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Coherent structures in turbulence

By P. O. A. L. DAVIES AND A. J. YULE
Institute of Sound and Vibration Research, University of Southampton, England

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This account of the Colloquium on Coherent Structures in Turbulence held at Southampton from 26–29 March 1974 presents a brief summary of two invited lectures and 42 formal presentations on turbulent shear-flow structure. A number of shorter contributions and discussions are also outlined. The present position of the study of turbulent shear-flow structure is reviewed and some new experimental techniques are discussed.

1. Introduction

In recent years there has been a growing interest in studying the large-scale coherent structures that are found in shear-flow turbulence. For some time also there has been growing evidence that these contribute significantly both to turbulent transport of momentum, heat or mass, and to aerodynamic noise. The Colloquium was organized to provide a forum for the exchange of information and views on recent advances in the investigation and understanding of large-scale turbulence structure. In particular the meeting was concerned with descriptions of many examples of practical interest in jet, wake and boundary-layer flows where repetitive and orderly eddy structures have been clearly identified.

The Colloquium was attended by 100 or so active workers in turbulence research, 60 of whom came from outside the United Kingdom. There were representatives from nearly all the institutions where a more deterministic view of turbulence structure has been adopted by one or more groups of workers, in place of the classical statistical one.

This involves concentrating attention on the larger-scale components of the flow and the way they interact and grow. The development of such studies has followed the growth of suitable experimental and data-processing techniques that the growing power of digital methods of real-time analysis provide.

Flow-visualization experiments have shown that many examples of boundary shear flows, including mixing layers or wakes, boundary layers and jets, have a coherent recurring structure. Statistical measuring techniques, however, only provide quantitative information on their time-averaged properties, so that much of the detail of such structures is lost. This is partly due to the fact that the repeating velocity patterns, when viewed at fixed points, are never sufficiently periodic to be clearly recognizable. It is also difficult to interpret information obtained at one or two fixed points as part of a somewhat complex moving structure. Finally, it is difficult to introduce arrays of transducers to obtain sets of simultaneous point measurements without significantly disturbing or modifying the flow.

Conditional data-sampling techniques have provided more ordered information within which clearly defined patterns emerge. They normally depend on some automatic logical process for deciding which parts of the signal arise from the flow structures of immediate interest. Results obtained by following such procedures must naturally enough be accepted with caution unless the logical conditioning process is related to some clearly identifiable repetitive physical characteristic of the flow pattern.

Further insight into certain aspects of the large-scale structure of shear-layer turbulence has been provided by an Orr–Sommerfeld type of stability analysis of turbulent flows. Experimental investigation of numerical models of unsteady flow provides an alternative method of studying the initial development and growth of the large eddy structures.

Contributions to the Colloquium ranged over all the approaches outlined above, including the combination of flow visualization with conditional data sampling. These individual formal presentations and the discussions are summarized briefly in §2. Where relevant published material is available a reference to this is included, but otherwise the reader should consult the person concerned for further details. This account of the Colloquium concludes with the authors' impression of the consolidated contribution that has been made to our understanding of turbulent shear-flow structure and the more recent developments in experimental and analytical techniques.

2. Contributions to the Colloquium

The summaries of the formal contributions to the Colloquium and their discussions have been arranged such that descriptions of observations of free shear layers are followed by those of boundary-layer structure. Studies of the stability characteristics of wave models come next while the results of numerical studies and experiments with numerical unsteady flow models complete the account of the presentations.

2.1. *Observations of free shear flows*

In the first invited lecture, A. Roshko described recent experimental work at the California Institute of Technology on two-dimensional mixing layers between gas streams of constant non-zero velocity (see also Roshko 1973). He discussed schlieren films, first described by Brown & Roshko (1971), which indicated that the mixing layer was composed of large-scale line vortices which clearly remained coherent for long distances downstream. The longitudinal increase in their scales, and thus the spreading of the mixing layer, was accomplished by the coalescence or merging of neighbouring coherent structures. The experiments did not indicate the presence of any significant small-scale motions. Roshko explained the basic differences between this turbulent flow and the quasi-laminar vortex street nearer the separating plate by showing the probability distributions of the eddy spacings which were measured from the schlieren films for different distances downstream (Brown & Roshko 1974). These showed a wide range of spacings for a given position which indicated that, compared with the discrete vortex passing frequencies and coalescence positions in the laminar flow, the vortex movements and coalescence in the turbulent region were much more random. Otherwise the structures of the laminar and turbulent regions were basically similar.

It was proposed that the entrainment process involved engulfment, particularly by coalescing vortices, as opposed to the view of entrainment consisting of a viscous 'nibbling' action at the outer edge of the turbulent region. Checks on the entrainment rate produced by an engulfment mechanism agreed with observations. Thus the dominant mixing, entrainment and energy-transfer processes did not involve viscous mechanisms, a view which was echoed in many of the subsequent presentations and discussions. Hence there was general agreement on the minor role of viscous action in free turbulent shear flows. This view was further supported by the sharp dividing lines observed between the different gases in the mixing layer in spite of the presence of relatively smooth velocity distributions.

Roshko also discussed coherent vortex-like motions in other types of turbulent flow, showing photographs of atmospheric jet streams and the edges of ocean currents. He pointed out that the apparent differences between coherent motions observed in different types of flow made the search for a universal approach unprofitable.

In the discussions that followed the acceptance of this mixing layer as a fully developed turbulent flow was queried. In reply Roshko stated that the Reynolds number was sufficiently high for turbulent flow to be assumed and the turbulence intensity, mean vorticity and spreading rate agreed with previous data for turbulent flows. The two-dimensional line-vortex structure for the eddies proposed by Roshko was questioned and the need for measurements of the spanwise turbulence intensity $\overline{w^2}$ to establish the three-dimensional nature of the flow was noted.

T. Maxworthy presented a contribution by F. K. Browand & P. D. Weidman of the University of Southern California describing investigations of two-dimensional mixing layers which were instigated by Roshko's experiments. In these experiments, the first results of which have been described by Winant & Browand (1974), dye visualization in a water channel again suggested that the flow was mainly composed of interacting and coalescing large-scale vortices. Averaged measurements of instantaneous velocity distributions at different stages of the coalescence process were obtained by phase-averaged conditional sampling with a reference probe on either side of the mixing layer. It was found that large contributions to the turbulent shear stress occurred during the pairing process and some detail of the orderly structure found during this process was described.

A. J. Yule described investigations of coherent motions in the first ten diameters of round jets (see also Yule *et al.* 1974). Domination of the turbulent flow by interacting and coalescing ring vortices was inferred from flow-visualization films. However these coherent structures in the round jet were less clear than the equivalent vortex structures described previously for two-dimensional mixing layers. The large organized structures in the turbulent round jets differed fundamentally from the laminar ring vortices nearer the nozzle from which they developed. In particular they possessed a strong but relatively well ordered three-dimensional structure which included circumferentially distributed mixing jets. The importance of making simultaneous flow-visualization and quantitative investigations so that observed phenomena could be related to measured velocity time histories was stressed. Such experiments showed that coherent motions observed in the turbulent jets were directly associated with distinct repetitive features in the velocity signals. The importance of differentiating between turbulent and unsteady laminar flow regions, when investigating coherent structures, was also stressed and criteria for making this distinction were suggested.

H. H. Bruun described associated hot-wire measurements which used the characteristic velocity signatures discussed by Yule (i.e. very large negative or positive peaks depending on radial position) as triggering signals to educe the average motions of the large-scale coherent structures. The major contributions to the turbulent energy, shear stress and statistical cross-correlations obtained from continuous records for the mixing-layer region of the round jet were associated with these large eddy structures.

H. H. Fiedler & D. Korschelt outlined experiments at Berlin with two-dimensional mixing layers and round jets. Their films exhibited similar coherent turbulent structures and laminar vortex-ring flows in round jets at different Reynolds numbers. Conditional-sampling measurements in a mixing layer with one stream heated suggested a predominant bulk convection mechanism for temperature which was explained by the presence of large-scale eddies of line-vortex type. Visualization of the structure of the turbulent round jet revealed less obvious coherence than that found by Roshko and Browand in two-dimensional mixing layers. This was particularly true in the outer jet region, where Yule had observed an obscuring of the underlying flow pattern by the outward ejection of fluid.

