.1.3. *The Turbulent Wake*

One of the earliest objects of research was the turbulent wake, where coherent structures were always well known but taken as a specific feature of just this flow. Papers on this subject are numerous and the method of stabilization of the shed vortices was well established long before the advent of the coherent structures concept. There is little point in commenting on any of the well known results. There are, however, some recent investigations worth reporting: Wygnanski *et al.* (1983) have presented experimental and theoretical findings for the two-dimensional far wake, which show that the coherent structures appear not only in the characteristic (anti-symmetric) sinuous mode but also, for an appreciable percentage, in the varicose (symmetric) mode.

Another unexpected observation is the 'unforgetfulness' of the flow for the upstream boundary condition. Different spread rates as well as turbulent intensity distributions are found for different bodies of equal resistance, which touches upon the frequently disputed question of the uniqueness of the self preserving state. The work of Cimbala (1984) adds a further interesting aspect, showing that far downstream in the plane wake a three-dimensional structure emerges. An example of a recent investigation into the near wake structure of an axisymmetric body is the work of Scholz (1985) on the circular disc. It included the case of the stationary disc as well as that of an axially vibrating and a tumbling one. Scholz found a dominating helical mode as inferred from the perfect lock-in behaviour of the tumbling disc case (see Fig. 19). Comparative measurements with a sphere show little difference from the disk situation other than the (expected) Reynolds number dependence (which in fact is also observed for the analogous situation of a jet issuing from a venturi-nozzle).

7.2. Wall-Bounded Flows

7.2.1. *The Wall-Boundary Layer*

The turbulent boundary layer is the final result of turbulent spots, the transitional structures, having eventually grown together. Consequently the idea nearest at hand would be to take the spot (see Fig. 1) as the basic structure of the fully developed flow. This idea was particularly fostered by Coles, who investigated the 'synthetic boundary layer' as a superposition of evenly spaced, artificially created spots in a laminar surrounding [Savas and Coles (1985), also Zilbermann (1981)]. One prime objective of these studies was to obtain typical signal traces then to be taken for the characteristic 'footprint' of the turbulent structure.

As many investigations [e.g. Wygnanski *et al.* (1976, 1979), Cantwell *et al.* (1977), Van Atta and Helland (1980), Perry *et al.* (1981), Riley and Gad-el-Hak *et al.* (1985)] have demonstrated, the turbulent spot is a complex agglomeration of (hairpin-like) vortices, the number of which increases with increasing Reynolds number until eventually the whole boundary layer flow is turbulent. It appears therefore reasonable to assume that not the spot

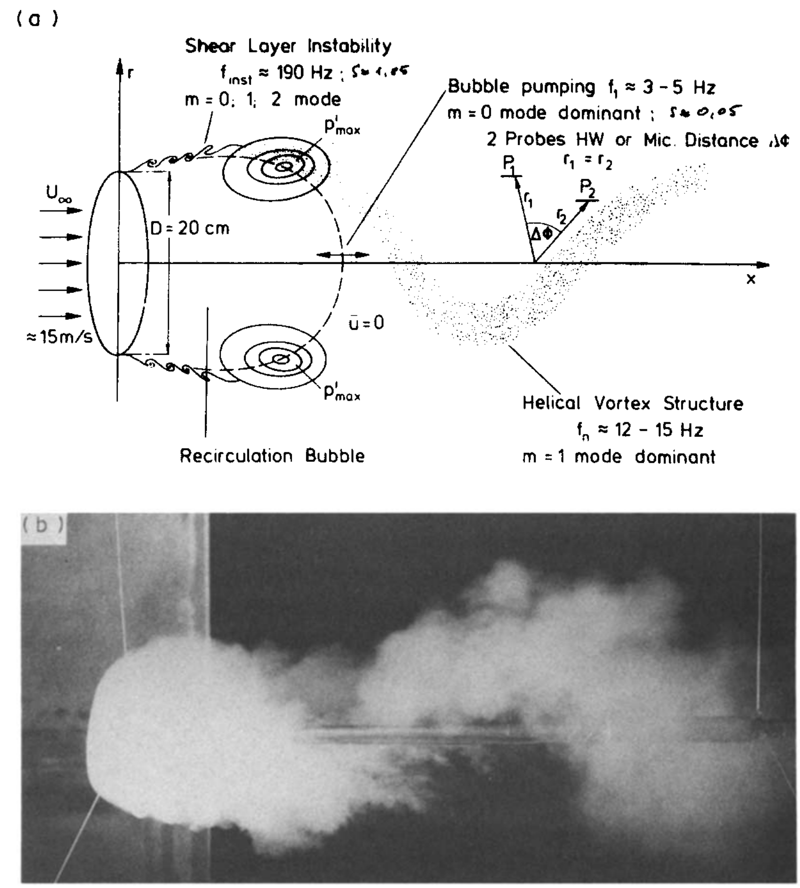


FIG. 19. The turbulent near wake behind a circular disk: (a) near wake geometry and characteristics, (b) smoke photograph (overall flashlight) of helical wake flow behind tumbling disk at lock-in frequency [Scholz (1985)].

as such but its constituents, i.e. the vortices, are the basic structure. The majority of observations support, however, the concept of a more complex scenario of structures and their 'cyclic' interplay rather than simple coherent structures, which indeed in boundary layers (as in all wall-bounded flows) appear to be indistinct as compared to, say, the structures in a mixing layer (Fig. 20).

The 'official' picture of boundary layer structure is painted from a considerable number of elements [Falco (1977, 1979)]. To try to sketch the essence of this scenario, for which Fig. 21(a) may provide a schematic, the boundary layer is (crudely) subdivided into a wall region and an outer region.

The viscosity-dominated *wall region* is characterized by elongated structures of small scale, partly embedded in the viscous sublayer. These structures are called:

(a) Streaks—longitudinal vortices with alternately changing sign of circulation, which were probably first observed by Hama (1957) and by Kline *et al.* (1967), and whose generation mechanism was only recently explained by Jang *et al.* (1985), see also Coles (1978), Blackwelder and Eckelmann (1979) and Fleischmann and Wallace (1984).

