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A Description of Eddying Motions and Turbulence

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ABSTRACT

This paper reviews recent developments in the measurement of three dimensional unsteady flow fields and the combining of these measurements with flow visualization techniques. The critical point concept in the theoretical description of these eddying motions is discussed and it is shown how the topology of complex three-dimensional steady and unsteady flow patterns can be understood. Some of these concepts are applied to simple eddying motions in periodically disturbed laminar jets and wakes and ideas gained from this are applied to some examples in turbulence.

INTRODUCTION

One motivation behind the study of the description of eddying motions is to gain an understanding of turbulence. This aim of course is long term and one of the lessons to be learnt in this field is that our understanding of some of the most basic phenomena in fluid flow is meager and we have a long way to go in understanding even simple three-dimensional fluid motion let alone complex turbulent flows.

The practicing engineer may well ask why we torture ourselves in attempting to gain an understanding of turbulence since this has proved to be a most difficult if not impossible task. Surely with modern large computers we could solve the complete time dependent Navier-Stokes equations by specifying the appropriate initial and boundary conditions and allow the solution to run its course. As Leslie (1973) states (and it is still true today) "the short answer is that large though they are, present day computers are not large enough." The problem is that a mesh must be sufficiently fine to resolve the dissipating eddies. The so called "Full Direct Simulation" or "Full Turbulence Simulations" currently being studied at NASA Ames (e.g. see Moin & Kim 1985) attempt to do this. However, they are limited to low Reynolds numbers (Re). For channel flow, Leslie quotes 10^8 mesh points are required for Re = 10^4 and 10^{13} for Re = 10^6. Also the number of time steps required for numerical stability rises rapidly with Re. Corrsin (1961) gives similar estimates. For the NASA Ames calculations the mesh is of order 10^6. Then there is the question of running time and cost. A simulation needs to be run many times to obtain ensemble averages with stable statistics although if there exists a homogeneous direction in the flow we could average along this homogeneous direction. It has been the experience of the author that using "nature's own computer" - namely the wind tunnel, 40,000 data samples are needed for convergence of quantities like Reynolds shear stress at a point for 1% repeatability although with appropriate filtering contributions from large scale quasi-periodic structures require much less data samples.

The general consensus of opinion is that some sort of modelling is required and this needs to be applied to averaged versions of the Navier-Stokes equations which have been truncated to a finite number of probability moments. Lumley (1978) reviews the "second order modelling" methods of which the k-ε model is an example. Unless someone can come up with a better idea, these second order models or single point closure schemes offer the best hope for "reasonable men" working to produce a cost effective calculation. However, in the author's opinion, these methods at best should be regarded only as sophisticated interpolation schemes which cannot be applied with confidence to flow situations which are outside of a certain range of observation. Also the equations involved contain complex quantities which are difficult to interprete physically. The keywords used earlier are "Unless someone can come up with a better idea". This should be the aim of most experimental and computational research. Better ideas can come only from an understanding and this usually means looking at relatively simple cases to begin with.

The Full Direct Simulations being studied at NASA Ames are the most satisfying form of computations but will require an enormous development in both hardware and software before practical calculations are produced. Even if this development is successful we still have the problem of knowing what to do with all the "data"produced, i.e. how to interprete it and how to present it in a most meaningful way and also to know whether the computations are producing physically realistic results.

What is attempted here is a review of simple eddying motions in fluid flow which possess some of the characteristics of turbulence, i.e. we will consider among other things three dimensional motions which are unsteady and where vortex stretching processes are occurring. The relevence of these simple flow cases to turbulence will then be discussed.