The above presentations brought out the important roles of vortices and vortex-like structures both in the transition process and in the turbulent flow itself. T. Kambe and his co-worker Y. Oshima presented experimental and analytical work aimed at understanding the three-dimensional interaction of discrete viscous vortex rings and also their stability characteristics (see also Kambe & Takeo 1971; Oshima 1972). Flow visualization demonstrated the splitting of deformed vortex rings into two or three rings and the combination of several rings into a single ring. The coalescence process and also the observed and predicted growth of vortex-core waves had basic similarities with phenomena observed in continuously running round jets.

Two investigations concentrated upon conditional sampling in the outer regions of turbulent jets with the object of understanding the intermittency region and the laminar/turbulent 'interface'. O. Wehrmann conditioned hot-wire signals to obtain distribution functions of 'laminar time', 'turbulent time', intensity and 'frequency' of intermittency. These had forms which indicated a minimum size of the turbulent elements producing the intermittency and they were in fact consistent with vortex-like structures in the jet. Discussion followed in which the arbitrariness inherent in the conditioning of measurements when studying intermittency was considered. V. W. Goldschmidt described measurements of velocity and temperature conditioned with respect to what was considered to be the turbulent interface of a heated plane jet. The interfaces of the temperature and velocity fields were found to be coincident, while the apparent wider transport of heat was a result of a flatter temperature profile in the turbulent region. The transport coefficients were constant in the turbulent region.

A. J. Reynolds gave a further contribution on the relative diffusion of heat and mass in turbulent flows and discussed the role in this process of the intermittency produced by the large coherent structures. He pointed out the inaccuracy of assuming a constant Prandtl number across turbulent shear flows and showed that published data in general indicated two regions: the fully turbulent 'body value' region and the outer region with a higher 'edge value'.

In the first of two presentations concerned with aerodynamic noise production by coherent motions in round turbulent jets, H.V. Fuchs described how Michalke's (1972) analysis implied that the lower-order azimuthal components of the fluctuating pressure field could be particularly efficient sound producers (see also Fuchs 1972, 1973). Filtering azimuthal cross-correlations of the pressure indicated that such pressure-field constituents did indeed dominate the flow. Fuchs described how pressure and velocity cross-correlations indicated the presence of coalescing coherent motions in the turbulent flow. Unlike the pressure correlations, azimuthal cross-correlations of the fluctuating velocity u indicated that the strongest contributions came from fifth-order modes, i.e. strongly asymmetric structures. These findings appeared to correlate with the wave growth in the vortex-ring cores and the three-dimensional structures of the coherent motions which were observed by Yule *et al.* (1974) in front views of a jet. Fuchs pointed out that the coalescence of purely axisymmetrical vortices, which Laufer, Kaplan & Chu (1973) proposed as a basic jet noise mechanism, ignores the contributions of other equally important azimuthal modes.

J. E. Ffowcs Williams further discussed aerodynamic noise in relation to coherent structures and repetitive events in jet turbulence. In particular the 'crackling' of high velocity jets was discussed and he described the recognition of jet crackle by the skewness in measured amplitude probability densities of pressure. It was argued that the motions responsible for jet crackle were distinctive large-scale events analogous to a sudden buckling of the jet column. A demonstration of this phenomenon was provided by a jet model using a water table.

The structure of jets subjected to some form of periodic forcing was described in contributions from Grenoble and Berlin. As well as providing flows of practical interest this device has been exploited to investigate the development of instability and also to provide a more ordered structure amenable to both flow-visualization and conditional-sampling methods. J. P. Girard presented observations on a round jet with a fluctuating pressure field applied to the upstream settling chamber. Hot-wire measurements and schlieren photographs indicated that appreciable effects occurred for forcing Strouhal numbers greater than 0·04. These effects were a higher initial spreading rate due to the formation of large vortex rings near the nozzle and also an associated periodic velocity component which decayed with distance downstream.

The account of these experiments was continued by G. Binder, who described the results of applying periodic-sampling and phase-sampling techniques to hot-wire measurements of the flow. The pulsating jet was found to have a faster increase in turbulence intensity and also large fluctuations in its instantaneous width due to the strong vortex-ring flow. The wave crests associated with the pulsations near the nozzle moved more quickly than the jet mean velocity. All discernible effects disappeared after twenty diameters downstream, where the jet reached the normal spreading rate for an unforced jet. Subsequent discussions included a querying of the positions of laminar and turbulent regimes in the jet, particularly because of the relatively low Reynolds number involved.

G. Binder also described experiments with periodically flapping slot jets (see also Binder & Favre-Marinet 1972). Considerably increased rates of spread were found and this effect was maintained for an indefinite distance downstream although periodic velocity fluctuations disappeared after twenty diameters. The initial flapping was found to induce a wake-like vortex structure in the jet.

E. Pfizenmaier described velocity and pressure measurements in a round jet mixing layer with a periodic disturbance introduced by a loudspeaker in the settling chamber. The experiments concentrated on the instability of the initially laminar shear layer and on the early stages of the subsequent vortex-ring formation. For low forcing Strouhal numbers reasonable agreement with Michalke's (1970) analysis was found and measured phase velocities higher than the jet exit velocity were found for the same Strouhal number range as that predicted by Michalke. Agreement was not found at higher Strouhal numbers because of effects caused by the finite shear-layer growth rate and the magnitude of the forcing field. The standing wave patterns observed were interpreted as a superposition of the existing sound wave and the excited stability wave. It was found that the frequency giving maximum amplification of signals inside the shear layer was considerably greater than the frequency producing maximum amplification of potential-core fluctuations, thus demonstrating that the highly amplified, high frequency disturbances had no great far-field effect.

N. A. Chigier described techniques developed to investigate unsteady wing-tip trailing vortices with the emphasis on obtaining 'instantaneous' velocity profiles across the flows rather than classical time-averaged measurements. Measurements were obtained by either a rapidly scanning laser anemometer or by a physically scanning hot-wire probe attached to a rotating arm. Flow visualization showed random meanderings of the discrete vortex core which produced a fluctuating velocity field and somewhat misleading mean velocity profiles. The scanning systems located the instantaneous vortex position and revealed the axial and tangential velocities in the vortex. The randomly meandering vortex wake flow has analogies with the quasi-randomly moving vortex structures noted by Roshko and others. The application of a similar scanning technique to the mixing-layer and jet flows could yield useful information on detailed structure and extend the flow-visualization and conditional-sampling experiments.

2.2. *Observations of boundary-layer and pipe flow*

I. J. Wygnanski described an experimental investigation of artificially instigated pipe-flow transition at lower Reynolds numbers in which phase-averaged conditional sampling was used to educe the average structures of 'turbulent puffs' (see also Wygnanski, Sokolov & Friedman 1974). These events were found to differ from the 'turbulent slugs' previously investigated by Wygnanski & Champagne (1973) for higher Reynolds numbers and consisted of two co-rotating ring-vortex eddies with a smaller eddy between them which contributed most of the turbulent activity and shear stress.

J. Sabot discussed the investigation of fully developed pipe flow by using extensive space–time cross-correlation measurements. On the basis of these measurements he proposed that the core flow consisted of narrow organized rotational structures generated near the pipe wall. The core region was thus basically similar to the outer region of a boundary layer and it could be considered to contain many uncorrelated 'bulges' or structures of different ages and originating from different sectors of the pipe. A new type of conditional-sampling technique for investigating such a flow was thus suggested.

R. S. Brodkey described experiments which were aimed at obtaining a better understanding of the turbulent energy balance in terms of the turbulence structure and hence improving the formulation and simplification of the equations (see also Brodkey *et al.* 1973). The apparent anomaly of regions of negative energy production in certain flows was considered and a more useful definition of the production term was proposed. Measurements of this term in an asymmetric channel flow indicated positive values throughout the flow. In the discussion that followed, the meaningfulness of the usual interpretations of the turbulent energy balance was queried. It was generally agreed that improvement of analytical techniques, which used forms of the energy equation, would ultimately require the replacement of the Reynolds averaging method, to enable the effects of dominating coherent motions and events to be included.

Measurements in a channel flow by J. L. Livesey were used to propose the existence of simple empirical linear relationships between the magnitudes of the three turbulence intensity components throughout the flow. Similar relationships were also proposed for other turbulent shear flows. The ratio between the auto-correlation $R_{uu}(t)$ and cross-correlation $R_{uv}(t)$ was found to be independent of t and spectral measurements of the different components showed that the u and v spectra were also linearly related at the mid-band frequencies. It was proposed that, in addition to providing useful correlations, the results could be significant in terms of coherent structures in the flow.