Streaks have characteristic horizontal dimensions of $s^+ \simeq 100$, reaching vertically up to $h^+ \simeq 50$ (i.e. into the buffer layer), with a downstream extent of $l^+ \simeq 1000$ [see Jang *et al.* (1985)]. They trigger instability events in the mean flow, which result in the so-called:

(b) Bursts—the universal frequency scaling laws of which were first given by Laufer and Narayanan (1978), who found for the characteristic period $T_B U_0/\delta = 5$ (wall layer) and $= 2.5$ (outer region)—see also Blackwelder and Haritonidis (1983). The symbols used are T_B = typical burst period, U_0 = free stream velocity and δ = boundary layer thickness.

It is suggested by all observations that it is the structures and the structural events in the wall region that are responsible for the production mechanism of the turbulent energy.

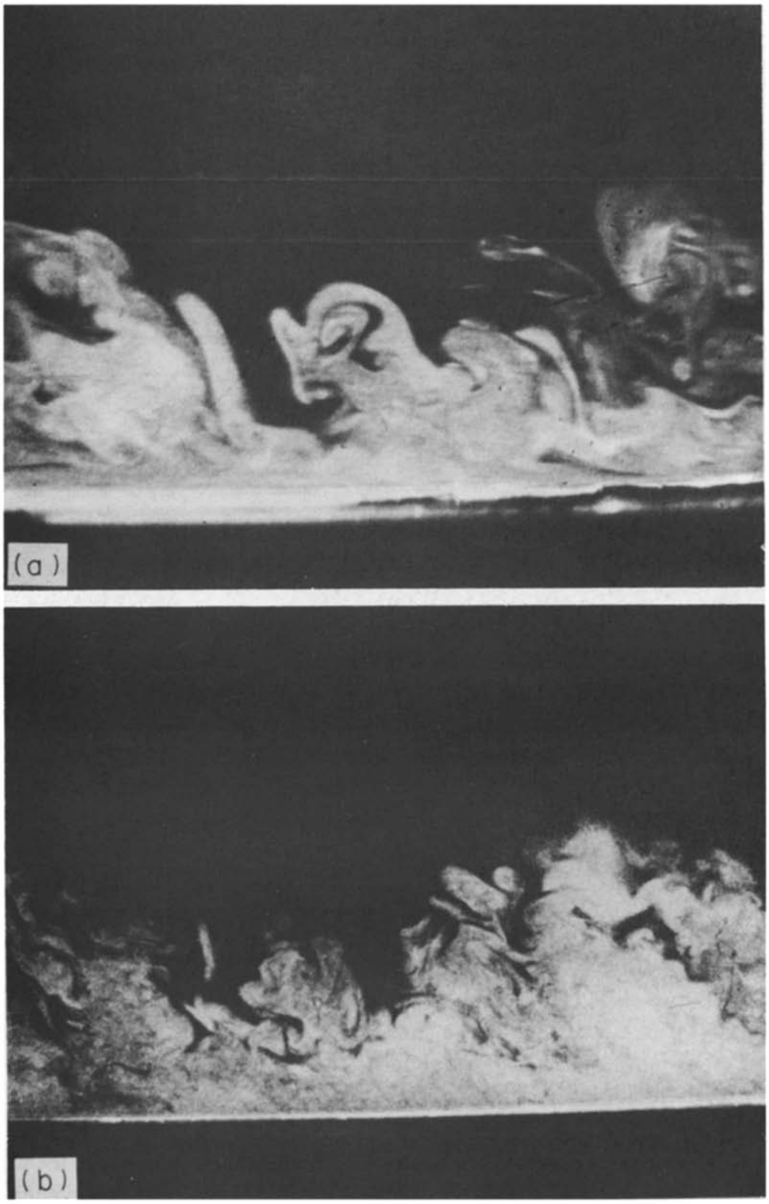


FIG. 20. The structure in a turbulent boundary layer: longitudinal light sheet visualization of smoke filled boundary layer showing complex structures of strong Re number dependence. (a) $Re_\theta = 1000$; (b) $Re_\theta = 5000$. (Photographs by S. A. M. Thornley.)

Another process connected with the burst is the lifting of the longitudinal vortices away from the wall. This motion is called ejection.

(c) Pockets—according to Falco (1979) these are streaks which differ from the 'ordinary' streak in a number of significant items, e.g. their typical dimensions and their shorter evolutionary frequencies. Pockets are typically observed in the interaction region between wall and outer region.

(d) Large scale sweeps—which are wallward directed motions of faster fluid, causing local acceleration.

The inviscid *outer region* is characterized by

(a) Large scale motions—bulges of the outer layer of dimensions comparable to the overall boundary layer dimension and

(b) Mushroom eddies—also known as 'Typical eddies' or 'Falco eddies', having dimensions around $d^+ \approx 100$.

