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13. ABSTRACT *(Maximum 200 words)*

Phase A: Community-wide survey of existing knowledge on turbulence producing structures in the boundary layer. Creation of a uniform nomenclature for the field.

Phase B: Study of questions focused by *Phase A* using a work station to interrogate the Direct Navier-Stokes Simulation Data Base for the Flat Plate, at R-theta = 670, created by P.R. Spalart at NASA Ames. Results include: (i) creation of the first clear picture of the spatio-temporal relations among the eight kinds of structure previously documented and their connections to regions of high and low pressure at the wall and in the flow; (ii) demonstration of the centrality of two types of vortices to the turbulence producing structures in the boundary layer: tilted streamwise vortices in the wall layers and transverse vortices in the outer layer, and the range of overlap of the dense range of the distribution of the two vortex types is the log region; (iii) establishment of two computer methods for identification of vortices (as distinct from lines of vorticity); documentation of sizes, circulations and distributions of vortices for preliminary sample.

This work establishes a basis for considering connections between knowledge of the physics and computer models of turbulence in the next phases of research.

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FINAL REPORT

AFOSR CONTRACT AFOSR 87-0304E

From

Thermosciences Division
Department of Mechanical Engineering
Stanford University California 94305-3030

Principal Investigator: Prof. S. J. Kline

30 June 1991

91-07416

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GOAL

Contract Goal: Improve understanding of the physics of the processes by which turbulence is produced and dissipated in the turbulent boundary layer--often called the "structure" problem

WORK PROGRAM

Work under this contract consisted of two major elements:

1. A review of the available data on structure from roughly 30 years of laboratory work.
2. Use of DNS data bases to answer residual questions surfaced and focused by item 1.

SUMMARY OF RESULTS

Work on both phases of the contract was extremely successful. A major increase of understanding concerning the kinematics of the structure problem was achieved, and the groundwork laid for continuing the work into consideration of the dynamics and the connections to modeling. A summary of the central results follows. Details appear in the reports and publications produced under the contract. The latest two of these reports from the 1990 IUTAM meeting at the ETH in Zurich are attached as a part of this report.

Central results achieved included the following:

1. The spatio-temporal relations between the eight kinds of structure which had been documented largely separately in the laboratory experiments was determined. The relation of high and low pressure regions in the flow to these structures, which had not been measured previously, was also determined.

2. The critical distinction between vortices and lines of vorticity was clarified, and two independent means for locating vortices in the DNS computations created. The complete picture of all vortices in the Spalart DNS data base of the flat plate at R-theta = 670 was studied in detail.

3. The central features of the structure were revealed to be two types of vortices: in the inner region the dominant structures are tilted streamwise vortices; in the outer region the dominant structures are transverse vortices. Both types have a wide distribution in Y^+ space. The overlap of the dense range of the two types of vortices is the log region for this case. We believe these results are general since they fit much known

data and explain it, but proof via data for other cases including high Reynolds Number flows is not accessible currently.

4. The two dominant forms of vortices appear both separately and connected. When they are connected, rapid distortion occurs leading to strong vortex stretching and the highest zone of dissipation of turbulent energy in the flow field.

5. Vortices appear to be formed by instability of the lifted-low speed streaks first documented in earlier work done for AFOSR under predecessor contracts.

6. Promising ideas have been generated for investigating the dynamics of the outer flow based on the relation between vortex heads and the "bulges" in the outer flow region documented by many workers, notably Kovasznay and Blackwelder in 1971. These ideas are being pursued in the next phases of work.

7. A good deal of information on the relation of high and low pressure regions and structure in the flow has been generated. This is all new, and includes wall pressure which is of particular concern in many aircraft designs.

8. Many other details not previously documented are contained in the reports from the project cited in the final section below.

HONORS AND CITATIONS

Work under this contract was twice cited for honors by NASA once in its annual highlights and once in the form of an award to S. K. Robinson as NASA Ames Scientist of the Year. The work has appeared on the cover of two computer graphics journals and has been used in advertising by Silicon Graphics, the maker of the workstation used in the project. The paper in item #4 below was selected as one of two for special distribution by the International Center for Heat and Mass Transfer of Belgrade Yugoslavia. A special request for presentation of results were made by the Chairman of the invited meeting on turbulence to be held in Sept 1991 at Monte Verita, Switzerland, under IUTAM sponsorship.

PUBLICATIONS GENERATED

1. Robinson, S. K., Kline, S. J. and Spalart, P.R. 1988, Spatial Character and Time Evolution of Coherent Structures in the Numerically Simulated Turbulent Boundary Layer, AIAA Paper 88-3577.

2. Robinson, S. K., Kline, S. J. and Spalart, P.R. 1989 A Review of Quasi-Coherent Structures in a Numerically Simulated Turbulent Boundary Layer. NASA TM-102191.

3. Kline, S. J. and Robinson, S. K. 1989 Quasi-Coherent Structures in the Turbulent Boundary Layer: Part I: Status Report of a Community-Wide Summary of the Data. In Near Wall Turbulence: !988 Zaric Memorial Conference, Hemisphere 1989, ed. S. J. Kline

4. Robinson, S. K., Kline, S. J. and Spalart, P.R. Quasi-Coherent Structures in the Turbulent Boundary Layer: Part II Verification of New Information From a Numerically-Simulated Flat Plate Flwo. In Near Wall Turbulence: !988 Zaric Memorial Conference, Hemisphere 1989, ed. S. J. Kline

5. Kline, S. J. and Robinsion, S. K. Turbulent Boundary Layer Structure: Progress, Status, and Challenges, 2nd IUTAM Conference on Structure of Turbulences and Drag Reduction, ETH Zurich, Switzwerland

6. Robinson, S. K. 1989 A Review of Vortex Structures and Asscoiated Coherent Motions in Turbulent Boundary Layers. 2nd IUTAM Conference on Structure of Turbulences and Drag Reduction, ETH Zurich, Switzwerland

7. Robinson, Stephen Kern 1991 The Kinematics of Turbulent Boundary Layer Structure. PhD dissertation, Mechanical Engineering Department Stanford University, CA, and NASA TM 103859

COMMENTS ON PUBLICATIONS

The most complete single report is item 7. This contains nearly 100 full size plates in color and black and white and should remain an important reference work on many kinds of data for some years to come. Copies furnished AFOSR separately.

Items 5 and 6 attached as a portion of the final report.

TURBULENT BOUNDARY LAYER STRUCTURE: PROGRESS, STATUS, AND CHALLENGES

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ABSTRACT

The current community-wide cooperative study reviewing structure in the turbulent boundary layer has allowed construction of a list of the various forms of structure observed in laboratory experiments and provided a number of detailed features of each structure. The study also has revealed a lack of consensus on three matters: spatial relationships among the forms of structure; temporal relations in creation, evolution and decay of structures; a complete model of the important structure(s).

An ordering of the various known structures in terms of relative importance to the creation of turbulent Reynolds stresses and in the production and dissipation of turbulent kinetic energy is tentatively suggested. This ordering suggests a central role of vortices in boundary layer turbulence structure. Recapitulation of some essential concepts needed to understand the relationships of vortices to other structures is therefore given. The validity of a central role of vortices is then tested by examining two questions: (i) Are the vortices proximate in space to other known structures and features of importance in the flow? (ii) Are the vortices of sufficient strength so that they could induce other observed features and do they have proper orientation and direction of rotation to do so?

Since direct Navier-Stokes simulations allow inspection of a sample of all vortices throughout a volume of a simulated turbulent layer, it becomes possible to examine individual realizations of vortices as well as various types of statistics concerning the forms of vortices observed. The sample of individual realizations reveals a wide variety of vortex element orientation and also of shapes of more complex vortical structures.

Some features for which we still need further information are noted, and steps which may aid in moving toward increased agreement on the overall picture of structure and its use in forming useful predictive models in wall-bounded turbulent shear flows are suggested.

SPECIAL NOMENCLATURE AND DEFINITIONS

DNS = Direct Navier Stokes: Used in connection with numerical simulations; assumed to have sufficient numerical accuracy, but may be open to questions about sufficiency of grid resolution.