A series of four related talks by a team from the Max Planck Institute, Göttingen, and the Ohio State University described an experimental programme which was aimed at understanding boundary-layer structure by looking for and investigating repetitive events and coherent motions in the flow. S. G. Nychas described flow visualization of the boundary layer in a water channel by using particles and a ciné camera moving with the main flow (see also Nychas, Hershey & Brodkey 1973). A repetitive sequence of ordered motions was revealed in the outer boundary-layer region by the film. These events produced coherent motions in the form of transverse vortices which persisted for long distances downstream. Typical fixed-point velocity time histories which would be produced by the passage of these vortices were derived by analysing the particle paths. The objective was to develop distinctive criteria for recognizing these vortices in the velocity time histories measured by fixed hot-film probes.

The digital pattern recognition procedure that was developed was described by J. M. Wallace (see also Wallace, Eckelmann & Brodkey 1972; Brodkey, Wallace & Eckelmann 1974). The basic pattern suggested by the flow-visualization studies and recognized by the computer program was a slow deceleration in the u velocity followed by a more rapid acceleration. This pattern was recognized, normalized and stored, and the corresponding v and uv signals were simultaneously stored. Approximately 50 % of the velocity time history was recognized and the educed v patterns were on average in antiphase with u, thus the structures were contributing to the shear stress $\overline{uv}$. In the general discussion that followed the necessity for a three-dimensional structure of the observed vortices was proposed on the basis of other data. The wide range in the scales of the patterns recognized in the time histories was queried and the experimenters interpreted this as a result of the probe seeing different sections of the structures at different stages of their development. H. Eckelmann described an investigation of coherent motions and repetitive events in the viscous region near the wall by H. P. Kreplin, H. Eckelmann & J. M. Wallace. The propagation of perturbations of the instantaneous velocity gradients $\partial u/\partial y$ and $\partial w/\partial y$ at the wall and the associated velocity fields was measured by hot films using sampling techniques. Perturbations in $\partial u/\partial y$ were recognizable up to a distance $x^+ = 250$ downstream and these perturbations travelled at an approximate velocity of $15u_\tau$. Perturbations in the streamwise velocity u propagating towards the wall at u_τ were found and these were connected with perturbations at the wall of $\partial u/\partial y$ at a later time. However, velocity-gradient perturbations could be recovered over relatively small spanwise distances only. The perturbation patterns were interpreted as narrow flow structures with inclined fronts. Approaches adopted to link the observations with those of other investigations of boundary-layer flow were described.

R. S. Brodkey described an optical technique used by J. Heibel & R. S. Brodkey for measuring the fluctuating pressure field on the wall beneath a turbulent boundary layer. An array of flexible diaphragms produced pressure-related interference patterns for a matrix of positions at the wall. High-speed ciné films were analysed digitally to produce contour plots of the pressure field.

An investigation of a separating turbulent boundary layer using laser and hot-film anemometry techniques was described by R. L. Simpson. The sublayer bursting frequency agreed with the frequency of the first moment of the wall shearing-stress spectra and the passing frequency of the intermittent structures in the outer region was proportional to this frequency. Observed variations in the separation position were related to the large-scale coherent structures upstream. The convection velocity of these large-scale structures agreed with that reported by Eckelmann.

W. W. Willmarth described investigations of repetitive 'bursting' phenomena and resulting coherent motions in the inner region of a turbulent boundary layer (see also Willmarth & Lu 1972). These bursts involved eruptions of low-speed fluid from the wall which were convected downstream and gradually lost their coherence in the process. Measured *uv* signals were sorted into four quadrants in the *uv* plane and burst-like contributions to the shear stress were revealed throughout the boundary layer. The bursts were found to be accompanied by large areas of low pressure near the wall and appeared to be consistent with a previously proposed flow model involving 'hairpin' shaped vorticity distributions.

A. Favre described three-point space–time correlations of the temperature fluctuations in a boundary layer with a heated wall found by L. Fulachier, R. Dumas, L. S. G. Kovasznay & A. Favre. The temperature was considered as a passive scalar contaminant and used to aid the investigation of the large-scale boundary-layer structure. Triple correlations were found to be more sensitive for the detection of strong large-scale structures than double correlations. The large-scale structures were found to be strongly three-dimensional and compatible with the observations of Eckelmann and Willmarth.

R. E. Falco showed ciné films of the outer region of a smoke-filled turbulent boundary layer which were recorded by a camera moving with the free-stream velocity (see Falco 1973). The medium-scale vortex-like motions which were often seen near the edge of the smoke-filled region were discussed. These structures were typically of dimensions $\frac{1}{10}\delta$ for higher turbulent Reynolds numbers, where δ is the boundary-layer thickness, and they remained coherent for some distance downstream. It was unclear whether these structures corresponded to those investigated by Nychas and Wallace. The vortex structures, as marked by the smoke, had length scales which depended on the Reynolds number of the flow and at lower transitional Reynolds numbers they were effectively the large eddies of the flow. Front views showed that the structures were strongly three-dimensional with a 'mushroom' appearance. Typical velocity distributions over cross-sections of individual vortex motions were measured by recording the signal of a hot-wire probe while simultaneously filming the flow. As in the pattern recognition of Wallace, the passage of a structure was accompanied by a positive and then a negative *u* peak. Falco pointed out that this was not compatible with a symmetric line-vortex model. Yule and Brunn discovered similar distortions in the coherent structures in the round jet and in fact such vortex deformation and asymmetry is necessary for any contribution to the mean shear stress $\overline{uv}$.

J. P. Johnston showed films of flow-visualization experiments which investigated flow stabilization and destabilization by Coriolis forces produced by system rotation (see also Johnston, Halleen & Lezius 1972). The suppression of wall-layer turbulence in a stabilized boundary layer and the establishment of large-scale longitudinal vortex cells on the unstable side of a channel flow were shown. Side views of a plane mixing layer showed that the stabilized flow contained clear line-vortex motions which coalesced as opposed to the less well defined coherent large eddies seen in the turbulent flow. Top views of the mixing layer indicated a spanwise waviness in the vortex cores and coalescence involved entanglement of these cores, a three-dimensional mechanism similar to that observed earlier for the vortex rings in round jets. The clear differences between the regular well-defined vortex motions in the stabilized flows and the more obscure motions in the normal fully turbulent flows illustrated the importance of establishing whether a flow is truly turbulent when interpreting the significance of observed coherent eddy patterns.

M. V. Morkovin described experiments investigating the stability and transition to turbulence of the shear layer behind a rectangular obstacle buried in a laminar boundary layer. Acoustic forcing at a frequency f in the precritical regime produced vortex loops, but no transition. Simultaneously applied frequencies f_1 and f_2 produced vorticity waves with frequencies f_1+f_2, $2f_1+f_2$, etc., and higher harmonics, but the transition to turbulence was produced by the amplification of the very low level component f_1-f_2. Direct forcing at this frequency did not produce transition and the possible generality of this nonlinear phenomenon was considered. As with other speakers there was speculation on the similarity between the vortex structures which are clearly observed in transitional flows and the resulting turbulent coherent motions, which are less amenable to investigation.

Experiments which were planned on the basis of this similarity were discussed by A. Roshko, who presented the work of D. Coles & S. Barker on the design of a 'synthetic turbulent boundary layer'. The work proposed the hypothesis, apparently generally accepted at the meeting, that each turbulent shear flow contains its own coherent structures and characteristic events and these phenomena are basically similar to those found during the transitional stage of the flow. The transitional flow is more easily studied, as it is amenable to external forcing to produce orderliness and is relatively uncluttered by small-scale motions and interactions. The synthetic turbulent boundary layer was produced by the superposition of a large number of transitional structures which were artificially created in an initially laminar boundary layer.