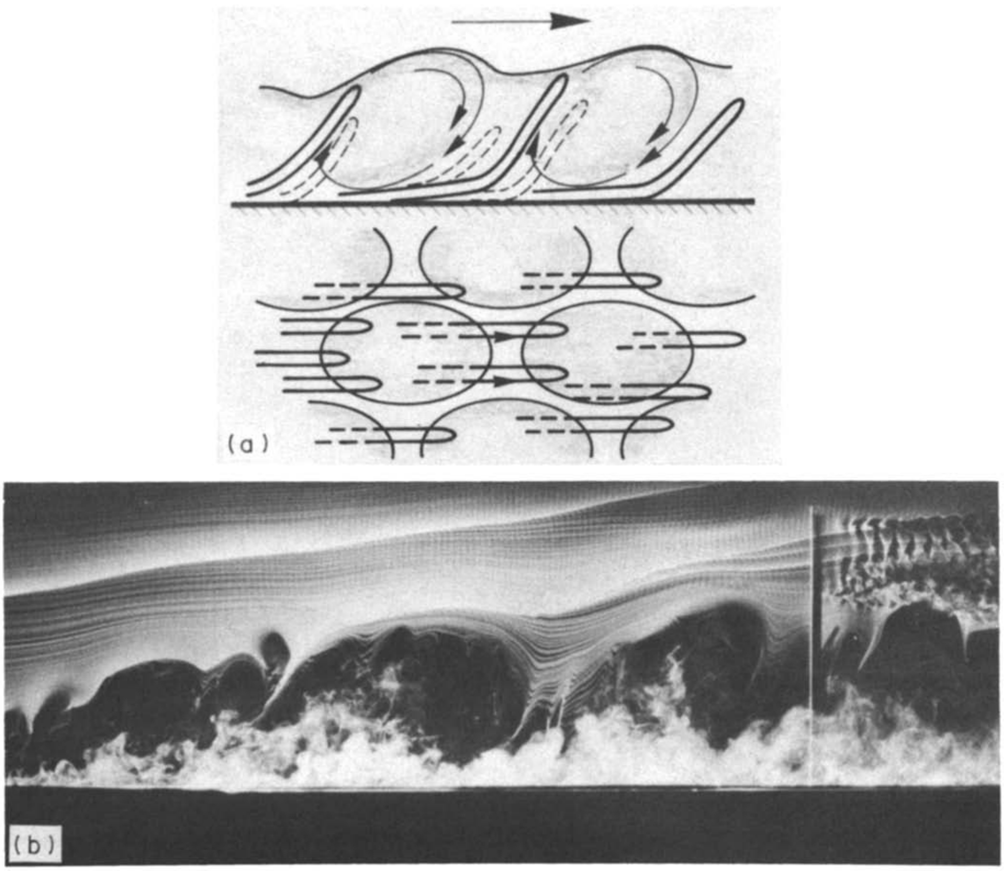


FIG. 21. (a) Simplifying schematic of boundary layer structure, (b) supporting flow visualization: section of smoke wire photograph of turbulent boundary layer with Re = 1000 by Taneda (1985).

Studying the vast literature on boundary layer flow one is soon lost in a zoo of structures, e.g. horseshoe and hairpin eddies [Perry *et al.* (1981), Head and Bandyopadhyay (1981)], pancake and surfboard eddies [Landahl (1984)], typical eddies, vortex rings, mushroom eddies [Falco (1979)], arrowhead eddies [Zakkay and Barra (1982)], attached eddies [Townsend (1976)], etc...

If we now compare this complex picture with the well documented transitional spot it seems, at least at first glance, that the resemblance is but superficial. Indeed Zilberman *et al.* (1981) have tried to educe the 'characteristic eddy' in a turbulent boundary layer, and compared it with the 'transitional spot'. It appears that there are significant differences in that the turbulent structure is markedly smaller in the plane parallel to the plate than the spot, while exhibiting no apparent self-preserving form. It was found, on the other hand, to have close similarity with the bulges of the outer layer. Its characteristic convection speed of $U_c/U_0 \simeq 0.9$ is slightly larger than the value of 0.88 as obtained by Savas and Coles (1985) in the synthetic layer.

Head and Bandyopadhyay (1981) have, on the other hand, very convincingly demonstrated that some of the structural varieties as reported above appear to be mainly in the eye of the beholder, and that the primary element of coherent boundary layer structure seems to be essentially the simple, Reynolds number dependent, 'hairpin' (see Fig. 21).

One of the first, more elaborate models of organized vortical structures in a turbulent boundary layer, was proposed by Black (1968) on the basis of observations of Kline *et al.* (1967). He assumed a mechanism of turbulent momentum transfer by a system of horseshoe vortices which have their origin in a non-linear instability of the flow in the viscous sublayer (see Fig. 22). Some more recent attempts for mathematical modelling of the turbulent

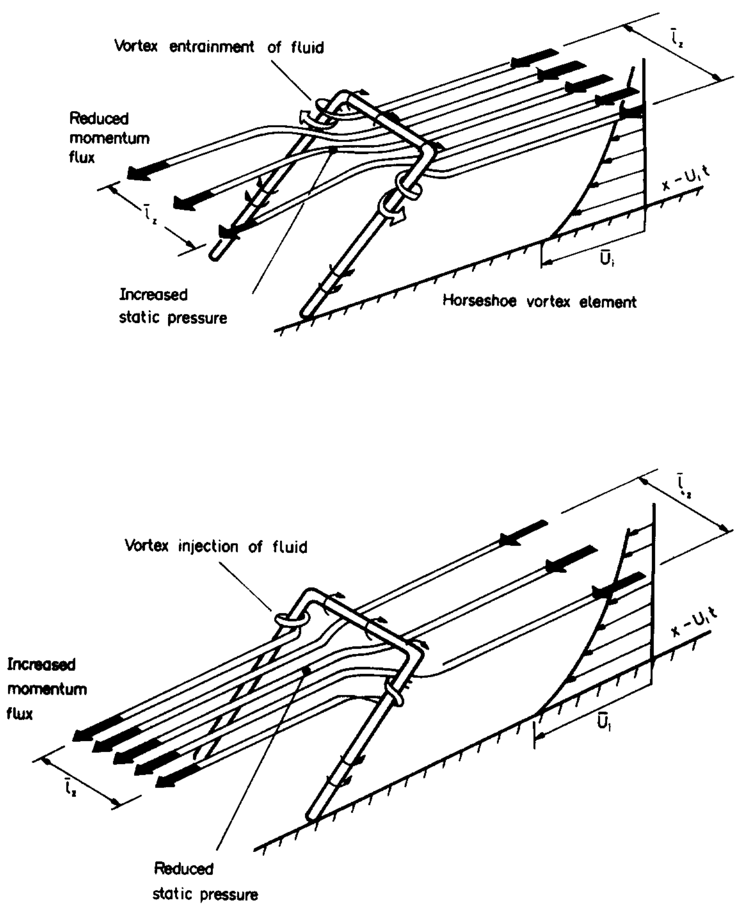


FIG. 22. Model of turbulent boundary layer structure, after Black (1968).

boundary layer as we see it now, have been proposed by Landahl (1984), Beljaars (1979) and Wallace (1984).