Ejection = Velocity perturbation with positive v' and negative u'.

Foot = The part of a leg in a vortical structure farthest upstream and nearest the wall.

Head = A transverse vortex element either alone or as part of a vortical structure

Inrush = A special class of sweep with high negative v′, and which emanates from the outer portion of the layer and moves to, or very near, the wall.

Leg = A quasi-streamwise vortex either alone or as part of a vortical structure.

Neck = Portion of a vortical structure turning from transverse to quasi-streamwise.

Sweep = A motion with positive u′ and negative v′.

TKE = Turbulent Kinetic Energy

TRS = Turbulent Reynolds Stress, $\rho \overline{u'v'}$

Vortex, vortices, vorticity lines: see section titled, "Vorticity Lines, Vortices and Their Observation".

Vortex element, vortex structure, vortical structure: See section titled "Vortex Elements and Vortical Structures."

INTRODUCTION

If we take the term "Structure" to denote "those motions (or events, or eddies) which convert mean motions into Turbulent Reynolds Stresses and/or produce and dissipate TKE, then the structure is, by definition, the center of the physics of turbulence. If we accept this idea, we do not need further justification for the study of structure provided only we are willing to follow the guide of the history of science. That guide, if it tells us anything with high assurance, tells us that understanding the physics cannot hurt, and, in fact, nearly always aids us in the long run in predicting and controlling physical processes.

Statistical representations fill the important needs of providing *quantitative* information about turbulent flows and providing numbers usable in Reynolds-averaged equations. However, there has been considerable difficulty in relating the quantitative statistics to the underlying structures as observed in visual studies. Part of the reason for these difficulties is that statistics of the fluctuations may or may not provide information equivalent to the full details of the structure, depending on the "completeness" of the statistics given. Moreover, it is not a priori obvious what statistics are needed to be complete in this sense. Thus one of the things we can learn from study of structure is a better understanding of what "completeness" in this sense requires in the statistics which need to be measured in order to determine structure using methods like that of Aubrey et al (1988), for example.

Since a primary purpose of using statistical representations is to capture enough of the structure to represent the physics well and at the same time provide a description simple enough for use in practical predictive models, a second thing we can learn from an accurate picture of the structure is what conditions to put on the statistics so that we can use procedures such as that of Adrian (1988) to learn more about structure quantitatively in efficient ways.

Beyond these gains, one hopes that agreement within the research community of what constitutes the structure will prove of direct aid in both modeling and control of turbulent flows. This is not to suggest that using structure information to guide either modeling or control will be an easy task, for both are likely to be difficult. It is to suggest that lack of an agreed complete picture of the structure in the research community has almost certainly hampered use of information about structure in both model formation and control of turbulent flows.

THE COOPERATIVE, COMMUNITY-WIDE REVIEW: SOME GENERAL RESULTS

When the cooperative review project began in late 1986, there was little agreement on the appropriate model of the structure features in the boundary layer. There also appeared to be some lack of knowledge of the results of other laboratories within each particular research group. The central purpose of the cooperative study was therefore to create a data base of "truth assertions" which would do two things. First, distinguish results that were founded on reliable data on the one hand from results which involve speculative extensions which pass well beyond the data on the other.. Second, from this data-base we had hoped to distill a complete, or nearly complete, model of structure on which at least most of the research community could agree. As part of this process, we also have carried out one or two day discussions with many of the leading researchers on structure in wall-bound shear layers.

As we had anticipated, some groups suggested that hairpin-like (or other forms) of vortical structures explain what occurs; other groups emphasized the effects of sharp shear layers or 'fronts'. Still other groups believed the structure near the wall was largely the result of the passage of outer large-scale-motions (also called 'bulges') and what we now call 'backs' which are narrow regions of high vorticity observed on the upstream face of the large-scale-motions*. Other groups had additional differing ideas concerning a complete model of structure. There is no intent in this paper to review all these model ideas. We are, however, collecting the model ideas for discussion in a later community-wide meeting. Nor is an exhaustive list of references on boundary layer structure given in this paper since that now runs to several hundred entries. The intent of this section of the paper is rather to make two points as clear as possible: (i) there is good agreement in the research community on the existence of a number of structure features in the boundary layer and many of the details about each feature; (ii) there is a distinct lack of consensus on three matters: (a) the spatial relations of the various structures; (b) the time evolution of various structure features; (c) a complete picture of the important structure(s). Both items (i) and (ii) need comment.

Based on the cooperative study, a list of eight of the major types of structure was given by Kline and Robinson (1988). As the 1988 paper shows, quite a lot is known about each of these structures; all of them are at least reasonably well documented by experiments. In a section below some improvements to list of the eight types of structure are given. An ordering of the eight types of structure with regard to which are probably more important in creation of TRS and creation and dissipation of TKE is also provided since a mere listing of all of these structures provides an undifferentiated eclecticism which does little to aid our understanding. This ordering is tentative and will hopefully be subjected to intensive discussion.

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* The 'backs' have been called 'fronts' in much of the literature. However, the word 'front' had also been widely used by various groups to describe the far more numerous sharp regions of high vorticity observed below $y^+ = 100$ or so, which we now call 'near-wall shear-layers'.

Despite a long history of excellent contributions by many members of the research community, the cooperative study showed a good many questions remained open concerning spatial relationships among the eight kinds of structures. The review also showed relatively little was agreed upon about the temporal order in which the individual structures appear, evolve, and disappear. If, as seems to be the case, a number of the structures act sequentially in the central dynamics of the production and dissipation of TRS and TKE, then information about them one-by-one, or even in pairs, lacking information on how they behave over time is not sufficient for formation of a complete model.

Given these residual uncertainties and lack of knowledge about the spatio-temporal relationships, it is not surprising that various researchers and research groups filled in details of a complete model of structure in different ways. Since a complete model is the central goal of structure research, and is needed even to guide strategy on further structure research, it seemed appropriate to seek the missing spatial and temporal relationships via study of the DNS generated data bases available at NASA-Ames. These simulated turbulent flows are the work of several people, notably Parviz Moin, John Kim, Philippe Spalart, Bob Moser and co-workers. A great deal has already been contributed to the goal of understanding structure via study of the simulations by a number of workers. Here only some results which are particularly important for the current paper are summarized; a more complete review of these results appears in Robinson (1989b).

Particularly notable is the pioneering work of Moin and Kim using both LES and DNS simulations primarily of channel flows (Kim and Moin 1979; Moin and Kim 1982; Kim 1983; Moin 1984; Moin and Kim 1985; Kim and Moin 1986; Moin 1987; Kim, Moin and Moser 1987). Some particularly important results of these papers include not only confirmation of many structure features which had been measured in the laboratory but also improved understanding of the orientation of vortices. Agglomerated vorticity lines were often seen with tilted or "quasi-streamwise" orientation; the tilt angle gradually increased along the vortex element with increasing y^+ up to 45°; however truly streamwise agglomerations of vorticity lines were very rarely observed even near the wall. Another particularly important result is given by Moin (1987); Moin reported regions of high $u'v'$ were associated with every observed quasi-streamwise vortex in the wall region, and concluded that relatively short, single vortices are fundamental structures associated with regions of high turbulence production. The studies also confirmed that the wall-proximate streaky structure had the well-known mean-transverse-scale of 100 wall units; however, the low-speed streaks were observed to be far longer than the quasi-streamwise vortices. Moin (1984) also confirmed that a large fraction of TKE was captured in a first eigenfunction similar to that found by Bakewell and Lumley (1967). Kim and Moin (1985, 1986) also showed that agglomerations of vorticity lines often appeared as "hairpin-like" shapes. These vortex-line bundles were interpreted as true vortices; and the shapes observed included both downstream-leaning upright horseshoe like shapes associated with high $u'v'2$ and upstream-leaning inverted horseshoe-like shapes associated with high $u'v'4$. Moin and Kim also showed that one-sided shapes with a head and one leg were more common in the agglomerated regions of compact vortex-lines than symmetrical horseshoe shapes in which a head had two attached legs.