The laminar boundary layer was periodically 'tripped' at a number of spanwise positions. The tripping frequency and the separations between the tripping positions were selected to give approximate agreement between the length scales of the resulting transitional 'turbulent spots' and those scales implied by correlations in natural turbulent flow. Phase-averaged conditional sampling in the flow was performed relative to the tripping frequency and the structures were found to be '∪' or 'hairpin' shaped inclined vortices which grew linearly and lifted fluid from the wall region. These structures were basically similar to those found by other workers in normal turbulent boundary layers. The experiment was intended to lead to a modelling technique for practical boundary layers. It led to a general discussion on the merits of either (*a*) assuming coherent structures to be pre-existing universal turbulent flow features which are independent of initial conditions and thus modelling the flow in terms of these structures, or (*b*) hypothesizing that the structures were derived from laminar and transitional flow and thus that the understanding of turbulent flow structure involves an understanding of the instability and transition process.

A. Gyr discussed the very limited information on turbulent flow structure that spectral representations provided. He reviewed the possibility of modelling turbulent flows by using appropriate arrays of vortices. After some speculation on the limitations of this approach† he described pattern recognition analyses of channel-flow data which assumed the flow to consist of an array of circular vortices giving double-peaked velocity contributions. Distributions of the characteristic lengths and passing frequencies for the vortices in such a model were derived.

2.3. *Waveguide and the other models of turbulence structure*

In the second invited lecture G. M. Lilley discussed the mathematical modelling of the large-scale structure of turbulent shear flows with emphasis on the stability-analysis approach. He described how recent experimental results had emphasized the importance of large-scale coherent motions in turbulent shear flows and had justified analytical work on this subject, which had been in progress for some time. It was proposed that the large-scale organized structures could be represented by wave packets with characteristics derived from linear stability theory. This representation infers a similarity between the turbulent structures and those motions in the laminar flow which lead to transition. Such a similarity had been proposed on an experimental basis by several of the preceding lecturers. Lilley described the results of such a 'waveguide' approach to the analysis of turbulent two-dimensional mixing layers and round jets.

Small-scale turbulence was assumed to produce an eddy-viscosity effect and the effects of the predicted large-scale motions themselves on this eddy viscosity were taken into account by an iterative procedure. The effect of flow divergence was also taken into account and this was found to limit the amplification of the large-scale disturbances. The vortex-like large-scale wave motions predicted by the analyses showed at least qualitative agreement with the observations described previously and there was good agreement between the measured and predicted turbulence intensity distributions for a mixing layer.

This stability-equation approach was used in several of the subsequent presentations which analysed turbulent and transitional flows. Some attention was focused on its use to analyse transitional mixing-layer and jet flows affected by a periodic forcing field. D. G. Crighton described how the large-scale jet structure was exposed in Crow & Champagne's (1971) periodically forced jet. Michalke (1970) predicted the most amplified frequency for this forcing using linear stability theory, showing that it depended upon the ratio of mixing-layer momentum thickness to jet diameter. Parallel-flow stability theory could not lead to the experimentally observed amplitude limitation and subsequent decay and Crighton discussed how the spreading of the mixing layer or jet could produce these phenomena. H. V. Fuchs presented a short discussion prepared by A. Michalke on mixing-layer instability, in which past and future analytical work on this subject was outlined. D. Bechert described present work at Berlin on analytical studies of the effect of periodic monopole or dipole pressure fields on the development of a shear layer from a flat plate (see also Bechert & Michel 1974). An infinitely thin boundary layer was assumed which the authors considered restricted the accuracy of the theory to predicting low Strouhal number

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† These reservations were largely confirmed by the results of the earlier, basically similar, work of Base & Davies (1967, 1974).

forcing. The resulting wave-motion magnitudes were found to depend on the forcing field only.

G. E. Mattingly described analytical treatments of spatially growing large-scale disturbances in a plane and a round jet (see also Mattingly & Criminale 1971). Solutions of the Orr–Sommerfeld equation gave the amplified waves and fluctuating velocities and predicted the vortex-street-like formation found experimentally in plane and round jets at lower Reynolds numbers. A helical disturbance was found to be most highly amplified far downstream in the round jet. These stability studies, as did those of Crighton, Bechert and Michalke, concentrated on laminar and transitional flows, but the extent to which they might apply to fully developed turbulent flows was not clear.

J. T. C. Liu described attempts to model the large-scale structures in the turbulent regions of free shear flows, with an eddy-viscosity assumption to model the small-scale turbulence by a method similar to that used by Lilley (see also Liu 1974). The stability of the mean velocity profiles was investigated using an Orr–Sommerfeld approach. M. Lessen described laminar instability solutions for axisymmetric swirling and non-swirling jets and wakes which predicted the optimum swirl for destabilization (see also Lessen, Singh & Paillet 1974). The extension of this approach to the turbulent flow problem was discussed in terms of eddy-viscosity assumptions.

In the first part of his presentation W. C. Reynolds described an experiment which involved applying a fluctuating pressure field to a channel flow and recovering the signal downstream by conditional sampling. The objective was to test turbulence theories using the waveguide approach. He pointed out that, although low Reynolds number transitional flow can be predicted reasonably well by stability methods, extensions of these approaches to turbulent flows, assuming an effective eddy viscosity, meet with varying success. Various other analytical approaches to turbulent flows were discussed and particular attention was focused on turbulence closures based on Lumley's (1967) work. The derivation of the constants involved in these closures using experimental 'homogeneous' flow data was described and the wavenumber spectra which they imply were discussed.

Reynolds also discussed a new approach which was intended to solve equations for two-point correlation tensors and involved decomposing the turbulence into deterministic eigenfunctions, etc., by using a general description of a random field. This approach, which is analogous to the problem of finding the 'most turbulent' state, was of interest because of the lack of empirical constants.

Numerical modelling. Numerical studies presented at the Colloquium included descriptions of numerical solutions of the Navier–Stokes equations either in a complete or simplified form. Other approaches were based on various modifications of the treatment of the turbulent energy equation. Finally some investigations of potential-flow modelling of unsteady flow with concentrated regions of vorticity were described.

A. J. Grant described numerical calculations of the initial stages of round-jet development which used finite-difference solutions of the complete Navier–Stokes equations. The solutions predicted a street of vortex rings in the transitional flow near the orifice which was in qualitative agreement with experimental observations and the results of stability analysis. Associated experiments were intended to investigate the roles of vortex structures in the mechanisms of entrainment and flame stability in jet diffusion flames. Shadowgraphs exhibited vortex structures for Reynolds numbers up to 20 000. Experiments with a methane jet using a laser scattering technique and a periodic forcing field indicated that very sharp interfaces existed between the two gases in the mixing-layer region. Thus, as was observed by Roshko, Goldschmidt and others, molecular diffusion played a minor role in such mixing, while entrainment was the result of a potential engulfment process induced by the large-scale motions.

J. W. Deardorff described numerical calculations of atmospheric boundary layers. Attention was focused on the shapes and sizes of the convectively driven eddies, as derived by three-dimensional numerical integrations in time, for a model using 64 000 grid points in a volume $5 \times 2 \times 2$ km. The model included temperature variations, moisture content and earth rotation, while the effect of small-scale motions between the grid points was approximated by an eddy-diffusivity assumption. Films of the computed results for different boundary conditions showed large-scale coherent eddies which agreed broadly with observed flows. The addition of heat flux from the ground increased the coherence of the eddies. Deardorff described how conditional-sampling and correlation methods could be used to compare the details of the numerical flow with measurements.

J. C. R. Hunt described a potential-flow theory which predicted the distorting effects of solid boundaries on the fluctuating field, or eddies, of turbulent flow (see also Hunt 1973). He described how this approach had advantages over methods involving the turbulent energy equation in certain cases. Examples were given of the calculation of large-scale grid turbulence near a wind-tunnel wall and reattachment behind a bluff body on a plane surface.

A vortex model of unsteady shear flow was proposed by S. F. Birch. He discussed the modelling of jet structure by assuming a superposition of vortex-like large eddy structures on a homogeneous mean flow. A general discussion by participants followed which considered the necessity for vortex coalescence to occur in such a flow in order that shear-layer growth could occur.