DESCRIPTION OF FLOW PATTERNS AND EDDYING MOTIONS

Firstly, we will discuss flow patterns described in terms of instantaneous streamlines. Such patterns can be

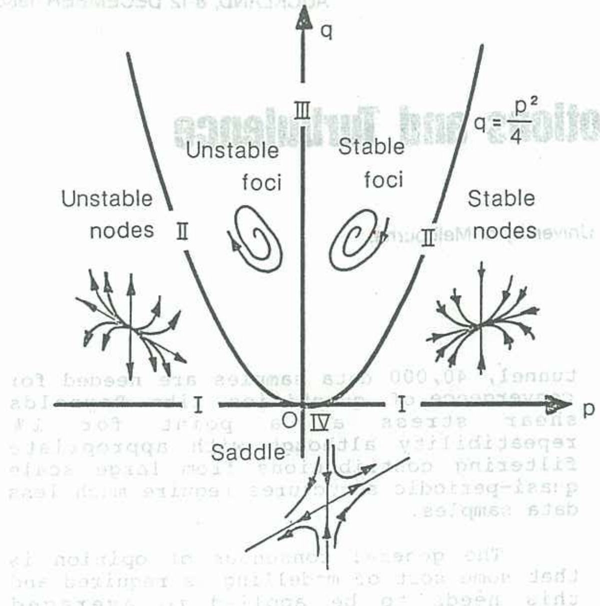

Figure 1. Classification of critical point on the p-q chart.

understood when the description is carried out in terms of certain salient features. Critical points are such flow pattern features. A critical point is a point in a flow field where the streamline slope is indeterminate. Local series expansion solutions to the Navier-Stokes and continuity equations have been developed and a classification of all possible critical point patterns have been made, e.g. Oswatitsch (1958), Lighthill (1963), Legendre (1956,1965), Werle (1962,1975), Smith (1970), Davey (1961), Perry & Fairlie (1974), Hunt et al. (1978), Perry (1984a,1984b). Certain planes passing through the critical points can be identified as containing instantaneous streamlines and the patterns contained in these planes are classified in figure 1 as nodes, saddles and foci. The quantities p and q are certain invarients of a Jacobian matrix which occurs in the series expansion analysis. The quantities can be related to local gradients of pressure and vorticity or strain rates. Figure 2(a) shows a surface flow pattern of the downstream side of a missile shaped body at an angle of attack. This pattern has been referred to as an owl-face of the second kind. It at first looks most complicated but it can be seen that it can be described quite succinctly by an arrangement of nodes, foci and saddles points as seen in figure 2(b). Figure 3 shows the instantaneous streamline pattern down the plane of symmetry of a coflowing wake at a Reynolds number of order 1000 as seen by an observer moving with the eddies. This was obtained experimentally. Again such a pattern can be succinctly described by an appropriate arrangement of nodes foci and saddle points. There are certain topological rules which have been developed which enable one to partially deduce the three dimensional properties of a flow field given the flow in a plane of symmetry. Figure 4 shows such a deduced pattern using the saddle-node combination theorem (Perry & Chong 1987). Given a collection of critical points and their classification there are a limited number of ways in which the streamlines can

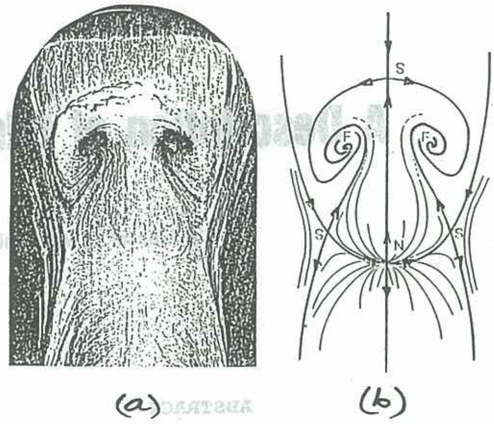

Figure 2. (a) Surface flow pattern on the downward side of a missile shape body at an angle of attack. (After Fairlie 1980). (b) Interpretation using critical points. F= focus, N = node, S = saddle.