Spalart (1988) observed delta-scale bulges in the outer part of the boundary layer with sharp turbulent/non-turbulent interfaces on the contorted outer face of the bulges. Spalart also reported interspaced deep valleys of irrotational flow between bulges. These features had been reported by many others in earlier laboratory measurements, notably Kovasznay et al (1970).

In 1987 the present authors began to investigate some of the remaining open questions focused by the cooperative study. The DNS simulation of the flat plate at Re_θ = 670 by Philippe Spalart (1988) was chosen as a first flow for investigation. Emphasis was placed on study of the spatial and temporal relationships among the various known forms of structure. In this work, vortices were made visible by inspecting iso-contours of low static pressure in the flow field utilizing the idea that the Euler n-equation specifies the existence of low pressure cores in true vortices, and thus distinguishes true vortices from regions of distributed vorticity which do not contain vortices. This has led to a significant amount of information about the spatial relationships among the structures reported in Robinson et al 1988a, 1988b. It has also led to increased knowledge about the shape of vortex elements and vortical structures and about their orientations in the flow. Work over the past year has revealed relationships between the vortices and dissipation of TKE which is reported in Robinson (1989b). These results taken together with the vast amount of earlier results suggest a central role of true vortices in boundary layer structure. This suggestion is investigated more fully below.

SOME ESSENTIAL CONCEPTS

As part of the work of the cooperative study, the project coordinators constructed a nomenclature list and circulated it for comment to interested members of the research community. After two rounds of comments and revisions, this list is reasonably complete, and seems agreed upon by at least most members of the research community. Construction of this list seemed necessary since various terms had been used in conflicting and overlapping ways in the literature. As a result there was considerable misunderstanding in the community from miscommunications. One hopes these communication difficulties are reduced for the structure problem by the nomenclature list just mentioned. This list will be supplied by the authors on request to any interested worker.

However, there is a second level of the use of words, namely as concepts, that also needs clarification. In particular, with regard to the problem of boundary layer structure, observations in both the laboratory and in the DNS simulated flows have employed a variety of concepts. The relationships among these concepts is readily misinterpreted in some cases. In order to think clearly about the structure results, we therefore need to be as clear as we can about the concepts involved. Hence a discussion of three concepts is given which addresses this task, in part. Patience on the part of the reader already entirely familiar with this conceptual territory is solicited.

The three sets of concepts are:

- Vorticity lines/Vortices
- Vortex elements/Vortical structures
- Average model/Realization

VORTICITY LINES, VORTICES, AND THEIR OBSERVATION

The phrase "vorticity line" is used to denote what most textbooks call a "vortex line", that is, *a line everywhere parallel to the direction of the vorticity vector.* We use the phrase "vorticity line" (or "line of vorticity") rather than the more conventional phrase "vortex line" in order to emphasize the distinction between vorticity lines and what we will call a vortex or vortices.

Vorticity lines move at particle speed in the absence of viscosity, as we know from Helmholtz' theorem. Even in viscous flows, we can assume with good accuracy that *vorticity lines move at local particle speed* for short distances in the flow.

There seems to be no agreed definition of what constitutes a vortex. In this paper, the word "vortex" will denote a structure for which an *observer moving with the structure sees* a circular (or near circular) pattern of the direction of the velocity vectors (or instantaneous streamlines) in the plane normal to the center (core) of the structure. Such a pattern of vectors represents either closed (near) circular streamlines or a spiralling motion.

Several points about vortices need noting. First, all vortices contain lines of vorticity, but not all bundles of vorticity lines constitute vortices. There are two cases which need to be considered.

The first and simpler case is vortices normal to the direction of flow, in either the transverse or wall-normal direction. Consider for example a planar, laminar Couette flow with x the flow direction, y the wall-normal, and z transverse. In this flow there are z-oriented (transverse) vorticity lines everywhere. However, until instabilities arise, there are no transverse vortices whatsoever since dv/dx nowhere has a value the same order of magnitude as du/dy, and hence the necessary circular pattern of vector directions cannot be present in an xy-plane regardless of the frame of reference. Similar remarks apply to wall-normal vorticity lines and vortices. So long as the vorticity lines or the vortex is normal to the flow direction there is not much likelihood of confusion between vortices and lines of vorticity.

The second case concerns streamwise vorticity and vortices. In this case, there is considerably more likelihood of confusing lines of lines of vorticity with true vortices because a strong streamwise vortex will induce motions which create loops (or hairpin-like shapes) in the vorticity lines on each side of the vortex, but outside the region of circular motions. If this occurs in a flow with a mean strain the loops of vorticity lines will become tilted as time proceeds. The kinematics are illustrated in Robinson (1989a). Moreover, the marker particles will make visible true vortices only if the markers are introduced at points lying inside the closed streamlines of the vortex unless very rapid vicious diffusion occurs, and we normally try to arrange markers so that viscous diffusion is not rapid. These remarks also apply to any vortex with a significant component of streamwise orientation of the vortex axis.

These same ideas apply to the speed of vortices. *Vortices can move at any speed in the direction of the vorticity lines.* Since the making (and unmaking) of a vortex comes from crowding together (or spreading) of the vorticity lines *normal* to the direction of these same vorticity lines, the process can go faster or slower than local particle speed along the direction of the vorticity lines. However, the speed of motion of the vorticity lines in the direction normal to the vorticity lines must be at approximately particle speed locally by virtue of Helmholtz' theorems. As a result of this difference, nearly streamwise vortices (legs) can behave quite differently from essentially transverse vortices (heads), and in fact appear to do so when observed in the DNS simulated flat plate flow.

Finally, vortices isolate regions of low pressure in their core from the surrounding flow; this is necessary by virtue of the Euler n-equation in inviscid, or nearly inviscid, motion. Lines of vorticity, which are not vortices, do not have this property. Observations of the flat plate flow via DNS show z-oriented vortices have a surprisingly long persistence, not infrequently thousands of wall units. Given these facts, and the preceding paragraph, it can be seen that it would be easy to interpret the passage of successive z-oriented vortices past a probe as a wave motion rather than a quasi-coherent structure moving in space but with considerable persistence over time. It is equally clear that output from a probe stationary in lab coordinates could suggest that the important structural events are more intermittent than is actually the case since the persistence observed is over time, and is therefore not observable except in an appropriate convected frame, a frame which is not known a priori.

VORTICAL ELEMENTS AND VORTICAL STRUCTURES

For reasons that will become more evident in the descriptions which follow, we make a distinction between vortex elements and vortical structures (Both are called vortices in the definitions and in the preceding sections).

The phrase "vortex element" will denote *a vortex with a single (or very nearly single) orientation in space.* Thus a streamwise vortex will be called a vortex element. So will a transverse vortex or a quasi-streamwise vortex which is tilted and has either a constant or slowly varying inclination to the wall.

The phrase "vortical structure" will denote *a linked set of vortex elements of several orientations possessing a single connected core threading through all the vortex elements of the particular structure.* For example, a head element connected to one or two necks, or a head connected to a neck and then to a leg will be called vortical structures.

This distinction is important not only because both solitary vortex elements and vortical structures are frequently observed in the boundary layer, but also because we have only a few studies that show complete vortical structures in the flow rather than vortex elements, notably those reported by Clark and Markland (1971), Head and Bandyopadhyay (1981); and C. R. Smith and his co-workers (e.g. Acarlar and Smith, 1987). Each of these experimental studies is limited in some ways which prevent obtaining a completely delineated picture of the spatio-temporal features of the various structures. Since the identification of a vortex requires measurement of two derivatives of velocity over space, it has been difficult to document even vortex elements, quantitatively. This is particularly true of spanwise vortex elements because the necessary frame of reference is not known a priori. Moreover, it has been extremely difficult, or impossible, to measure the instantaneous shape of a complete vortical structure with probes; this has restricted observations to visual studies.. These difficulties make it easy to understand why there has been a lack of consensus concerning a complete model of the vortical structures within the boundary layer.

AVERAGE MODELS/REALIZATIONS

The distinction between one realization of a flow, and an average over many realizations (ensemble average) is obvious to workers in the turbulence community. However, certain aspects of the distinction need to be re-emphasized in order to be fully clear about coherent structures in the boundary layer.