7.2.2. *Some Other Wall Flows*

For Poiseuille flow, Coles (1981) conjectured on the observation that a turbulent puff is essentially a ring vortex and that the turbulent structure in the fully developed pipe flow should be represented by the recurrent structure of a puff. Sabot and Comte-Bellot (1976) on the other hand found clear indication of helicity in the core region of the Poisseuille flow, as did Kovasznay *et al.* (1970) and Antonia (1972) in the outer region of the turbulent boundary layer. From a recent investigation by Stahl (1986) we know that in pipe flow, as in most other axisymmetric flows, the 1st (helical) mode has approximately the same probability as the 0th (and in some cases also the 2nd) mode. This then could explain Sabot and Comte-Bellot's findings without substantially contradicting Coles' model. Indeed only recently Bandyopadhyay (1986) in a re-investigation of the puff also discusses the probability of helical structures.

Channel flow has recently been looked into by Johansson and Alfredsson (1982). VITA technique was applied to detect typical structures, and typical time scales of the retardation and the acceleration events were obtained. Dracos (1984) investigated the open channel flow, where he identified oblique vortical structures (with positive and negative (!) tilt) which are considered responsible for most of the production of the turbulent shear stress. They correspond to Townsend's (1979) 'attached eddies' and to the model of wall turbulence introduced by Perry and Chong (1982).

8. ENTRAINMENT

One of the conceptually controversial phenomena in turbulent shear flows for a long time was the phenomenon of entrainment: the original understanding [Corrsin and Kistler (1954)] was essentially based on the idea of 'small scale nibbling' of the interface. Much work has since then been dedicated to its consistent physical explanation and a discussion would be incomplete without mention at least of the work of Townsend (1970), see also Chevray (1982). It was, however, Bevilaqua and Lykudis (1977) who actually proved the connection between entrainment and large scale (coherent) motions corrugating the free surface of a turbulent flow and entraining potential flow by 'engulfment' or 'folding'. This modern concept of entrainment was subsequently corroborated by a number of visualization experiments.

In the numerical simulation of the plane mixing layer one usually replaces the spatially developing flow by a temporally developing one with constant width along x, and thus perfect symmetry of the flow which is seen from a Lagrangean point of view, i.e. a moving frame where the structures (vortices) appear at a stationary position. Clearly then the entrainment rates from both sides must be identical and this was generally assumed to be true also for the real mixing layer. The situation for spatially developing and therefore non-symmetric flow is, however, different and the ratio of the entrainment flow rates is different from one. The proper ratio for the one-stream layer of approximately $V_{HIGH}/V_{LOW} \approx 1.4$ (1.3–1.5) was, indeed already given by Fiedler (1974), yet only its later publication by Dimotakis (1984) caused some unexpected surprise. In fact in 'real life' it is the momentum flux profile that is symmetric, while the mass flux (U) profile is the square root distribution of the first one [see Reichardt (1942)], which is non-symmetric.

Entrainment is one of the main features of lateral growth of a turbulent flow. It has frequently been conjectured that in a shear layer spread is achieved by vortex pairing alone (see above). Hernan and Jimenez (1982) on the other hand have shown that only about 20% of the total entrainment flux goes to the credit of pairing and indeed even the heretical suggestion that pairing is altogether a chimaera has been put forward by Wygnanski and Petersen (1985) and Wygnansky and Weisbrot (1987). In any case it is beyond doubt by now that the phenomenon of pairing, be it real or not, is of less significance for the flow development than was believed hitherto.

9. INFLUENCES–MANIPULATION

This is one of the most interesting and complex aspects of the coherence phenomenon. Knowledge of dependence of coherent structures on boundary conditions, fluid characteristics or any other condition opens ways for manipulating turbulent flows by influencing its coherent structures, with possibly great technical relevance. Meditations about this question are, however, only useful once it is established that the structures to be influenced have a sufficient bearing on the dynamics of the flow considered. It is well known that

—mixing and combustion (entrainment)
—heat transfer
—noise production and emission (pressure fluctuation) and
—wall-shear (frictional drag)

are essentially determined by large scale (coherent) structures. Which fraction E_c/E of the total turbulent energy E is then to be attributed to the coherent structures? An exact assessment of this quantity is practically, in view of the experimental difficulties described, impossible. Estimates will, however, suffice. We find for :

plane mixing layer:	~20%	Ho and Huerre (1984), Fiedler and Mensing (1985)
accelerated mixing layer:	~25%	Fiedler and Koepp (1987)
near jet:	~50%	Kibens (1980)
axisymmetric far-jet:	~10%	Nieberle (1985), Mumford (1982)

near wake: ~25% Scholz (1985)
plane far-wake: ~20%.

For wall bounded flow we may assume fractions of order 10%. From these data, impovements of turbulence models seem possible by adequately modelling the coherent constituents, and manipulation of turbulent flows by influencing the coherent structures is promising.

Some of the more important and obvious activities and results pertinent to this concept are the following:

Coherent structures have been recognized as principal sources of flow-noise. Their suppression or destruction in a given flow significantly reduces the radiated noise level [Michalke (1978), Crighton (1981), Armstrong *et al.* (1977), Armstrong (1981), Bechert and Pfizenmaier (1976)]. In a more recent investigation Laufer and Ta-Chun Yen (1983) reported the observation that acoustic sources in a round jet are not convected but are confined to the (fixed) locations of vortes pairing. This is to say that it is not the coherent structures as such that are responsible for the noise but rather their formation (e.g. by pairing), or more precisely, their highest amplification level.

The effect of coherent structures in chemical engineering processes, in mixing and combustion is well established and has been a central object of research and increasing interest in recent years [Breidenthal (1978), Peters and Williams (1981), Eickhoff (1982a,b)].

Knowledge about coherent structures and their manipulation has only recently proved its importance for problems of airplane design: high lift can be achieved by delay of separation on a stalled airfoil via manipulation [e.g. excitation of coherent structures, Stone and McKinzie (1984), Wygnanski (1985)]. The economically most attractive possibility of drag reduction again via influencing the coherent structures in boundary layers appears already within reach.