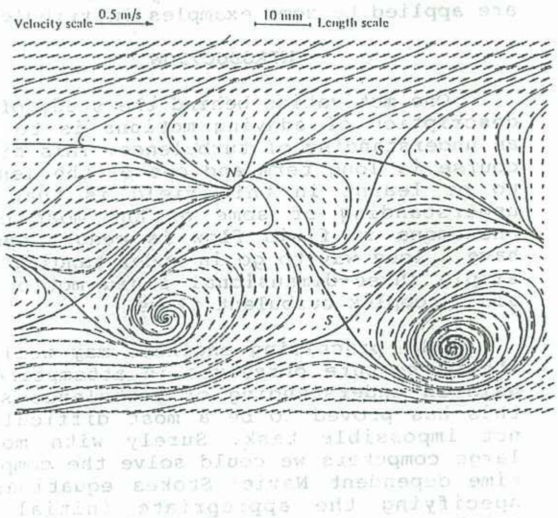

Figure 3. Typical instantaneous (phase-averaged) velocity vector field for coflowing wake. After Perry & Tan (1984).

be drawn. Thus a qualitative understanding can be found just by knowing the types of critical points involved. Also in many flow situations a Galilean frame of reference can often be chosen such that the pattern is almost steady, i.e. quasi-steady. The streamline patterns then give considerable insight into the transport properties of the flow pattern. Besides critical points there are other flow pattern features which need to be noted. These are bifurcation lines and limit cycles and are discussed by Hornung & Perry (1984) and Perry & Hornung (1984).

One of the disadvantages of using instantaneous streamline patterns is that they can become extremely sensitive to the velocity of the observer. Cantwell (1978,1981) has shown that if certian similarity coordinates are used, this problem can be overcome and unsteadv

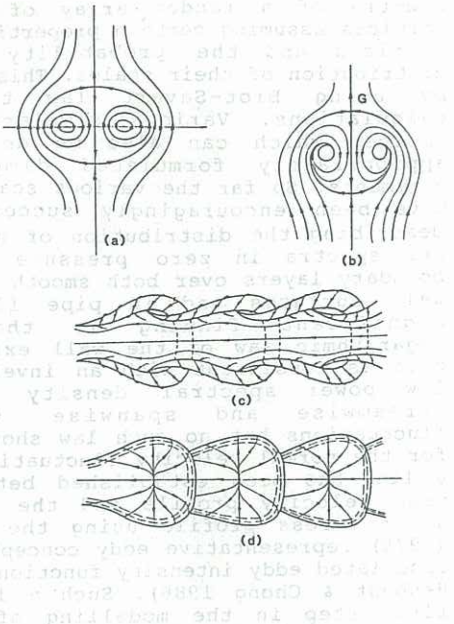

Figure 4. (a) Two-dimensional flow field generated by a vortex pair. (b), (c) and (d) Conjectured three-dimensional streamline patterns for figure 3.

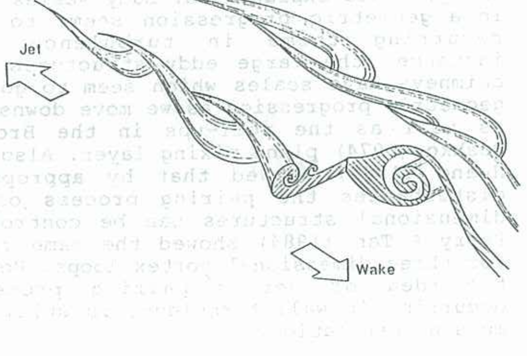

Figure 5. Oblique view of single-sided smoke structures in coflowing jets and wakes. After Perry et al. (1980).

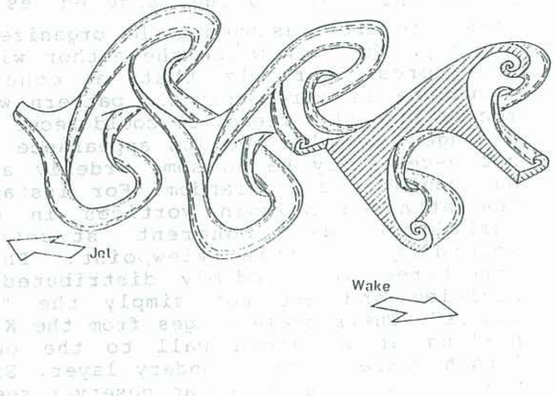

Figure 6. Oblique view of double-sided structures in coflowing jets and wakes. After Perry et al. (1980).