The literature abounds with statistics that are limited to planes or other two-dimensional representations of flow structures which are intrinsically four-dimensional. These statistical measurements are essential in providing quantitative knowledge about turbulent fluctuations. However, they need to be interpreted with considerable care. Specifically, the ensemble average representations, unless interpreted with great care, can give the impression that there exist in the flow stationary structures which move with the flow in a convective sense. As discussed below, many of the vortical elements and many sections of the vortical structures do not move with the local convective speed of the flow, and the shapes of the vortical structures change over time as elements are created, evolve and decay.

Another quite surprising result has arisen from the cooperative, community-wide study. Several important structures are created in more than one way, each of which appears to be statistically relevant to one or more processes that are important in the dynamics. (See also further comments in the section discussing evolution of structure.) These facts provide another reason why establishing the full model of the structure in the boundary layer from ensemble average measurements has been difficult.

GENERAL DESCRIPTION OF OBSERVED VORTEX ELEMENTS AND STRUCTURES

Before we discuss ordering of structures, it will be useful to note several features which are observed when one looks at a large sample of vortices in an instantaneous realization of a large volume of flow in Spalart's (1988) simulated, flat-plate boundary layer by examining a surface defined with a contour of negative p'. An example is shown in Figure 1. This sample covers a volume extending through the layer in y, 1200 wall units in z, and over 4000 wall units in x. One observes many isolated vortex elements with various orientations, and also many vortical structures of various shapes. There is no single shape which dominates the observed type of vortices by its frequency of appearance. Also, the shapes of vortical structures vary more continuously than discretely. The contour level used in Figure 1 was $-4.2\,\rho\,U_\tau^2$. However, variation of the contour level over a wide range (covering all the appropriate values) does not alter the qualitative nature of the descriptions given.

Because of the variety and continuous variation in shape observed in figure 1, it is hard to decide on a set of categories to describe the vortex elements and structures. However one shape does occur more commonly than most others, and can be used to delineate some distinctions and associations. This relatively common vortical structure is illustrated in Fig 2.

Fig. 2 shows a hook-like shape which includes three vortex elements designated: Head (spanwise element), leg (near-streamwise element) and neck (a curving structure which connects the head and leg). The wallward (upstream) end of the leg is called the foot. The inboard side toward the head and the outboard side are marked in Figure 2 for reference. One observes many more hook-like vortical structures than full hairpin-like structures with two legs and two necks.

One also observes a significant number of what appear to be piled up "complexes" of vortical elements that are tangled together in a variety of shapes. These "complexes" of vortices must be observed from more than one perspective since when observed in plan view they may appear to touch, but when viewed observed in side view, are sometimes seen to be separate vortical structures lying at different y^+ locations. Not infrequently as many as four or five separate layers of vortices are seen in a side view. This description stands in considerable contrast to many attempts to describe a single characteristic vortex structure. It suggests that we may need to deal with a distribution of vortex elements rather than a single structure or even single form of structure; this point needs further study.

Despite these complications, some clear associations between various types of vortex elements and other structures appear to be characteristic, and can be delineated. These associations are discussed, in part, and specific references cited on specific points below.

A PRELIMINARY ORDERING OF THE IMPORTANCE OF STRUCTURE ELEMENTS WITH RESPECT TO CREATION OF TRS AND CREATION AND DISSIPATION OF TKE

The list which follows was obtained by creating a series of interconnectivity diagrams showing how many other features preceded (inputs) and followed (outputs) each of the eight known structures in time (Robinson, 1989b). Structures with more inputs and outputs have then been taken as probably more central to the processes. The results of this input/output study were checked by considering which structures appear to actively influence the flow, and are most closely associated in space with volumes of high Reynolds stresses and/or high dissipation of TKE. The list is presented below. It is highly preliminary; we expect and hope it will be subjected to discussion by many others.

A TENTATIVE PRIORITY OF STRUCTURES

MOST CONNECTED AND APPARENTLY MOST ACTIVE

- Vortices-- Vortex elements and vortical structures

PLAYS AN IMPORTANT ROLE

- Ejections (including lifted Low-speed streaks)
- Sweeps (including inrushes)
- Near wall shear-layers

PLAYS SOME ROLE

- Bulges
- Backs
- Pockets
- Wall-attached low speed streaks

These are the same eight elements listed by Kline and Robinson (1988), but, in addition, include two improvements and provides a tentative ordering of importance. The improvements are: (i) lifting of low-speed-wall-streaks is a included as a special case of ejections; (ii) Inrushes are included as a special case of sweeps, where 'inrush' is used in the sense of Grass (1971) and of Praturi and Brodkey (1978); that is, an inrush denotes: motions containing a large negative v' component and also emanating from the outer region of the layer and moving to, or very near to, the wall. Not all sweeps are inrushes since many sweeps move only short distances in the y direction and/or have a low angle of inclination to the wall, as Praturi and Brodkey (1978) explicitly noted. Sweeps which are not inrushes are known to play a significant role in the near wall region. We have delineated the concept of inrushes because the observations suggests inrushes play a significant role in the *inward* interaction between the outer and inner layers. However, it is noteworthy that the *outward* interaction between the inner and outer layers appears to have a different character. Details will be reported separately.

Of these elements of structure, the most important, as many others have suggested earlier, seem to be the vortices. However, most earlier studies have suggested one single form of vortical structure. Observations of the DNS data base for the canonical plate flow suggest a variety of vortex elements (each with varying orientations) and vortical structures of a variety of shapes all play a role.

If this suggestion is taken as a hypothesis to check, then we can examine it by asking two questions:

- Do the other seven forms of structure occur close enough to vortex elements or structures so that the vortices could play a central role in what occurs?

- Are the strengths of the vortices sufficient and the directions of rotation such that the observed motions could be induced by the vortices?

The answer to both these questions appears to be, "Yes!" Some specifics follow; more details are reported elsewhere as noted in context.

THE ASSOCIATION OF VORTICES WITH OTHER ELEMENTS OF STRUCTURE

The following forms of structure from the list above appear most commonly immediately adjacent to vortices (for pictures see Robinson et al 1988a):

- ejections
- strong sweeps at the wall
- inrushes
- many (but not all) near-wall shear layers
- many (but not all) bulges
- many (but not all) backs
- attached low-speed wall streaks. (These occur wherever a leg vortex element is observed near the wall; however the low-speed wall streaks persist longer than the leg vortex elements; the streaks therefore are also observed when there is no proximate leg vortex element.)
- pockets (observed beneath intense near-wall sweeps)

In addition to these associations, a number of other observations also point to vortex elements and structures as central to the structure of the boundary layer.

As noted above, Moin (1987) reported from study of a DNS channel flow that regions of high $u'v'$ occurred adjacent to every observed quasi-streamwise vortex element. Robinson et al (1988a) reported observations of high values of $u'v'2$ primarily in two places, along the inboard side of leg vortex elements where low-speed streak lifting was observed, and underneath and upstream of vortex head elements. These observations held regardless of whether vortex elements were observed alone or as part of vortical structures. They also reported that high values of $u'v'4$ were observed primarily in two places: outboard of necks and outboard of leg vortex elements. Moreover, the $u'v'2$ inboard of leg elements, and the $u'v'4$ outboard of legs occur very close to the wall, and thus include the region where production of TKE is known to be a maximum.

There is also an observed association between vortices and regions of high static pressure in the flow. Specifically regions of high pressure are observed wherever high speed fluid overtakes slower moving fluid downstream. This occurs primarily in two places: upstream of backs which lie just upstream of vortex head elements and downstream of inrushes near the wall, motions which are associated with neck vortex elements. These results are reported in Robinson et al (1988b). In the same paper, it is noted that large regions of high pressure are observed just upstream from the piled up vortex elements. These regions of high pressure are of considerable extent both normal to the wall and spanwise. Alfredsson et al (1988) report high pressure regions upstream of lifted-low-speed streaks near the wall. Here also one observes high speed fluid overtaking low-speed.