How then can these structures be efficaciously handled? We shall sketch some of the better understood ways. Thus enhancement of coherent structures is possible:

(a) By periodic excitation [e.g. Ho and Huerre (1984), Wygnanski and Petersen (1985), Fiedler and Korschelt (1979)].

(b) Polymer additives produce significant intensification of coherent structure-constituents and, at the same time, attenuation of the incoherent small-scale structure in free shear flows [Kwade (1982)]. Reduction of wall shear stress in turbulent wall-flows by polymers has been well established for some time by a number of investigations. Correlations of this welcome effect are, however, only of recent date; Yoda (1981) finds significant increase of frequency as well as of lateral dimension of the pockets in a turbulent boundary layer from polymer additives to the flow (Sapran AP273). As an example Fig. 23 shows the (laminarizing) influence of additives on the development of a turbulent jet.

Suppression of coherent structures is achieved by a periodic excitation of comparatively high frequency ($S_\theta = f\Theta/U_0 = 0.017$ [Zaman and Hussain (1981), and Berger (1967)], where S_θ = Strouhal Number based on the momentum thickness

$$\Theta = \int \frac{(U-U_1)}{(U_2-U_1)} \frac{(U_2-U)}{(U_2-U_1)} \, dy.$$

Suppression of coherent structures can also be achieved by special boundary conditions or additional manipulators to destroy or disrupt the coherent structures, e.g. winglets (LEBUs = Large Eddy BreakUp devices), straighteners, screens etc., for which there is already an abundance of literature [e.g. Yajnik and Acharya (1978), Corke (1981), Dowling (1985), Nieberle (1985), Rashidnia and Falco (1986)]. Another simple and efficient concept was recently derived from examination of shark-skin, the simplest abstraction of which appears to be a surface with longitudinal parallel grooves. Cross-sectional shape and, more important, lateral spacing of the grooves are of the essence. Since the most evident explanation for its effect is an interference with the sublayer streaks the most effective spacing should be expected around the typical spacing of the latter (i.e. at $s^+ \approx 100$). Indeed a maximum reduction of ~8% (LEBU's give only around 2% reduction!) of the wall shear

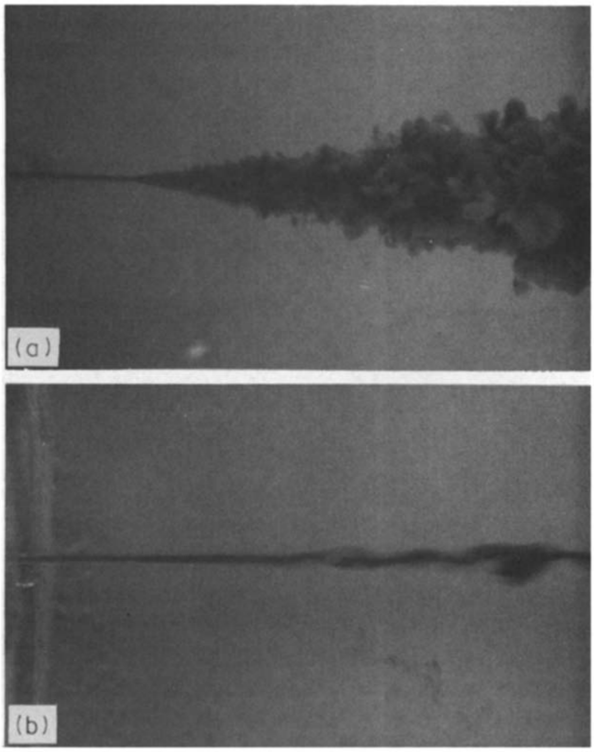


FIG. 23. Influence of polymer additives on flow structure: (a) axisymmetric jet—water in water, (b) same flow-situation, however jet flow with polymer additives: turbulence is essentially suppressed.

stress is achieved for groove spacings $s_G < 0.3\ s$. This points to a combination of two effects: an interference with the turbulence production mechanism and at the same time a lift-up of the longitudinal vortices (streaks) and thus, in essence, a reduced velocity gradient in the viscous sub-layer [Bechert *et al.* (1986)] see Figs 24 and 25.

10. THEORETICAL MODELLING

The experimental knowledge of coherent structures as collected during the last decade or so has only to a limited extent been converted into mathematical models for numerical treatment of turbulent flows. The various prediction schemes currently in use for practical, i.e. engineering, problems based on statistical models, have in fact already reached a standard which seems to leave little incentive for further complication with possibly only little improvement. A major reason for this 'non-development' may come from the fact that with the extremely capable computers of our generation, direct numerical simulation becomes more and more feasible; and a very promising way to support and in some cases even to replace experiments, and thus make the classical approaches of flow prediction with all its fallacies obsolete.

For a direct numerical simulation of a turbulent flow the time-dependent equations of motion are solved numerically in a grid. There we find indeed large coherent vortical structures developing, similar to those known from visualization, as becomes evident from Fig. 26, showing results from Lummer (unpublished) and Orszag (1985), see also Riley and Metcalfe (1979, 1980) and Metcalfe *et al.* (1985). Limitations of this method are imposed by computer capacity and speed, and a sufficiently fine grid to account for the influence of small scale components (high Re numbers) still remains a future goal.