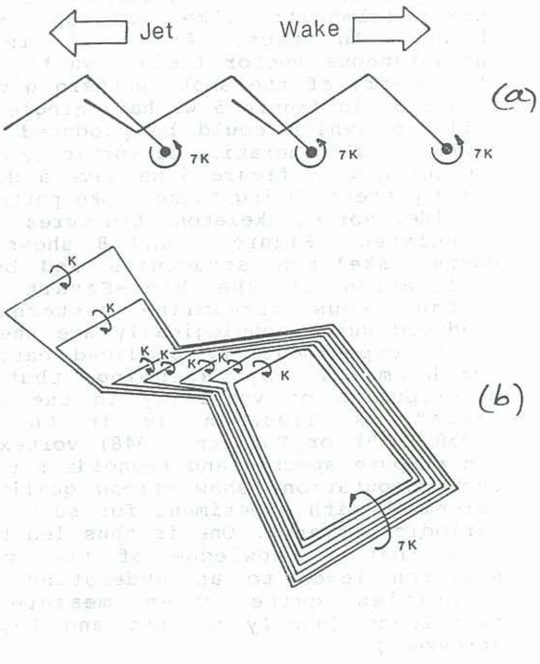

Figure 7. (a) Side view of vortex skeleton for single-sided structure. (b) Oblique view.

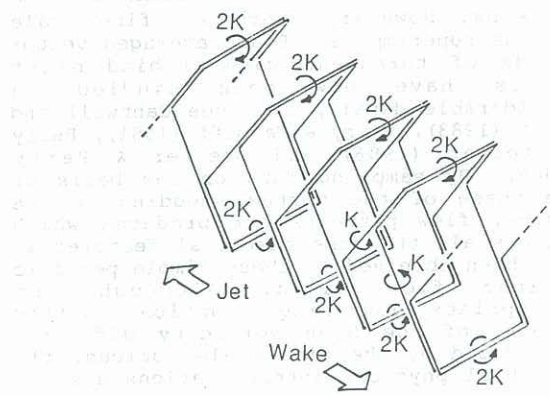

Figure 8. Oblique view of vortex skeleton for double-sided structures.

patterns become frozen and are invarient under Galilean transformations. In general we do not know the appropraite similarity coordinates particularly with experimental data and a very useful quantity to consider is vorticity. This is invarient under such transformations. In fact, vorticity is the most succinct quantity to use in the description of a flow pattern. It is the "genetic code" but is extremely difficult to measure accurately. Nevertheless if it is known the complete velocity field can be found using the Biot-Savart law.

Figure 5 and 6 show some sketches of the smoke patterns in coflowing jets and wakes at a Reynolds number of 1000. These are periodically disturbed patterns and the sketches were deduced from strobed laser sheets which cut through the smoke patterns. One can see the three dimensional Kelvin-Helmholtz like roll-ups which abound. In fact, figure 3 is the instantaneous vector field down the plane of symmetry of the smoke pattern given in figure 5. In figure 5 we have single-sided roll-ups (which could be produced by an asymmetrical generation of vorticity at the source) and in figure 6 we have a double-sided pattern. Using these smoke pattern as a guide, vortex skeleton structures can be postulated. Figure 7 and 8 shows such vortex skeleton structures and by the application of the Biot-Savart law, instantaneous streamline patterns are produced which topologically are the same as the experimentally produced patterns. Furthermore, by assuming that the distribution of vorticity in the vortex "rods" is Gaussian as in the Rott (1958,1959) or Burgers (1948) vortex, one can compute spectra and Reynolds stresses. Such computations show strong qualitative agreement with experiment for such simple periodic patterns. One is thus led to the idea that a knowledge of the vortex skeleton leads to an understanding of quantities quite often measured in turbulence (namely spectra and Reynolds stresses.)