Finally, observations of the complete dissipation term for TKE in Spalart's (1988) DNS simulated boundary layer (Robinson, 1989b) show that high values of dissipation occur along the leg of vortices, particularly toward the foot end of the leg and thus in the very near wall region which is the region of highest dissipation as indicated by extrapolation from the measurable elements of dissipation for example by Klebanoff (1955) for a boundary layer and Laufer (1952) for a channel flow.

In summary, this section indicates there are close spatial relationships between all the known important structures and some form of vortex element.

THE STRENGTH OF VORTEX ELEMENTS

In a study of Spalart's DNS simulated boundary layer Robinson (1989a) reports the strengths and other detailed properties of vortex leg and vortex head elements for isolated vortex elements and vortical structures. The results show that the vortex elements, both legs and heads, are clearly strong enough so that one can think of them as playing a major role in the dynamics of the nearby flow field via induction.

In summary, the data show three things about vortices in the boundary layer:

- No one shape, size or orientation of vortices is sufficiently common to be entirely characteristic; rather a variety of shapes, sizes, and orientations are observed;

- The vortex elements, whether solitary or in vortical structures, are associated directly in space with the other elements of structure, and have both the strength and direction necessary to induce, or at least augment, the observed motions;

- Head and leg vortex elements play somewhat different roles in the physics; however, this matter needs further study.

A FEW REMARKS ON TIME EVOLUTION OF STRUCTURES

When one observes low-speed streak-lifting either along the inboard side of leg vortex elements or beneath and behind head vortex elements, whether alone or in vortical structures, one sees the formation of the near-wall-shear-layers following from the streak-lifting. No sweep or dynamic action is needed for this creation of a near-wall-shear-layer since the lifting of the low-speed-streak creates a volume of low speed fluid at a distance from the wall of a surfboard-like shape or of a triangular wedge-like shape. This volume of low-speed fluid then lies away from the wall and downstream from a region of significantly higher speed fluid which already existed at this distance from the wall, virtually by construction. The near-wall-shear-layer then exists by virtue of kinematics alone; it is the interface between the lifted-low speed volume of fluid and the following higher speed fluid. No strong negative v' motion is needed for these things to occur, nor is such a motion typically observed; this has been reported by Brodkey and his co-workers (Corino and Brodkey, 1969; Praturi and Brodkey 1978), and is confirmed in the study of DNS simulation of the plate flow.

When one follows this near-wall-shear-layer farther in time after its formation, the observations show a significant fraction of the lifted near-wall-shear-layers roll-up, and create new spanwise vortex elements (heads) usually with one or two necks attached; see Robinson et al 1988a, 1988b. This roll-up appears to begin with a perturbation of the near-wall-shear-layer which creates rapid further mutual induction of the vorticity lines, and thus appears to be a local instability of the near-wall-shear-layer. Such roll-ups occur from both lifted streaks which form alongside legs and those which form behind and beneath heads as reported by Acarlar and Smith (1987) for perturbed laminar layers and as observed in DNS simulations of the plate. The vortex head elements formed in this way tend to persist in the flow for long distances downstream, in many instances farther than can be tracked in the available databases. In some instances the vortex head elements have been observed migrating, relatively slowly, to higher values of y^+. The near-wall-shear-layers which do not form heads, appear to break-up and disappear over significantly shorter times. The precise fraction of near-wall-shear-layers which roll-up into persistent vortex head elements as contrasted with those which break-up relatively rapidly has not yet been measured; however each fraction is significant.

When the vortex heads formed by roll-up of the near-wall-shear-layers are followed still further in time, one observes, not uncommonly, a rapid growth of a leg from the open end of a neck which moves inward and ends in the very near wall region. In some instances the observed growth of the vortex leg element moves directly to the wall, and in others it appears to run upstream. In either case it is elongated, often rapidly, over time since the neck region moves faster than the foot region of the leg.

In many cases ones sees two or three lifting sections of the low-speed-streak closely spaced in x lying inboard of a vortex leg element. Each lifting section typically moves into a volume of high $u'v'2$. We interpret this as representing the several ejections in a burst as documented by Bogard and Tiederman (1987). The observations then suggest that a "burst" in the sense used by Kim et al (1971) is associated with the passage of a vortex element; either a leg or a head.

Lifted streaks have spanwise dimensions of the order of approximately 20-80 wall units; sharp interfaces with high values of dU/dz exist along the xy faces on the sides of the lifted-low-speed-streaks. The formation of solitary leg vortex elements with varying orientations have been observed along the sharp interfaces on the xy faces of lifted low-speed streaks. High values of dU/dz in the near wall region have been documented by many observers, notably Blackwelder and Eckelmann (1979). Blackwelder also stressed the possibility and potential importance of instabilities occurring as a result of the high gradients of both dU/dy and dU/dz, of roughly equal magnitude, in a number of informal workshops and conversations over the years.

The preceding paragraphs describe a sequence of events consisting of: low-speed-streak-lifting; formation of near-wall-shear-layers; roll-up of some of the near-wall-shear-layers forming spanwise vortices (heads); and finally growth of a leg vortex element from the head with the leg often extending essentially to the wall. However, little was said about how lifting of low-speed-streaks is initiated. Some remarks on the initiation of low-speed-streak lifting are now added.

Data by R. E. Falco, communicated privately, show simultaneous plan and side views with laser sheet marking. Lifting of low-speed-streaks observed in these two views often occurs when a strong spanwise motion impinges on a low-speed streak lying adjacent to the wall. Thus one often observes a strong spanwise kinking of the low-speak-streak when observed in plan view. Such kinks of low-speed-streaks in plan view were commonly observed in the earliest pictures of streaks, Kline and Runstadler (1959), and have been confirmed in numerous later visual studies. However, the implications of this kinking of the low-speed streaks in the plan view had remained unknown up to the time Falco's two simultaneous views became available. In a quantitative study Alfredsson et al (1988), using VISA statistics in a DNS simulated wall flow, showed that the ensemble average lifted-low-speed-streak and the associated high values of $u'v'2$ lying downstream from the lifted streak, both have a strongly spanwise skewed orientation at $y^+ = 15$. Alfredsson et al did not track the results to the wall; they suggested the triggering source may be the pressure perturbation which they also mapped. In this paper, and in Robinson et al (1989b) we have suggested a different source and different role for the pressure perturbations. Thus we need also to suggest a different source of the spanwise kinking of low-speed streaks commonly associated with streak-lifting. The descriptions in Robinson et al 1988a, 1988b suggest the following possibility. The spanwise kinking of low-speed-streaks associated with lifting may arise from motion induced by the foot of a quasi-streamwise leg vortex with its underside lying essentially at the wall. In visual study of the DNS simulations, one can observe the resulting spanwise motions as part of the lifting of low-speed-streaks on the inboard side of vortex legs. This includes motions generated by inrushes around a vortex neck as well as those arising from a vortex foot. This suggestion needs more detailed studies to determine statistical relevance.

WHERE DO WE GO -- RESEARCH CHALLENGES

Let us first recapitulate where we stand in summary. Two main facts stand out. First, the sum of three decades or so of work in the laboratory has provided us with documentation of eight major structure features one-by-one, and a number of possible models of ensemble averages of the structure. Recent study of DNS data bases made accessible by workers at NASA-Ames have begun not only to confirm many characteristics of the eight structure features measured by laboratory experiments but also to provide several kinds of added information concerning: regions of high and low pressure; the location of regions of high dissipation of TKE; details of a variety of shapes of vortex elements and vortical structures and their creation, evolution and decay over time; considerable information about the size, distribution in y^+ space, circulation, and intensity of vortex elements in the flow. Perhaps most important, in terms of constructing a complete model of the structure, these studies are providing considerable information about the spatio-temporal relations among the eight kinds of structure and regions of high and low pressure. All these results, from both laboratory and DNS studies, taken together suggest that vortices, which move through the flow in various shapes and orientations, and often persist for long distances measured in wall units, are the central features of the structure.