An interesting and more economic combination of direct simulation and statistical (classical) modelling is the so called 'large eddy simulation', where only the large scales (eddies) are properly simulated in a relatively coarse grid, while the 'viscous' action of the

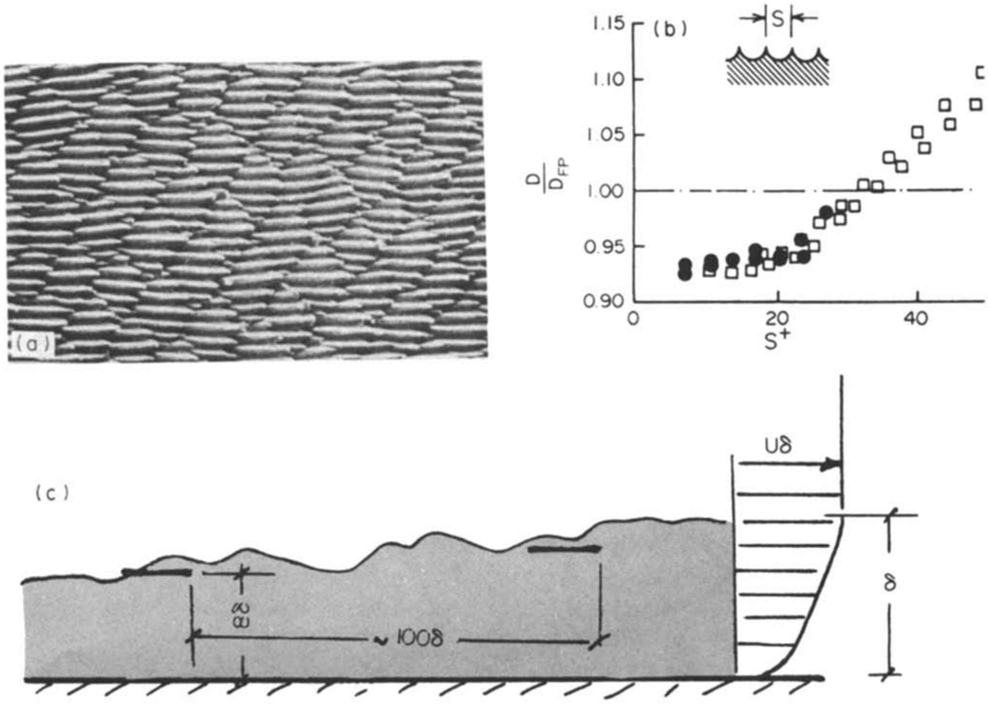


FIG. 24. Manipulators to reduce skin-frictional drag: (a) photograph of shark-skin (*Carcharhinus obscurus*), Reif (1985). (b) Drag reduction by longitudinal scalloped riblets: drag normalized with smooth-surface drag versus riblet spacing (in boundary-layer coordinates) showing a maximum gain of ~8%[Bechert *et al.* (1986)]. (c) LEBU's in a turbulent boundary layer in typical arrangement. Maximum net gain approximately 2% drag reduction [after Rashidnia *et al.* (1986)].

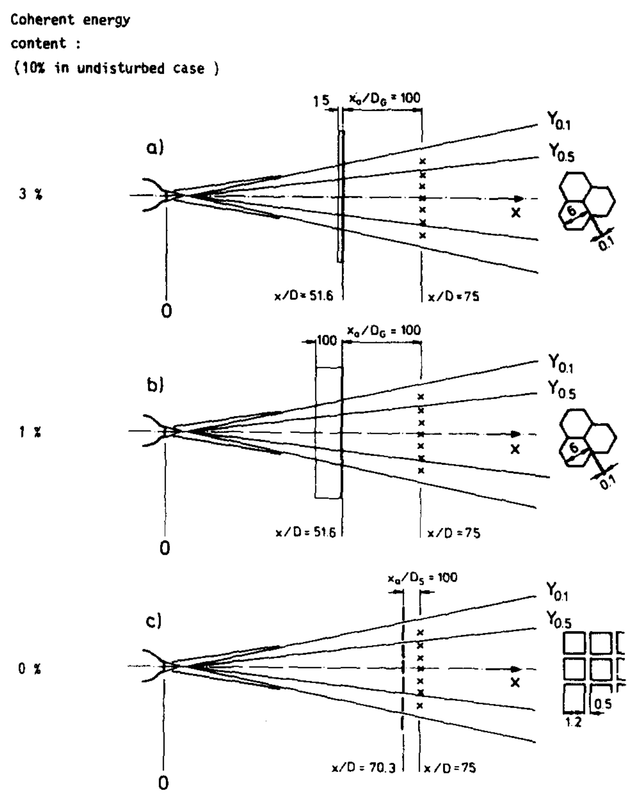


FIG. 25. Reduction of coherent energy by breaking up of large scales in an axisymmetric jet [Nieberle (1986)], manipulation of mixing.