APPLICATION TO TURBULENCE

Large Scale Motions

The patterns so far discussed are not turbulent but should be regarded as periodic laminar flows. However, coflowing jets and wakes from chimneys and the turbulent wakes from bodies bear a striking resemblence to these simple laminar flow patterns. However, there are fine scale motions superimposed. Phase averaged vector fields of turbulent wakes behind bluff bodies have now been studied in considerable detail, e.g. see Cantwell and Coles (1983), Perry & Watmuff (1981), Perry & Steiner (1986) and Steiner & Perry (1986). By sampling data on the basis of the phase of the vortex shedding at the source, flow patterns are produced which possess all the same essential features as have been observed in these simple periodic laminar flow cases. Although the appropriate governing equations differ because of the high vorticity diffusion introduced by the fine scale motions, the essential physical interpretations are the same.

Wall Turbulence

One of the most outstanding problems is the understanding of wall turbulence. One might ask "What is the vortex skeleton of wall turbulence?" Perhaps a clue to this can be found by studying turbulent spots (e.g. see Perry, Lim & Teh 1981). Head & Bandyopadhyay (1981) showed very convincingly by flow visualization that wall turbulence consists of a forest of hairpin vortices. This idea seems to fit in quite well with the Townsend (1976) attached eddy hypothesis. Also instantaneous streamline calculations produced from such hairpin vortices appear to possess all the correct transport properties (i.e. vorticity being lifted from the surface and fluid from above being brought down to the wall). Perry & Chong (1982) and Perry, Henbest & Chong (1986) have pursued this idea and have developed mathematical techniques which enable one to deduce the mean flow, broadband "turbulence" intensity distribution and spectra of a random array of hairpin vortices assuming certain properties of the vortices and the probability density distribution of their scales. This was done by using Biot-Savart law types of calculations. Various similarity laws emerged which can also be deduced by appropriately formulated dimensional arguments. So far the various scaling laws have been encouragingly successful in describing the distribution of quantities and spectra in zero pressure gradient boundary layers over both smooth and rough wall surfaces and in pipe flow. One significant finding is that if a logarithmic law of the wall exists then this is consistent with an inverse power law power spectral density for the streamwise and spanwise velocity fluctuations but no such law should occur for the normal velocity fluctuations. Also a link has been established between the mean velocity profile and the Reynolds shear stress profile using the Townsend (1976) representative eddy concept and the associated eddy intensity functions (Perry, Henbest & Chong 1986). Such a link is a first step in the modelling of adverse pressure gradient boundaary layers.

One of the essential features of this model is that there must exists a range of eddy hierarchies whose probability density function is an inverse power law of hierarchy scales or else the scales could be thought of as going in a geometric progression. How these hierarchies are formed is a mystery but vortex pairing is one possible explanation. Eddy scales going in a geometric progression seems to be a recurring theme in turbulence. For instance, the large eddy structures from chimneys have scales which seem to go in a geometric progression as we move downstream as well as the roll-ups in the Brown & Roshko (1974) plane mixing layer. Also Ho & Huang (1982) showed that by appropriate disturbances the pairing process of two dimensional structures can be controlled. Perry & Tan (1984) showed the same result for three dimensional vortex loops. However the idea of vortex pairing processes occurring in wall turbulence is still very much a speculation.