However, the available DNS data bases cover only a few canonical flows, are limited to very low R_θ values, and have thus far only been studied for significant times by a relatively small number of workers. Can we take these results from DNS to be reliable pictures of the structure of near-wall turbulence? What questions remain open, and how can we best approach them?

Let us deal with the problem of restriction to low values of R_θ first since that is in some ways the easiest to deal with. The question of the effect of R_θ has been much discussed; it constitutes a real problem since we cannot expect DNS to manage much higher R_θ for at least a long time. Nevertheless, we believe it would be easy to overemphasize the importance of this question for boundary layers. Kline and Robinson (1988), summarize data from many sources which show that the large fraction (of the order of 80%) of the creation of TRS and production of TKE occur in the near wall region. In this region, effects are known to scale, or at least nearly so, on U_τ. U_τ in turn is known to scale as the minus one-tenth power of R_θ. Moreover, for the canonical plate flow we do not see changes in slope on the curves of either Ln(Cf) or Ln(St) vs Ln(Re). Experience, covering many cases in viscous flows, tells us when the slope remains constant in this type of non-dimensional correlations, we ought not expect *qualitative* changes in the flow structure (or in what we sometimes call flow regime). Thus in so far as the structure of the near-wall region is concerned, we do not expect to see much effect of Reynolds number. After all, 100 to the minus one-tenth power is 0.63, and R_θ of 67000 is large in terms of most applications. Thus we expect what is found at $R_\theta = 670$ for the near wall region to be a reasonable qualitative picture for flat plate layers in general. Moreover, we also know the law of the wall is surprisingly tenacious; it applies when properly used to rough wall flows, to pressure gradient cases; to curved wall flows, and other applications. It is possible to create flows which do not obey the law of the wall, but one has to work at it rather hard. This suggests that the qualitative features of structure observed in the inner layers of boundary layers for the canonical plate flow ought to provide guidance in a much wider class of flows albeit the idea needs firmer proof via laboratory and DNS investigations.

In so far as the inward and the outward interactions between the inner and outer layers are concerned, we must expect changes as R_θ increases. Changes in the shape of the space-time correlations as presented for example by Antonia et al (1988) verify changes in the outer layer. Moreover, the ratio of outer to inner scales increases along a flat plate as x to the 0.7 power. Hence, we can anticipate, other things being unchanged, that the direct connection between the outermost part of the layer and the innermost regions of the layer will weaken as R_θ increases. The saturation of profile at $R_\theta = 5000$ given by the Coles (1968) tends to support this idea. So do recent data by Anders (1989) investigating the effect of LEBUS as a function of Reynolds number. Thus some changes are likely to be seen in the interactions between the inner and outer layer at least up to $R_\theta = 5000$. However, these interactions account for the smaller portion of the creation of RNS of the order of 20% for canonical plate flow. The inward interactions do not dominate production in the canonical flat plate layer albeit they are not without effect right to the wall. Moreover, even in the outer region of the flow, if we find, for example, that the vortex head elements are central to the structure, we ought to assume, in the absence of contrary information, that this will also be *qualitatively* true at higher R_θ since this is far more likely than the contrary assumption. Also, the results of Head and Bandyopadhyah (1981) suggest a linkage of the heads to the wall layers through an outward interaction with an aspect ratio that increases as R_θ increases.

Thus there is a need for investigation of structure at higher Reynolds number, but the authors believe this is less important as a research priority than investigation of many other effects which we know occur when we depart from canonical flat plate conditions. These include roughness, free-stream fluctuations, pressure gradients, three-dimensional layers, wall curvature. compressible cases, and body-force effects. Many of these effects will not be available for study in DNS data bases for some time to come, if ever. Hence there remains much to do experimentally. And we need to keep in mind the connections between the statistical measurements and the structure picture suggested by the comments on concepts and the results indicated above; these problems of connections between the statistics and the structure and the associated questions are unlikely to change significantly from one flow to another.

Let us move on then to a discussion of what we can do in utilizing experiments and DNS to move toward a more complete, generally agreed picture of structure in the boundary layer.

Let us begin by enumerating some open questions that appear important.

The comments in the section "Association of Vortices With Other Elements of Structure" suggests a long list of structure features for which we need to gather improved samples in order to have reliable statistical means and distributions. The availability of DNS simulated flows now makes this feasible.

Some questions which probably cannot be studied by using the existing DNS data bases include: the details of the outward interaction between the inner and outer layers; the origin of the large vortex head elements frequently observed at the center of bulges and why these heads are much longer spanwise than heads near the wall. What are the origin and role of the large "piled-up complexes" of vortex elements observed in the layer and their relation to high pressure regions. It may also be difficult to determine the dynamics of how leg vortex elements grow from heads with available data bases and software.

There is also a need for extensions of the DNS data bases to other flows, to cover the cases mentioned above. A good many workers are proceeding with such studies, and we have little doubt that the results will prove important in advancing our understanding of structure for a larger class of wall-bound shear flows over the next decade or so. These studies need to be linked to, augmented, and confirmed or disconfirmed by parallel experimental work.

If vortices are the central element of structure then several questions assume importance. How can we provide improved methods for observing vortices (in contrast to visually observed streaklines and VITA detected shear-layers) in the laboratory? What is the nature and the details of the formation of vortices? Is it as suggested above an unstable roll-up of near-wall-shear-layers with dU/dy and/or dU/dz orientation? Is this also true for the vortices under bulges far from the wall?

The central questions which remain seem to be. "How do we combine the results from study of DNS data bases with the experimental results to approach consensus on a complete model of structure?" and, "How do we capture the essence of such a model in a simple enough way so that it becomes useful in creating predictive models and controlling turbulence?"

This question leads naturally to a further question. If we assume that we know the distribution of location, sizes and strengths of head and leg vortex elements not only for the plate but also for other cases such as flows with pressure gradients, can we use that information to form a "Statistical-structural model" which has more physics built in than available Reynolds Stress Averaged models, and still is simple enough to provide practical engineering predictions? At the present state of knowledge this question seems worthy of investigation.

Finally, it seems very desirable for a wide based group of researchers to discuss the existing experimental results together with the emerging results from study of the DNS data bases in order to see to what degree consensus can be obtained on a complete model picture of boundary layer structure. Since this discussion requires in-depth examination, and that in turn requires a significant amount of time, a workshop type meeting open to all members of the research community seems indicated.

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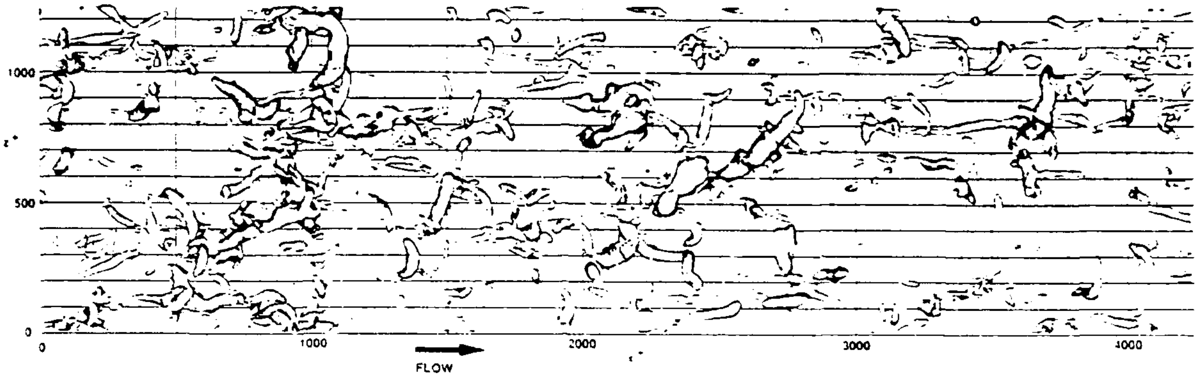

Fig. 1. Top-view of instantaneous three dimensional low-pressure structures in numerically-simulated turbulent boundary layer. Isobaric surfaces computed for $p' = -4.2\rho u_\tau^2$.