P. O. A. L. Davies presented the results of a potential-flow calculation of the development of an isolated vortex ring and of a circular jet (see also Davies 1973). The results were illustrated by alternating films of a visualization of the flow and its computed equivalent. The cylindrical vortex sheet shed at the jet lip was represented by a row of periodically generated elementary vortex rings. Uniform flow through the jet orifice was maintained by an appropriate updated source distribution. Streaklines were simulated by arrays of periodically generated passive points. The jet model showed the rolling up of the vortex sheet into a train of vortex rings. It also showed that the spreading of the jet was achieved by the coalescence of neighbouring vortex rings into larger but still coherent structures. The models were constrained to be axisymmetric and therefore the structure remained more orderly than that of a real flow. The effect of this constraint appears to be similar to that of forcing the jet by some initial disturbance, which also encourages order in the flow. The value of extending such models to provide a more realistic three-dimensional structure was discussed, though it was agreed that the practical problems of maintaining reasonable economy of computer time is a major constraint.

A. Leonard described the initial results of numerical simulations of interacting three-dimensional vortex filaments which had the ultimate objective of modelling turbulent shear flows in a three-dimensional manner. Ciné films of the computed movements and distortions of the vortex filaments were shown for the interactions and instabilities of vortex rings, helical vortex filaments, trailing vortices and a round starting jet.

3. Review and discussion

Experimental evidence presented at the Colloquium and other evidence in the literature (e.g. Townsend 1956) have demonstrated that it is physically realistic to regard shear-flow turbulence as an assembly of repetitive ordered structures which interact strongly with each other and coalesce as they move with the flow. The structures, and the vorticity concentrations which they contain, remain coherent for large downstream distances. Furthermore many of the observable effects which are characteristic of turbulence, such as enhanced transport rates of momentum, mass or heat, are strongly influenced if not controlled by these interactions.

Observation has also shown (Lau 1971; Davies 1973; Brown & Roshko 1974) that these structures found in turbulent shear layers have an irregular spacing whose probability density approximates to a Rayleigh distribution. This and other characteristics of the flows where such structures are found display all the characteristics of turbulence in terms of accepted statistical criteria. Earlier observations (Tani & Hama 1953) had revealed similar coherent interactions and growing structures during boundary-layer transition but they had then been regarded as a transitional state of the flow.

Among the examples of coherent structures presented during the Colloquium, some did not include sufficient data to decide whether they were representative of turbulence or of some transitional flow, or might fit both these categories. Of particular interest, perhaps, were those where the flow was periodically disturbed or forced since, qualitatively at least, the resultant structure appeared more orderly than the unforced flow, which might suggest that transition to turbulence was thereby delayed.

Despite such reservations, the experimental evidence clearly demonstrated the existence of large-scale coherent structures in turbulence. This was perhaps a major achievement of the Colloquium since many contributors, provided with the limited evidence of their own experiments, had been concerned as to whether their observations might represent a special case. Coherent structures that were observed independently by several contributors included the large-scale vortex-like eddies which dominate mixing-layer and jet flows and the repetitive coherent vortex motions in the outer region of boundary layers and in pipe and channel flows.

The idea that shear-flow turbulence is dominated or to a certain extent controlled by the 'big eddies' is not new. The difficulties in defining the characteristics of such eddies from statistical measurements have, however, been clearly set out by Townsend (1956). An example of the use of correlation measurements to provide the structure of the big eddies in a wake was given by Grant (1958). The collection of clear and abundant new evidence of the presence of coherent regions of concentrated vorticity in turbulent shear flow has depended for its recent success on the development of improved quantitative flow-visualization techniques and of new techniques for the conditioned analysis of velocity, displacement and pressure records in real time.

The development of these new techniques has been a consequence of the realization by some experimenters that traditional statistical techniques of measurement and analyses were of limited value in defining the structure of a flow comprising irregularly spaced, coherent structures. Thus the direction of the experiments has been towards a more deterministic description of turbulent shear flows.

The clearer picture of the large-scale structure of turbulence that has begun to emerge has led to a series of attempts to model the flow with varying degrees of success. It is clear that the wave models can provide fair agreement with observations for some of the predicted modes of instability in the flow, although it should be understood that the organized structure of such concentrated regions of vorticity differs in many respects from that of the turbulent eddy in statistical theories of turbulence, as is discussed in §3.2.

3.1. *Coherent structures in shear flows*

The existence of coherent structures in shear flows can be most readily observed in the mixing between parallel streams (Brown & Roshko 1974; Winant & Browand 1974). Observations reveal that the interface, which is initially a plane vortex sheet, quickly rolls up by a Kelvin–Helmholtz instability into coherent line vortices. Subsequent growth of the mixing layer and line vortices occurs owing to coalescence.

What is puzzling, perhaps, is that the flows in the two experiments cited apparently remain two-dimensional over the field of observation, though the spacing of the individual vortices becomes increasingly irregular as they coalesce. The fact that this process has not been reported previously may be due to the care taken to provide steady uniform initial flow in these experiments. One would, however, expect that ultimately a three-dimensional structure would develop since such line vortices are unstable along their length to small perturbations (Hama 1963). Indeed in figure 8 of Brown & Roshko's paper there are hints that such a development has just started.

The initial development of a circular jet is similar (Wille 1963; A. J. Yule, H. H. Brunn & D. R. J. Baxter), as was also demonstrated by several contributors to the Colloquium. Individual vortex rings are unstable (Widnall & Sullivan 1973), developing a standing circumferential wave which can also be observed on the cores of the vortex rings formed as the jet shear layer rolls up. This results in an ordered three-dimensional structure with smaller mixing jets being ejected from azimuthal positions between the wavy rings. The development of such three-dimensionality in the coherent structures makes them more difficult to identify or study.

Clear evidence of the existence of similar ordered structures in turbulent boundary-layer flows was also reported to the Colloquium. In jets, mixing layers and wakes, development of coherent structure usually commences at a well-defined origin but the continued generation or vorticity at the wall increases the complexity of boundary-layer flows. The origin and growth of vortices near the wall has been widely reported as wall bursts.

One might surmise that, once they exist, regions of concentrated vorticity will always grow by migration and coalescence and produce the large-scale structures found in the outer part of the boundary layer (Offen & Kline 1974). But in boundary-layer flow, identification of coherent structures is further complicated by the occurrence at the same streamwise station of a succession of smaller younger and larger older structures (see, for example, J. M. Wallace, H. Eckelmann & R. S. Brodkey). J. Sabot & G. Comte-Bellot made a similar observation in relation to the identification of coherent structures in fully developed pipe flow. Indeed, Wygnanski & Champagne (1973) have demonstrated that the large eddies in pipe flow possess an ordered structure.

Although they are present in shear flows, one can only speculate whether similar processes occur in the unsheared turbulent flows generated by grids. After an initial adjustment region, the limited evidence that does exist suggests that the large-scale eddies grow very slowly if at all, while the slope of the wave-number spectrum at zero wavenumber remains almost invariant. Shear flows are characterized by a distribution of vorticity which is predominantly of one sign while grid flows differ in this respect. Thus one might expect their behaviour to differ. On the other hand it is difficult to generate experimental grid flows which are large enough in cross-section to avoid the possible constraints imposed by the boundaries which limit the growth, a feature which is absent in free shear flows. Recent measurements in fully developed pipe flow (J. Sabot & G. Comte-Bellot; K. D. Bullock, private communication) hint that a tendency for such growth exists, but is limited by the constraints mentioned.

The development of the three-dimensional structure in free shear layers seems to display the characteristic of continued growth in scale as the vorticity migrates towards larger concentrations. It is easy to visualize that such an ordered structure would convey an impression of great complexity and random motion, as the potential fields of several discrete structures interact.

It appears that both the development of the Kelvin–Helmholtz instability and the subsequent coalescence and migration of vorticity to provide the growth of the vortices can be illustrated by potential-flow models (P. O. A. L. Davies & A. J. V. Edwards). The way in which most transport properties may also be related to the potential flow fields of arrays of vortices has been demonstrated by Christiansen & Zabusky (1973). That these purely kinematic models of the velocity field should model quantitatively so many of the characteristic features of high Reynolds number flows is interesting. It also demonstrates the relatively minor role in their development played by viscosity, whose global effects can be replaced by appropriate distributions of vorticity.

The quantitative description of the detailed flow patterns in the coherent eddy structures and the investigation and quantification of their interactions present a challenge to the experimentalist. The new techniques which are required for such observations are discussed later. We must also develop adequate conceptual tools to organize and interpret the new information in a meaningful and useful way so that the understanding and modelling of turbulence structure can be improved.