Coherent Structures

The large scale phase averaged structures mentioned earlier are often referred to as coherent structures. There is considerable controversy as to what constitutes a coherent structure (e.g. see Hussain 1986). Many workers appear to relate this term to the large eddies and these are often assumed to be organized or orderly. The view which the author wishes to express here is that a coherent structure is a recognizable pattern which recurs in a flow field. It could recur over a range of scales and its appearance need not necessarily be in some orderly array but could be quite random. For instance, the attached hairpin vortices in wall turbulence are coherent structures according to this viewpoint. These structures are randomly distributed in position and are not simply the "big eddies". Their scale ranges from the Kline scaling at a smooth wall to the outer length scale of the boundary layer. Since the eddies are attached an observer sees a wider range of scales as the wall is approached. They have a definite characteristic direction and lean in the streamwise direction at approximately 45°. However, these are not the only structures which occur in wall turbulence. Perry, Henbest & Chong (1986) have shown considerable support for the existence of fine scale detached eddying motions which contribute very strongly to a Kolmogorov inertial subrange. Such structures would be approximately isotropic in the statistical sense and would not contribute to the mean vorticity nor to Reynolds stresses but would contribute significantly to the energy dissipation. Such detached incoherent motions might be the result of dead attached eddies being convected away from the wall region by the more active attached eddies. Expressed in the more classical terms, the above model has energy transfer from moderate wave numbers to low wave numbers (an inverse cascade process) and also from moderate wave numbers to high wave numbers (the usually assumed Kolmogorov cascade process).

Recent Full Direct Simulation work at NASA Ames (e.g. Moin & Kim 1985 and Kim 1985) show strong support for the existence of hairpin vortices in wall turbulence. However the Reynolds number is low and only a limited range of hierarchy scales are produced in these calculations. Nevertheless with these calculations Dr. P. Spalart (private communication) has found encouraging support for the spectral scaling laws as postulated by Perry, Henbest & Chong and there is considerable motivation to increase the Reynolds number of these calculations by a factor of four.

Plane Mixing Layers

It has often been asked "If coherent structures are found and understood, how will this help in our modelling of turbulence?" This question is partially answered in the case of wall turbulence but it has not yet led to a predictive scheme. It simply aided us in describing what has already been observed and if it is correct, we can say we have a better physical understanding of the phenomenon. Another example of this application of coherent structures in the description of turbulence is in the plane mixing layer. Although so far the developement is still in its very early stages, Perry, Chong & Lim (1982) have modelled the layer with vortices which have a longitudinal component and lean in the streamwise direction. They are somewhat similar to the hairpin vortices of wall turbulence but are stretched right across the shear layer. Hairpin vortices have been observed in the Full Direct Simulations of homogeneous turbulence with uniform shear by Moin, Rogers and Moser (1985) at NASA Ames. Also Breidenthal (1981) has shown that such vortices exist by flow visualization. In the model being described here all vortices start at the trailing edge of the splitter plate and this is where the smallest eddies are generated. It is then assumed that the larger eddies which form downstream come from a vortex pairing process such that the population of small scale eddies are depleted and the population of larger scale eddies increase. Thus as we move downstream, eddies migrate in "hierarchy space" and the "migration policy" is formulated from a dimensional argument. This leads to a large group of simultaneous differential equations which need to be solved and using the Biot-Savart law techniques developed for wall turbulence the evolution of spectra can be computed. Spectra and other quantities satisfy all the self-preserving flow constraints and agreement with experiment is rather good. Unlike wall turbulence no inverse power law spectra are formed but extensive -5/3 power law regions are apparent. The model actually predicts a -2 power law at infinite Reynolds numbers. The boundary conditions for the plane mixing layer are completely different from wall turbulence. In particular in the former all vorticity is created at the source upstream whereas in the latter there is a continual supply of vorticity at the wall giving a continual birth of new eddies and there is a balance between birth and death. This results in a completely different spectral evolution for the plane mixing layer. This is an example of a model which produces the correct spectral evolution for the range of data observed but is based on assumptions which are completely at variance with classical thinking. The whole development has been described by an inverse cascade process. Although highly speculative it is food for thought.

CONCLUSION

An understanding of eddying motions has considerably increased our understanding of phenomena ranging from three dimensional flow separation to the simple eddying motions in jets and wakes. In short, it has increased our knowledge and power of understanding fluid mechanics. The transfer of ideas from these relatively simple phenomena to turbulence modelling is still in its very early stages. Nevertheless it has caused some of us to think of other things besides pressure velocity correlation tensors and other such like quantities. This is not to say that the more classical approaches should be abandoned but they certainly need to a augmented by the more direct physical interpretations which are generated by the study of the geometry and topology of flow patterns.

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