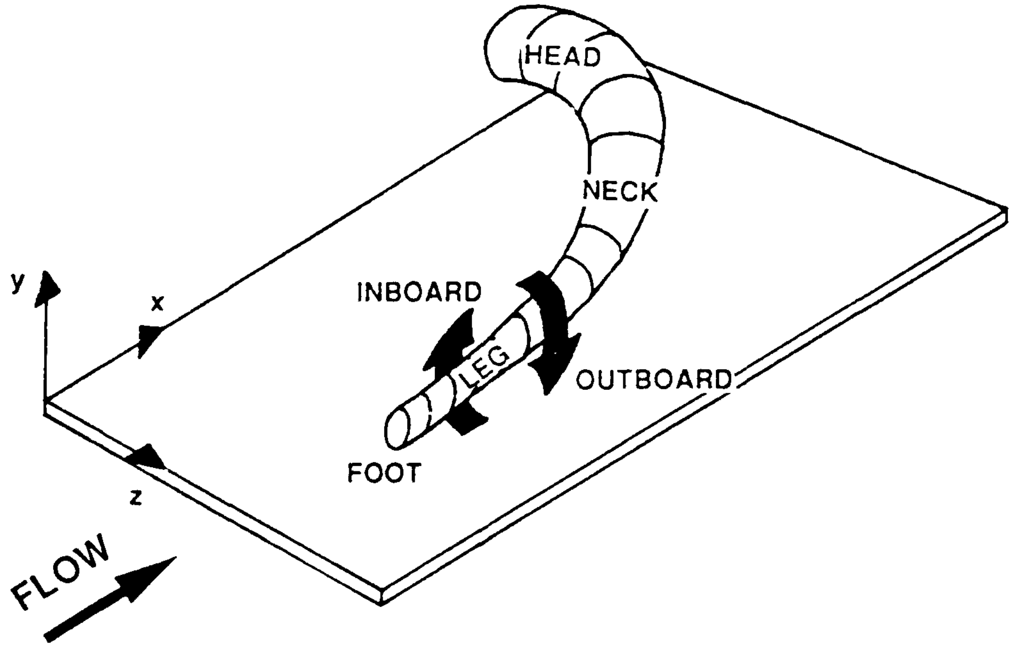

Fig. 2. Schematic diagram of one-sided, hook-shaped vortical structure.

A REVIEW OF VORTEX STRUCTURES AND ASSOCIATED COHERENT MOTIONS IN TURBULENT BOUNDARY LAYERS

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ABSTRACT

The experimental and computational evidence for the existence and role of vortices in turbulent boundary layers is briefly reviewed. Quasi-streamwise and transverse vortices are considered, and various published conceptual models for horseshoe-like vortical structures are compared. The causes for upright and inverted horseshoe-shaped vorticity lines are discussed, and the distinction between vorticity lines and vortices is demonstrated. Finally, results from a numerically-simulated turbulent boundary layer are used to compute distributions of diameter, height, and strength for quasi-streamwise and spanwise vortices. These results confirm that quasi-streamwise vortices are clustered near the wall, while spanwise vortices are distributed throughout the layer. The variation of spanwise vortex core diameter with distance from the wall is found to be consistent with the mixing-length distribution for a boundary layer.

INTRODUCTION

Objectives

The concept of vortical motion is intrinsic in the study of coherent structures in turbulent flows. Even in the term "eddy," we find an implied vortical motion. A review of 40 years of turbulence structure literature uncovers a mass of information, much of which has vortices and their effects as a common denominator. The motivation for investigating vortices is their potential to function as "pumps" which transfer mass, momentum, and heat while extracting energy from the mean flow. It is the intent of the current effort to briefly review this important concept of imbedded vortical structures as it pertains to turbulence physics in boundary layers.

The oldest and most common idea for coherent vortical structures in the turbulent boundary layer is that of the horseshoe or hairpin vortex. Therefore, attention will be focussed upon conceptual models that rely upon such vortical structures. Kinematical and dynamical aspects of the various published models are compared and experimental and computational evidence for their existence and importance is examined.

Motivations

Turbulence structure research does not generally aim to replace traditional, Reynolds-averaged modeling concepts. Instead, the motivation is to open a window upon the physics responsible for the statistics we are trying to model, in the hope that a deeper physical insight will provide

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guidance for improvements in Reynolds-averaged modeling and in turbulence control. The eventual objective is a class of models in which structural elements with modeled characteristics will provide the statistics of engineering interest. A leading candidate for the core element of such a modeling concept is a family of vortex structures, hence the topic of the current paper.

DEFINITIONS AND DISTINCTIONS

One of the hindrances to the study of vortex structures in turbulent boundary layers has been the lack of a rigorous, widely-accepted definition of a vortex for unsteady, viscous flows. For the present effort, the following working definition is employed: a vortex exists when instantaneous streamlines mapped onto a plane normal to the vortex core exhibit a roughly circular or spiral pattern, when viewed from a reference frame moving with the center of the vortex core. This definition requires an a-priori method for identifying vortex cores, and the process of choosing a reference-frame velocity may be iterative.

It is useful to distinguish between vortical elements and vortical structures (Kline and Robinson, 1989). In the present paper, a vortical element is defined as a vortex or vortex segment with a single dominant orientation. Examples are "leg," "neck," and "head" vortex elements of which a hairpin vortex is composed (Figure 1). A vortex structure is defined as any combination of elements, generally forming a complex three-dimensional shape. Vortex structures considered within this paper are hairpins (with extended trailing legs) and horseshoes (without well-defined legs). Horseshoe vortices possess a width/length ratio of approximately unity (as in Theodorsen's model, Fig. 2) and hairpins are longer in the streamwise direction than they are wide (as in Head and Bandyopadhyay's high-Reynolds number vortical structures, Fig.8c). This distinction is often unclear or unnecessary, however, and in those cases "hairpin/horseshoe" will be used. Horseshoe-shaped vortical structures will also be referred to as "arches".

The term "quasi-streamwise vortex" will be applied to any vortical element with a predominantly streamwise (x) orientation, although it may be tilted at a significant angle to the x-axis. Brodkey's (1987) term for streamwise vortices with an upward tilt is $\omega_{x/y}$-vortices, which is also a useful nomenclature.

A distinction must be made between vortices and vorticity. In the turbulent boundary layer, the association between regions of strong vorticity and actual vortices seems to be rather weak (Robinson et al, 1989). Thus additional methods are necessary for vortex identification. Visual techniques have been moderately successful in the laboratory (eg. Smith and Lu, 1988), and vorticity lines (Moin and Kim, 1985) and the pressure field (Robinson et al, 1988) have been useful for detecting vortices in numerical simulations.

Sweeps and ejections are defined here as $(u'v')_4$ (or Q4) and $(u'v')_2$ (or Q2) motions, respectively, in accordance with Wallace et al's (1972) $u'v'$ quadrant-splitting scheme. There are other interpretations of the terms, but the present usage is the most common, and has been chosen for its strong association with the Reynolds shear stress.

REVIEW OF EVIDENCE AND MODELS FOR VORTICAL STRUCTURES

The presence of Reynolds shear stress ($-\rho\overline{u'v'}$) in a boundary layer implies the existence of cross-gradient mixing; that is, transport of relatively low-momentum fluid outward into higher-speed regions and of high-momentum fluid wallward into lower speed regions. Since any vortex with an orientation other than exactly wall-normal will induce such transport, vortices are natural candidates for major (and perhaps dominant) producers of Reynolds shear stress in the boundary layer. A significant portion of the boundary layer structure literature is devoted to investigating the role and quantitative character of vortical elements and structures. Although the comments presented here are necessarily brief, an extensive discussion of boundary-layer vortex statistics and dynamics can be found in Robinson (1989).

Experimental and Computational Evidence for Quasi-Streamwise Vortices

The ubiquitous presence of an elongated low/high-speed streak pattern in the near-wall region of turbulent boundary layers has prompted suggestions that the streaks are fluid accumulated between counter-rotating pairs of near-wall streamwise vortices. These theories, along with the observed appearance of streamwise vortices during violent turbulence production events has continued to motivate new research into near-wall quasi-streamwise vortices.