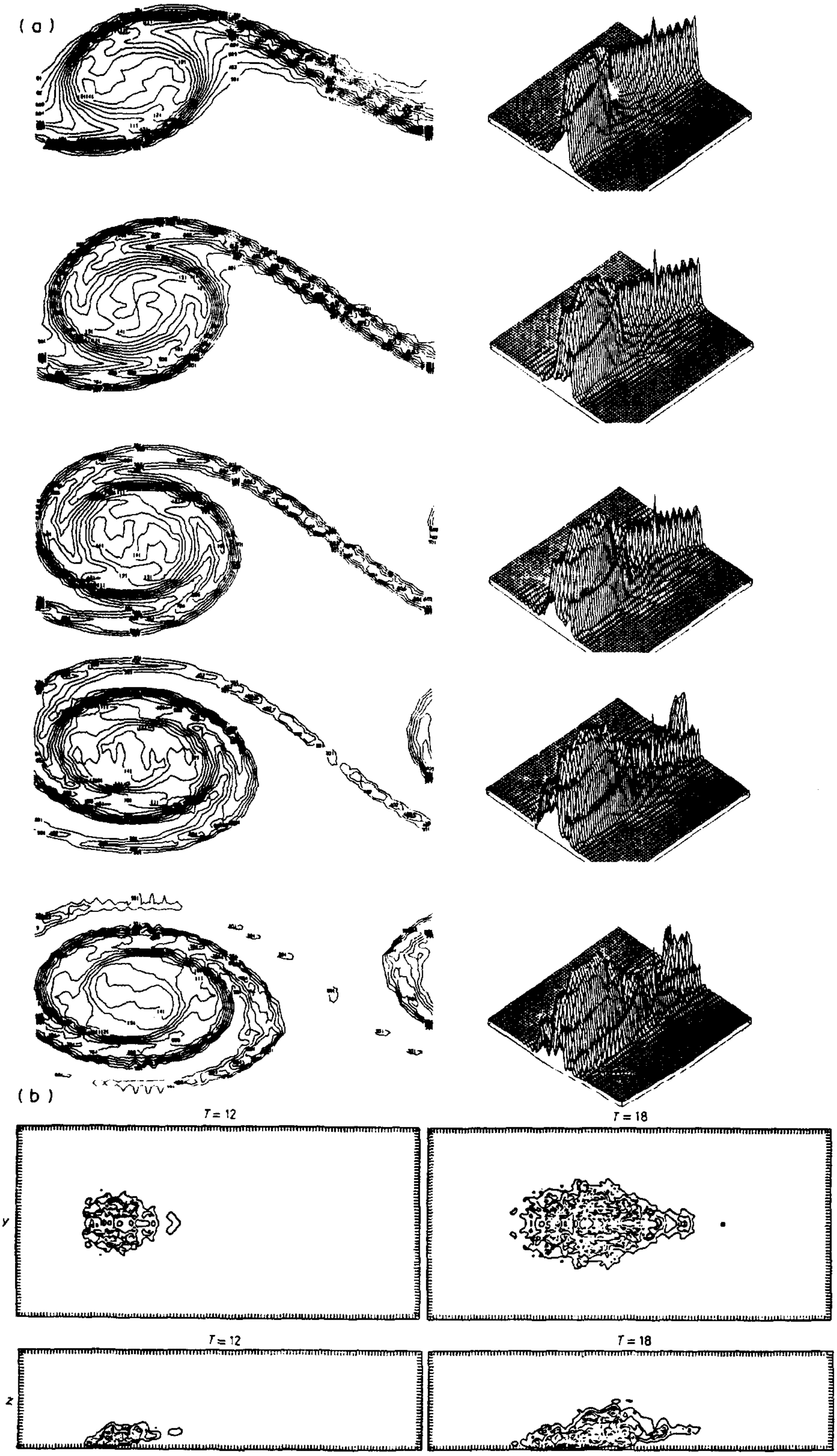


FIG. 26. Direct numerical flow simulation:
(a) rollup of mixing layer [Lummer (unpublished)]:
left: isovort-contours
right: vorticity plots,
(b) turbulent spot [Orszag (1985)]:
top: top view
bottom: side view.

small scale is taken care of by a statistical, so called 'subgrid', modelling. This method is, however, still far from being a standard tool for practical applications. A concise and up-to-date picture of the state of art in direct and large eddy simulation of turbulence is given by Schumann and Friedrich (1986).

Another alternative is discrete vortex simulation of a given flow. This is a considerably less ambitious and also less demanding approach of, however, amazing efficiency. As we see in Fig. 27, where a turbulent mixing layer is simulated by a mere 200 vortices, this method is clearly capable of developing the characteristic structural peculiarities of this flow. One shortcoming is, however, that it can only be applied to homogeneous fluids, i.e. fluids of constant properties; another is the difficulty in directly representing the effects of viscosity.

For further information see Saffman (1981), Landahl (1984) and Plaschko (1981).

11. SOME FINAL REMARKS

Knowledge about dominating structures in a flow has no doubt contributed to our understanding of certain phenomena, e.g. drag and shear-stress distribution, the origin of noise emanating from a turbulent flow and even quite simple observations like the difference between the mean velocity profile and the distribution of a scalar (e.g. the mean temperature profile in a heated flow). Figure 28 gives an explanation. Basic understanding of (and benefit from the concept of) coherent structures becomes, however, questionable or at least limited in view of the multitude and apparent complexity of structural shapes and dynamics as found in most wall-bounded flows, as well as (for example) in the far-jet. Looking at smoke pictures taken in these flows we can easily convince ourselves of the existence of 'characteristic structures' as well as of 'characteristic (cyclic) motions' and indeed in view of these flows it seems more appropriate to speak of coherent events instead of coherent

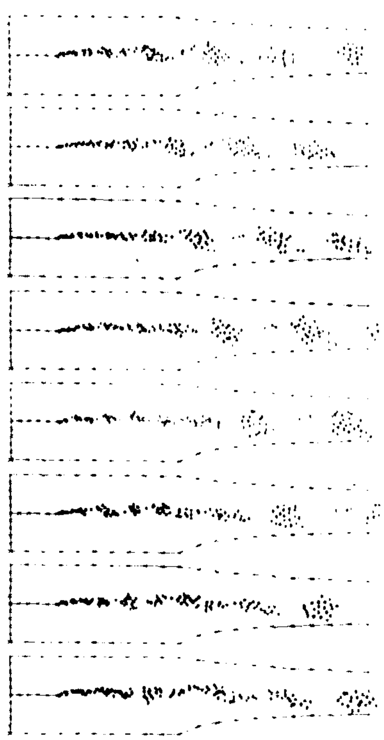


FIG. 27. Flow simulation by discrete vortex method: successive realizations of accelerated mixing layer flow, showing formation of structures and structural intermittency—simulation of wall contour by panel method [Lummer (unpublished)].