3.2. *Some tentative concepts*

There is some profit, perhaps, in making an initial attempt to correlate the new experimental information and ideas presented at the Colloquium with existing statistically derived models of turbulent shear-flow structure. The interaction and coalescence of large-scale vortex-like eddies have been proposed as characteristic elements of the structures of jets, mixing layers, wakes and also of the outer boundary-layer region and the core region of pipe flow.

The classical statistical turbulence structure is normally expressed in terms of a wavenumber spectrum $\phi(k)$. The theory defines individual component eddies within this structure as producing portions of the spectrum lying between wavenumbers k_r and $k_r + \delta k_r$. However, a single region of concentrated vorticity will always yield a broad wavenumber spectrum, the lowest wavenumber corresponding roughly to its physical extent and the highest roughly to its steepest local velocity gradients, whose magnitudes are limited by viscous diffusion.

Townsend (1956) has demonstrated that an array of organized structures with a single characteristic scale also produces a broad wavenumber spectrum. Further Base & Davies (1967) have shown that a synthetic flow consisting of an array of randomly spaced, identical vortices can reproduce both the probability and spectral characteristics of point turbulence measurements, by judicious choice of the spacing and scale.

Although, as illustrated by the earlier discussion, there are fundamental differences between coherent structures and the classical statistical concept of an 'eddy', one could always represent a homogeneous field of concentrated regions of vorticity by a group of statistical eddies. But it is known that the field for real shear flows is not truly homogeneous as the flow is bounded. Thus perhaps a physically more meaningful and informative model of flow structure is provided by an instantaneous picture of the velocity distribution than is given by transforming to a spectral representation, although such a representation is convenient analytically. Further, since the energy of any component eddy is bounded, the wave system must be dispersive. Thus, the spatial extent of each wavenumber component k_r is restricted to lie within the flow boundaries. This restriction is avoided in the classical, statistical theory by assuming that the turbulence is homogeneous.

The turbulent energy spectrum. The concept of coherent structures may also clarify certain practical problems in the direct measurement of point wavenumber spectra in shear-flow turbulence. Consider the velocity time history record at a fixed point in an unsteady flow consisting of a succession of irregularly spaced coherent structures. Since the velocity field must be continuous, one would expect to find a relatively high correlation between parts of the record lying close enough to be within a given structure. But one would expect a low, or negligible, correlation between parts arising from neighbouring structures and zero correlation between those parts of the record from structures remote from each other. There seems little doubt that such a record will be ergodic and random provided that sufficiently long records are analysed with an appropriately large time separation.

One can transform the frequency spectrum obtained from such a time history record to a wavenumber spectrum, either by assuming that the flow structure is frozen (Taylor's hypothesis) or by appropriate use of the phase-velocity spectrum. It turns out, not surprisingly perhaps, that the phase velocity varies with frequency (Davies & Mercer 1973), though there are some uncertainties in its measurement. What evidence there is suggests that shear-flow turbulence can never be taken as a frozen pattern, particularly for the high frequency components.

The transformation of space correlation measurements of the velocity to a wavenumber spectrum reveals similar difficulties, since such correlation curves are antisymmetric and yield a complex spectrum. This suggests that the joint statistical characteristics of time histories taken at nearby points have properties which differ from those of the ergodic velocity time histories from single points. The strong interactions found between neighbouring coherent structures suggests one reason for this lack of homogeneity.

However, if examined from the viewpoint of the statistical model, it is not difficult to see that information from such joint records might appear isotropic, particularly at wavenumbers (not scales) large compared with the characteristic wavenumbers of the coherent structures. Thus, although space–time correlations and spectral measurements permit the assignment of local wavenumbers and frequencies to the turbulence, strictly they must be regarded as local descriptions of the averaged properties of the information obtained from an array of vortices passing the point in question. Thus the transformation from a Lagrangian frame, in which such eddies exist, to the Eulerian one, in which we are normally obliged to make quantitative observations, has local significance only.

The same difficulty applies to the interpretation of such averaged reduced quantities as eddy viscosity, eddy equilibrium and the turbulent energy balance as anything more than localized descriptions of observations which do not strictly represent actual properties of the moving turbulent flow. This is not to say that these concepts are not both useful and convenient methods of summarizing experimental data for practical application.

Turbulent energy production and dissipation. The new information presented at the Colloquium provides further insight into some of the practical difficulties of interpreting statistical measurements of turbulence structure in terms of wavenumber models. It also provides a mechanism for the transfer of energy to the larger coherent structures and for their growth by coalescence.

If we consider the free shear layer or jet then experiments have shown that the largest contributions to the shear stress $\overline{uv}$ occur during the coalescence process. This is to be expected, as one can demonstrate that vortex structures can only contribute to the shear stress when they suffer significant deformations in core cross-section, or lateral movements of the core position (e.g. Lau 1971). These phenomena occur most strongly during the coalescence process. One can show that the largest contributions to the turbulent energy production term $\overline{uv}\,\partial U/\partial y$ will occur during this period of strong interaction and deformation. The experiments of Wallace *et al.* and Falco (1973) also suggest that the interacting vortex structures in boundary layers contain the asymmetries required to give $\overline{uv}$ contributions of significant magnitude.

Considering now the dissipation of energy in a typical structure, one might consider the decay of an individual vortex ring in a fluid of moderate viscosity. The ring can be characterized by its radius R, core radius r and circulation constant Γ. The maximum rate of strain in the flow associated with the ring occurs at a radius a little greater than r, while viscous diffusion ensures that r increases monotonically with time. Concurrently, therefore, the intensity of the local velocity gradients throughout the ring decreases.

If we relate viscous dissipation to the magnitude of the rate of strain, it occurs in a relatively large volume of fluid in the neighbourhood of the surface of the core. In a statistical sense, dissipation would always be associated with the highest wavenumbers, although the linear scale of the motion is increasing. This apparent paradox arises since the existence of a given wavenumber component in the spectral representation does not necessarily imply the existence of an identifiable coherent structure of similar scale in the flow. This is a consequence of the averaging that is made over all scales when evaluating each component of the wavenumber spectrum.

Entrainment and mixing. Recent observations suggest that the entrainment of ambient air by jets and mixing layers is accomplished by a potential-flow engulfment process which is controlled by the large concentrations of vorticity and their interaction. It appears that, in jets and mixing layers, entrainment is greatest during the later stages of coalescence. The fact that potential-flow models furnish satisfactory flow kinematics shows that entrainment may be described by a potential-flow mechanism. It is interesting to note that not only do interacting vortices promote mixing by entraining fluid, but they can also shed a significant proportion of the original potential flow associated with them. This is clear in the visualizations of Yule and Fielder and it also occurs in the 'turbulent' vortex-ring flow of Maxworthy (1974). Study of single vortex rings can play a useful role in describing the similar organized structures found in round turbulent jets.

As with entrainment, rapid mixing inside the coherent structures is predominantly a potential-flow process. This was brought out clearly by the results of the experiments of Roshko, Fielder and Grant described at the Colloquium.

3.3. *New experimental techniques*

Classical statistical space–time analysis of point measurements has provided broad insight into turbulent flow structure in its averaged state. Though very useful, such measurements yield little information on the causal processes in developing turbulence. Their value lies more in providing descriptions of practical flow distributions rather than any practical hint as to how these observed flows may be controlled. The development towards deterministic descriptions of turbulence to provide this insight has followed the growth of suitable experimental techniques and data-processing facilities.

Flow visualization using a variety of techniques combined with high-speed ciné photography provides a useful basis for qualitative and some quantitative observations of flow structure and its development. These techniques are of greatest value as an aid to interpretation of point velocity, pressure or temperature measurements by relating them to specific structural features of the flow patterns. Injected tracers can provide more quantitative information, though its collection tends to be laborious. Combined with ciné or time-lapse photography they provide the most direct method of describing some of the details of the complex velocity patterns that make up the coherent vortex structures. Such techniques remain perhaps the only practical method of evaluating the velocity field over a sufficient area to define the motion of complete disturbances.

Flow visualization combined with simultaneous recording of a point velocity time history has been used to identify specific features of the flow with characteristic patterns in the signal. This procedure has formed the basis of a number of new techniques described above and elsewhere in the recent literature. It has the advantage that velocity distributions in reasonably coherent structures can be determined with far less labour than is required for the equivalent analysis of film records alone.