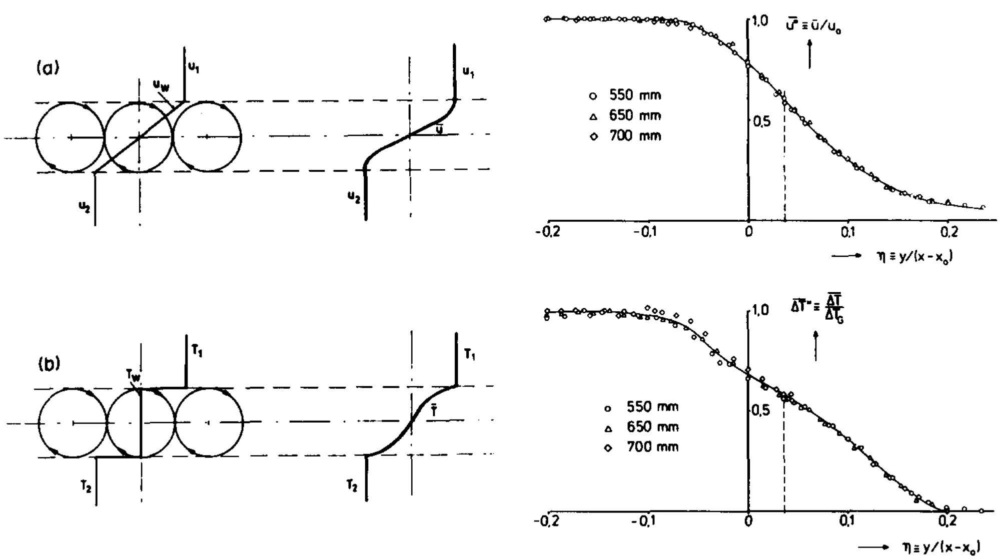


FIG. 28. Explanation model for different shapes of mean velocity and mean temperature profiles in mixing layer on the basis of large scale vortical structures: assumptions: (a) linear velocity distribution in single vortex, (b) constant (average) temperature in single vortex.

structures. But it needs imagination to see coherence in the simple sense as suggested by the pictures of, say, a mixing layer flow.

Detailed knowledge of these events may serve as a basis for physical understanding yet it is questionable whether it is needed or even useful for mathematical modelling, where a simplified pattern may be adequate. Besides, the various structures and sub-structures are not without ambiguity, which is certainly well understood in view of the experimental difficulties encountered. Consequently the picture becomes progressively more vague and less useful the more detailed and sophisticated it is. The obvious question then is: is it worth trying to improve on it (in the sense of further refinement)? The answer is again not a simple one: from the point of view of the predictor, who seeks a manageable model of high efficiency, it would certainly be unwise to simulate every detail of sub- and sub-sub-structures [see Beljaars (1979), and Landahl (1984)]. For the scientist who primarily seeks understanding, the limit may be further away but it is certainly there, since otherwise the coherent structures concept will inevitably metamorphose into the statistical and thus lose its meaning.

One of the many different aspects in structural development between wall- and free-flows is obviously its dynamical metamorphosis: while in free flows we observe continuous creation of new structures, preferably by some kind of amalgamation of older ones which thus decay, the corresponding process in wall flows might more accurately be described as agglomeration and/or decay and reformation. On the other hand there is an important piece of mutuality and thus universality: in all kinds of shear flows we find at least two kinds of structures coexisting (it is anyway more realistic to speak of coherent structural scenarios than of 'single' structures):

1. primary structures of large dimension, comparable to the overall (lateral) flow dimension and
2. secondary (longitudinal) structures, their dimension being typically one order of magnitude smaller than the primary structures.

It appears that the secondary structures are responsible for the energy production process via vortex stretching-like streaks in wall-flows and braids in free shear flows [Hussain (1984), Coles (1984)], while the large structures are responsible for the (energy, momentum, matter, etc.) exchange across the whole flow as is sketched in Fig. 29.

Here I should like to return briefly to the chaos concept, disposed of above somewhat casually. Chaos can be understood as the consequence of a continuous folding and

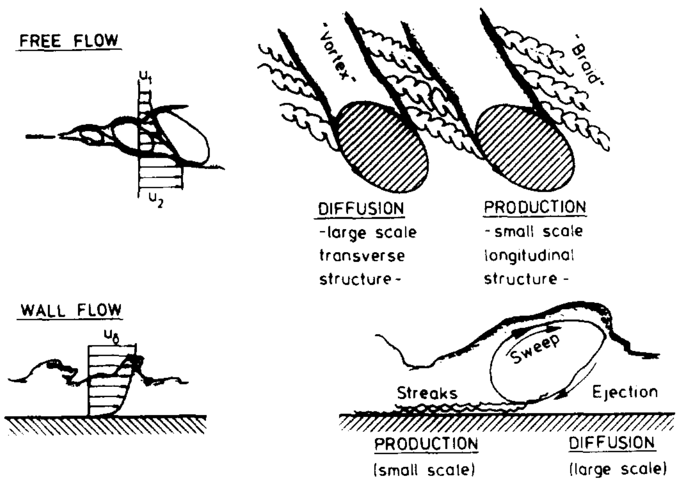


FIG. 29. Characteristic coherent structures scenarios for free and wall flows—simplified view.

stretching process. This then provides an analogy to (at least some) coherent structures, giving an almost perfect description for the latter. The coherent structure in a mixing layer for example is the rolled up (or folded) and, at the same time, stretched vorticity layer, i.e. a large scale event where small scale (and thus mixedness) is created by continuous folding and stretching. Thus, larger and larger adjacent surfaces of smaller and smaller dimension are created. One may wonder then whether any of the characteristics used in chaos theory, e.g. dimensions, might not provide a useful measure for the mixedness of a turbulent flow?

I am certainly aware that nothing has been said in the foregoing about coherent structures in complex or disturbed flows. I believe, however, that despite all the knowledge available on 'simple' flows we are not yet in the position to extrapolate that knowledge beyond the known limits. For this we need to understand the general principle and the 'law of order' for the coherent structures much more than just the bits and pieces we have been able to master so far.

There is a need for investigations into the more complex, and more than just a brave few ought to find the moral strength to attempt such investigations. One must keep in mind that, at least in a technical sense, the coherent structures concept will prove itself useful in the end only as long as the number of coherent structure modules remains not only finite but small and thus allows for a useful description of an arbitrary number of flow configurations. This touches on the question of research strategies: The majority of the experiments done so far were done under specifically 'clean' conditions in, preferably, self-preserving flow regions etc., which in a scientific sense should yield the best, i.e. least ambiguous, 'basic' information. Flows of some practical relevance are, on the other hand, almost invariably those which are unclean, disturbed, and/or, at least in free flows, transient (i.e. 'young'), and it is particularly in these regions that coherent structures were found to be dominant. Maybe the systematic approach via the clean and simple scenarios is too much of a detour to come to an understanding and thus to a basis of description and manipulation of the more complex cases. It seems that those should be tackled by way of a second, more direct route.

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are reproduced with kind permission. I wish to express my gratitude to all contributors mentioned.

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