Observations at Southampton have shown that high instantaneous positive values of velocity observed repetitively in point velocity signals from a jet mixing layer and similar high negative values can be associated with the front and rear portions of the coherent eddies. Conditioned analysis of the signal record or other single-point records obtained simultaneously from a different position in the jet using the occurrence of the peak as a time reference has been used by Lau (1971) and Bruun to obtain the averaged structures of the coherent structures in the flow. Other applications of the same principle have been described by Bearman (1972), Blackwelder & Kaplan (1971) and Wygnanski *et al.* (1974) using other identifiable events as their time reference. The resultant recovered velocity patterns should exhibit some close similarity with associated statistical cross-correlation measurements, if the coherent structures are significant elements of the flow structure. The technique, in favourable situations, provides better definitions of the phase relationships that are found between velocity components and pressures at different points in the flow. Developing free shear layers and boundary-layer sublayers appear to be suitable for the direct application of this procedure.

A slightly more sophisticated development of this approach was employed by Browand, who obtained his time reference signals from two probes set on either side of the mixing layer. He could then repeatedly reprocess his point velocity measurements, using different criteria related to the relative phases of the two reference signals, to provide instantaneous velocity profiles at different stages in the coalescence process.

The identification and study of coherent structures is more difficult in turbulent boundary layers owing to their greater structural complexity compared with free shear layers. One technique being developed by co-operative effort between Johns Hopkins University and the Institut de Mécanique Statistique de la Turbulence involves three-point space-time correlations to distinguish between alternative mechanisms of the large-scale coherent motion. A different approach involved attempts to increase the order in the flow structure by acoustic forcing. The advantage here is that the forcing signal provides the reference for time-domain analysis, while the frequency of forcing can be chosen to correspond to the more highly amplified modes in the flow.

A new technique which has involved much co-operative effort between workers from Ohio State University and the Max Planck Institute, Göttingen, involves a digital pattern recognition routine. The program was ingeniously arranged to recognize patterns with different time scales and amplitudes, a necessary feature for analysing flows with coherent structures of different scales found at different stages in their development. An outline of its basic characteristics was presented at the Colloquium and one looks forward to a fuller description in the literature before long. The same group described a different technique they have developed for observing unsteady pressure patterns at a wall, which was reported above.

It can be seen that many of the new techniques depend heavily on the fast, on-line, digital computer or its equivalent. The speed and versatility that this provides for data processing means that many variations of the processing procedures are possible, within the general framework of the various techniques sketched above. Since it has become relatively well known following the application and description of the technique by Kovasznay in the late 1960s, conditional sampling needs little further description here. Originally the signal being analysed was assigned to the turbulent or potential part of the flow field by a detector operated by a judicious choice of higher derivatives of the velocity signal. The interpretation of the results of such analysis presents difficulties, unless the interface between the two parts of the signal record is very distinct and is clearly indicated by the detector. Observations with flows composed of clearly defined structures have shown that larger instantaneous values of the velocity and thus its higher derivatives are not necessarily related to regions of high vorticity, but may be associated with relatively fast moving patches of irrotational flow. This recently has lent some weight to doubts that have been expressed on previous interpretations of conditionally sampled data.

4. Conclusions

The search for coherent structures in turbulence, now that it is firmly launched, should clearly be extended to seemingly more disordered examples of turbulent flow. At the same time, there remains much to be learned about those structures that have already been described, to uncover and understand the processes involved in their production and development.

For the organizers it was a stimulating, intense and sometimes hectic gathering and they are grateful to the contributors, who all took such obvious pains in preparing their material. They are grateful also to those who came prepared to take such an active part in the lively discussions which contributed so much to the Colloquium. Finally, they would like to thank their colleagues in the Institute of Sound and Vibration Research and at Connaught Hall for the willing help they gave so frequently.

REFERENCES

(An asterisk by a name indicates a lecture given at the Colloquium)

BASE, T. E. & DAVIES, P. O. A. L. 1967 Computer studies of vortex models to represent turbulent fluid flows. *Aero. Res. Counc. Paper*, no. 29072, N519.

BASE, T. E. & DAVIES, P. O. A. L. 1974 A vortex model to relate Eulerian and Lagrangian turbulent velocity fields. *Can. J. Chem. Engng*, **52**, 11–16.

BEARMAN, P. W. 1972 Some recent measurements of the flow around bluff bodies in smooth and turbulent streams. *Symposium on External Flows, University of Bristol.*

BECHERT, D. & MICHEL, U. 1974 The control of a thin free shear layer with and without a semi-infinite plate with a pulsating monopole or dipole. Some new closed form solutions. *Dtsche Luft- Raumfahrt Forsch.* no. 74–22.

BECHERT, D. & MICHEL, U.* The control of a free shear layer from a semi-infinite plate by a pulsating monopole or dipole.

BECKER, H. A. & MASSAROT, T. A. 1968 Vortex evolution in a round jet. *J. Fluid Mech.* **31**, 435–448.

BINDER, G., CURTET, R., FAVRE-MARINET, M. & PATUREL, R.* Flapping jets.

BINDER, G. & FAVRE-MARINET, M. 1972 Unsteady jets. *I.F.R.F. Aerodynamic Panel, France.*

BINDER, G. & FAVRE-MARINET, M.* The structure of pulsating turbulent jets.

BIRCH, S. F.* A vortex model for unsteady free shear flows.

BLACKWELDER, R. F. & KAPLAN, R. E. 1971 Intermittent structures in turbulent boundary layers. *AGARD Paper*, CP-93, 5.

BRODKEY, R. S. & NYCHAS, S. G.* On energy reversal in turbulent flows.

BRODKEY, R. S., NYCHAS, S. G., TANAKE, J. L. & WALLACE, J. M. 1973 Turbulent energy production dissipation and transfer. *Phys. Fluids*, **16**, 2010–2011.

BRODKEY, R. S., WALLACE, J. M. & ECKELMANN, H. 1974 Some properties of truncated turbulence signals in bounded shear flows. *J. Fluid Mech.* **63**, 209–224.

BROWAND, F. K. & WEIDMAN, P. D.* Large-scale structure in the turbulent mixing layer.

BROWN, G. & ROSHKO, A. 1971 The effect of density difference on the turbulent mixing layer. *AGARD Paper*, CP-93, 23.

BROWN, G. & ROSHKO, A. 1974 On density effects and large structure in turbulent mixing layers. *J. Fluid Mech.* **64**, 775–816.

BRUUN, H. H. & YULE, A. J.* Hot-wire eduction measurements in a round jet.

CHIGIER, N. A.* Wake vortex flows.

CHRISTIANSEN, J. P. & ZABUSKY, N. J. 1973 Instability, coalescence and fission of finite-area vortex structures. *J. Fluid Mech.* **61**, 219–243.

COLES, D. & BARKER, S.* Preliminary design of a synthetic turbulent boundary layer.

CRIGHTON, D. G. & GASTER, M.* Mathematical modelling of orderly jet structure.

CROW, S. & CHAMPAGNE, F. H. 1971 Orderly structure in jet turbulence. *J. Fluid Mech.* **48**, 547–691.

DAVIES, P. O. A. L. 1973 Structure of turbulence. *J. Sound Vib.* **28**, 513–526.

DAVIES, P. O. A. L. & EDWARDS, A. J. V.* Vortex model of a round jet.

Davies, P. O. A. L. & Hardin, J. C. 1974 Potential flow modelling of unsteady flow. *Int. Conf. on Numerical Methods in Fluid Dyn., Southampton* (ed. Brebbia & Connor), pp. 42–64. London: Pentech Press.

Davies, P. O. A. L. & Mercer, C. A. 1973 Phase velocity measurements using the cross power spectrum. *Proc. Int. Symp. on Measurement & Process Identification by Correlation and Spectral Techniques in Measurement (Bradford)*, pp. 27–36. Inst. Measurement & Control.

Deardorff, J. W.* Numerically calculated structure of three-dimensional eddies in the planetary boundary layer.

Falco, R. E. 1973 Some comments on turbulent boundary layer structure. *12th Aerospace Sci. Meeting, A.I.A.A. Paper*, no. 74–99.

Ffowcs Williams, J. E.* Large-scale eddying motions responsible for particularly intense transients in the jet noise field.

Fielder, M. E. & Korschelt, D.* Some observations of coherent features in a two-dimensional shear layer.

Fuchs, H. V. 1972 Space correlations of the fluctuating pressure in subsonic turbulent jets. *J. Sound Vib.* **23**, 77–99.

Fuchs, H. V. 1973 Resolution of turbulent jet pressure into azimuthal components. *AGARD Paper*, CP-131, 27.

Fuchs, H. V.* Analysis of circumferentially coherent pressure fluctuations relevant to jet noise.

Fulachier, L., Dumas, R., Kovasznay, L. S. G. & Favre, A.* Boundary-layer structure: three-point space–time correlations.

Girard, J.-P. & Curtet, R. M.* Time evolution of coherent structures in a pulsating jet.

Goldschmidt, V. W.* Comparison of heat and momentum transport in a plane jet.

Grant, A. J.* The time-dependent structure of turbulent jet flows.

Grant, H. L. 1958 The large eddies of turbulent motion. *J. Fluid Mech.* **4**, 149–190.

Gyr, A.* A statistical approach to interaction phenomena of particles with the structure in turbulent flows.

Hama, F. R. 1963 Progressive deformation of a perturbed line vortex filament. *Phys. Fluids*, **6**, 526–534.

Heibel, J. & Brodkey, R. S.* Digital analysis of optically obtained instantaneous wall pressure data.

Hunt, J. C. R. 1973 A theory of turbulent flow round two-dimensional bluff bodies. *J. Fluid Mech.* **61**, 625–706.

Hunt, J. C. R.* The effects of boundary conditions on the calculations of turbulent velocities.

Johnston, J. P.* Observations on the structure of turbulent shear flows in slowly rotating systems.

Johnston, J. P., Halleen, R. M. & Lezius, D. K. 1972 Effects of spanwise rotation on the structure of two-dimensional fully developed turbulent channel flow. *J. Fluid Mech.* **56**, 533–557.

Kambe, T. & Takeo, T. 1971 Motion of distorted vortex rings. *J. Phys. Soc. Japan*, **31**, 591–599.

Kambe, T., Takao, T., Oshima, Y. & Asaka, S.* Generation, development and interaction of viscous vortex rings.

Kreplin, H.-P., Eckelmann, H. & Wallace, J. M.* Propagation of perturbations in the viscous sublayer.

Lau, J. C. 1971 The coherent structure of jets. Ph.D. thesis, University of Southampton.

Laufer, J., Kaplan, R. E. & Chu, W. T. 1973 On the generation of jet noise. *AGARD Paper*, CP-131, 21.

Leonard, A.* Numerical simulation of interacting, coherent flow structures with three-dimensional vortex filaments.

LESSEN, M.* On the stability of rotationally symmetric, axial and swirling flow shear layers.

LESSEN, M. & SINGH, P. J. 1973 The stability of axisymmetric free shear layers. *J. Fluid Mech.* **60**, 433–457.

LESSEN, M., SINGH, P. J. & PAILLET, F. 1974 The stability of a trailing line vortex. Part 1. Inviscid theory. *J. Fluid Mech.* **63**, 753–763.

LILLEY, G. M.* A mathematical model of the large-scale structure of turbulent shear flows.

LIU, J. T. C. 1974 Developing large-scale wavelike eddies and the near jet noise field. *J. Fluid Mech.* **62**, 437–464.

LIU, J. T. C.* A nonlinear instability description of coherent structures in free turbulent shear flows.

LIVESEY, J. L. & EDWARDS, F. J.* Some studies of the turbulence structure in fully developed two-dimensional channel flow.

LUMLEY, J. L. 1967 The structure of inhomogeneous turbulent flows. *Proc. Int. Colloq. on Fine-Scale Structure of the Atmosphere and its Influence on Radio Wave Propagation* (ed. Yaglom & Tatarsky), pp. 166–178. Moscow: Nauka.

MATTINGLY, G. E.* Unstable disturbance characteristics in plane and axisymmetric jets.

MATTINGLY, G. E. & CRIMINALE, W. O. 1971 Disturbance characteristics in a plane jet. *Phys. Fluids*, **14**, 2258–2264.

MAXWORTHY, T. 1974 Turbulent vortex rings. *J. Fluid Mech.* **64**, 227–239.

MICHALKE, A. 1970 A note on the spatial jet instability of the compressible cylindrical vortex sheet. *Dtsche Luft- Raumfahrt Forsch.* DLR-FB 70-51.

MICHALKE, A. 1972 An expansion scheme for the noise from circular jets. *Z. Flugwiss.* **20**, 229–237.

MICHALKE, A.* On the instability of the turbulent jet boundary layer.

MORKOVIN, M. V. & NORMAN, R. S.* A curious mechanism of transition to turbulence downstream of an isolated three-dimensional roughness.

NYCHAS, S. G., HERSHEY, H. C. & BRODKEY, R. S. 1973 A visual study of turbulent shear flow. *J. Fluid Mech.* **61**, 513–540.

NYCHAS, S. G., WALLACE, J. M., DUFULA, D. & ECKELMANN, H.* Simulated probe signals of motions in the outer turbulent boundary layer region from visual data.

OFFEN, G. R. & KLINE, S. J. 1974 Combined dye-streak and hydrogen-bubble visual observations in a turbulent boundary layer. *J. Fluid Mech.* **62**, 223–240.

OSHIMA, Y. 1972 Motion of vortex rings in water. *J. Phys. Soc. Japan*, **32**, 1125–1131.

PFIZENMAIER, E.* On the structure of velocity and pressure fluctuations in a sound influenced free jet.

REYNOLDS, A. J.* The apparent Prandtl number in a free shear layer.

REYNOLDS, W. C.* Remarks on turbulence closures.

ROSHKO, A. 1973 *Conf. Proc. Free Turbulent Shear Flows, N.A.S.A., Special Paper*, no. 321, pp. 629–635.

ROSHKO, A.* Ideas about free shear flow structure from experiments on turbulent mixing layers.

SABOT, J. & COMTE-BELLOT, G.* Internal intermittency in the core region of pipe flow.

SIMPSON, R. L.* Quasi-periodic structures in a separating turbulent boundary layer.

TANI, I. & HAMA, F. R. 1953 Some experiments on the effect of a single roughness element on boundary layer transition. *J. Aero. Sci.* **20**, 289–290.

TOWNSEND, A. A. 1956 *The Structure of Turbulent Shear Flow.* Cambridge University Press.

WALLACE, J. M., ECKELMANN, H. & BRODKEY, R. S. 1972 The wall region in turbulent shear flow. *J. Fluid Mech.* **54**, 39–48.

WALLACE, J. M., ECKELMANN, H. & BRODKEY, R. S.* Pattern recognition in turbulent flows.

WEHRMANN, O.* Frequency and amplitude of intermittency in a free jet.

WIDNALL, S. E. & SULLIVAN, J. P. 1973 On the stability of vortex rings. *Proc. Roy. Soc.* A **332**, 335–353.

WILLE, R. 1963 Growth of velocity fluctuations leading to turbulence in a free shear layer. *AFOSR Tech. Rep., Hermann Föttinger Inst. Berlin.*

WILLMARTH, W. W.* Structure of individual contributions to Reynolds stress in a turbulent boundary layer.

WILLMARTH, W. W. & LU, S. S. 1972 Structure of Reynolds stress near the wall. *J. Fluid Mech.* **55**, 65–92.

WINANT, C. D. & BROWAND, F. K. 1974 Vortex pairing: the mechanism of turbulent mixing-layer growth at moderate Reynolds number. *J. Fluid Mech.* **63**, 237–255.

WYGNANSKI, I. J. & CHAMPAGNE, F. H. 1973 On transition in a pipe. Part 1. The origin of puffs and slugs and the flow in a turbulent slug. *J. Fluid Mech.* **59**, 281–335.

WYGNANSKI, I. J., SOKOLOV, M. & FRIEDMAN, D. 1974 On transition in a pipe – II. The equilibrium puff. *Tel-Aviv University Rep.* TAU/SOE-94/74.

WYGNANSKI, I. J., SOKOLOV, M. & FRIEDMAN, D.* On transition in a pipe – the turbulent puff.

YULE, A. J., BRUUN, H. H. & BAXTER, D. R. J.* Coherent motions in round jets.

YULE, A. J., BRUUN, H. H., BAXTER, D. R. J. & DAVIES, P. O. A. L. 1974 Structure of turbulent jets. *University of Southampton, ISVR Memo.* no. 506.