Vortices with a major streamwise (x) component are generally identified in experimental and computational results with single cross-stream (y-z) planes of marked fluid or computed velocity vectors. This method may not allow for differentiation between purely streamwise vortices and those tilted with respect to the wall. Thus, much of the data reviewed in this section could apply to both leg and neck vortices (in the nomenclature of Fig. 1), so the vortex elements are referred to here as "quasi-streamwise." Both purely streamwise and tilted quasi-streamwise vortices are capable of momentum transport across the velocity gradient, but the vortex dynamics are obviously affected by the orientation, since the wall-normal velocity gradient provides rapid stretching of the tilted vortices only.

Table 1 lists some of the many articles that make reference to quasi-streamwise vortices in turbulent boundary layers, either by flow-visualization in the $y-z$ plane, by probe measurement, or by numerical simulation. The A-F categorization shows that about half of the results are from visual studies, and half include quantitative data. Some studies provide both by using particle or bubble displacement techniques. Nearly a third of the references include some kind of simplified predictive model for near-wall streamwise vortices in the turbulent boundary layer.

Quasi-streamwise vortices were observed early in the history of turbulent structure research. Kim et al (1971) noted the common appearance of quasi-streamwise vortices in conjunction with the oscillation phase of the turbulence-generating bursting process. Grass (1971) also observed quasi-streamwise vortices, generally during near-wall "inrush" and "ejection" events. Clark and Markland (1971) made careful observations of relatively long quasi-streamwise vortices (often counter-rotating pairs) with a 3 to 7 degree upward tilt in the wall region of a turbulent water channel.

Perhaps the most extensive direct information concerning quasi-streamwise vortices has come from the end-view hydrogen-bubble visualization studies of Smith and Schwartz (1983) and Kasagi, Hirata, and Nishino (1986). These studies confirmed the common occurrence of quasi-streamwise vortices in the near-wall region, including frequent observation of counter-rotating pairs. In the simultaneous top and end views by Smith and Schwartz, counter-rotating vortex pairs in the near-wall region were always associated in space and time with low-speed streak formation. Further recent results by Kasagi (1988) suggest that solitary quasi-streamwise vortices are more common than vortex pairs in the near-wall region, and that the vortical structures are not as long as the near-wall low-speed streaks.

Additional visual evidence of the existence and character of quasi-streamwise vortices can be found in Kastrinakis et al (1978) (who re-analyzed the film of Corino and Brodkey, 1969), Praturi and Brodkey (1978), and Lian (1987). Probe-based (or quantitative flow-visualization) results from which vortex behavior is inferred are presented in Willmarth and Lu (1972), Blackwelder and Eckelmann (1979), , Utami and Ueno (1987), Kreplin and Eckelmann (1979), and Nakagawa and Nezu (1981).

The apparent association between near-wall quasi-streamwise vortices and both the generation of low-speed streaks and turbulence production has motivated a number of streamwise vortex models with at least some predictive abilities. These include Bakewell and Lumley's (1967) proper orthogonal decomposition of experimental data, which showed that most of the near-wall Reynolds shear stress and turbulence kinetic energy could be represented by a dominant eddy structure which consisted of a streamwise vortex pair. These results were confirmed and extended by Herzog (1986), and more recently by Aubrey et al (1988) with much more detailed data. Additional streamwise vortex models of have been proposed and developed over the years by a number of groups. Representative references of recent results are Hanratty (1988), Ersoy and Walker (1986), Pearson and Abernathy (1984), and Jang et al (1986).

Recent numerical simulations of turbulence have provided important new tools for investigating the structure of low Reynolds number wall-bounded flows, and have been used extensively to study the nature of embedded vortices in simulated channel flows and boundary layers. Although most of the attention has been given to three-dimensional vortex structures, quasi-streamwise vortices have been found in both instantaneous realizations and in conditionally-averaged results from the simulations.

Kim (1983) used VITA-type conditional averages to educe tilted streamwise vortex pairs in the near-wall region of a Large-Eddy Simulation (LES) of a fully developed turbulent channel flow. Kim's average near-wall vortices were considerably shorter than the low-speed streaks in the simulation. In an extensive study of the vorticity field of an LES channel flow, Kim and Moin (1985, 1986) only rarely observed quasi-streamwise vortices (bundles of largely streamwise vortex lines). The vortices that were detected were of generally limited longitudinal extent ($\Delta x^+ < 100$), in agreement with Kim's (1983) earlier conclusions from the same data.

In the results of a direct simulation of a channel flow, Moin (1987) observed that, unlike the u' field near the wall, the v' and w' contours do not show significant streamwise elongation and that the regions of large v' tend to occur in side-by-side inward/outward pairs, suggesting quasi-streamwise vortices. Moin found these vortices occurred most commonly singly, rather than in counter-rotating pairs of equal strength, in contrast to conditionally averaged results (e.g. Blackwelder and Eckelmann, 1979; Herzog, 1986; Kim, 1983; Moin, 1984). Moser and Moin (1984), Robinson et al (1989), and Guezennec et al (1989) have also concluded that single quasi-streamwise vortices are statistically more common than equal-strength pairs in direct numerical simulations of turbulence.

Moin's (1987) quasi-streamwise vortices were only 100 to 200 viscous units long, but retained their coherence while travelling several channel half-widths downstream. Moin reported regions of high $u'v'$ adjacent to every observed quasi-streamwise vortex in the wall region, and concluded that relatively short, single vortices are the fundamental structures associated with regions of high turbulence production.

Statistical decompositions of the simulated turbulence velocity fields have provided additional insight into the nature and statistical significance of quasi-streamwise vortices (Moin, 1984; Moin, Adrian, and Kim, 1987).

Given the available evidence, there is no doubt that quasi-streamwise vortices exist in numbers sufficient to play an active role in near-wall turbulence dynamics. Some association between quasi-streamwise vortices and both ejections and low-speed streaks seems certain, although the details have not been clear. The obvious potential for outward pumping of low-speed fluid by single and paired quasi-streamwise vortices has been confirmed, but the apparent violence of the ejection phase of bursting may signify a more complex and transient vortex behavior. In addition, the formation of near-wall shear layers are apparently associated with the upward-rotating sides of quasi-streamwise vortices (Stuart, 1965; Robinson et al, 1988). There is reasonable agreement in the literature on the size and location of quasi-streamwise vortices: diameters from $15\nu/u_\tau$ to $50\nu/u_\tau$, with centers occurring predominantly between $y^+ = 20$ and $y^+ = 70$. Although early papers proposed quasi-streamwise vortex extents on the order of the streak lengths ($\approx 1000\Delta x^+$), it now appears to be a consensus that quasi-streamwise vortices are about an order of magnitude shorter than the longest sublayer streaks. Quasi-streamwise vortices are generally considered to occur both singly and in counter-rotating pairs, and, in the near-wall region, to tilt upwards from the wall at a shallow (3 to 7 degree) angle. In the outer region, vortices more commonly make angles of approximately 45 degrees with the wall, which corresponds to the direction of maximum vorticity production due to stretching by the mean gradient. There is little information available on the strength (circulation) of quasi-streamwise vortices in turbulent boundary layers.

The formation mechanisms and evolution of the quasi-streamwise vortices are poorly understood. The most popular theory is that they are the trailing, stretching legs of hairpin vortices (see later discussion). However, Falco (1982, 1983) suggests that quasi-streamwise vortices are created from the passage of a ring vortex eddy over the sublayer. It has also been proposed that quasi-streamwise vortices arise due to local flow curvature and an accompanying Görtler instability (Brown and Thomas, 1977), and Acarlar and Smith (1987) propose yet another means by which quasi-streamwise vortices may be generated (see Fig. 12). None of these theories are fundamentally contradictory, and in fact multiple formation mechanisms of quasi-streamwise vortices seems probable.

Experimental and Computational Evidence for Spanwise Vortices

In the spanwise (x-y side-view plane) of a turbulent channel or boundary layer, the detection of a vortex in the velocity field is obviously dependent upon the motion of the observer's reference frame. The mean velocity gradient combined with the turbulent unsteadiness make experimental detection of transverse vortices in the boundary layer difficult and often ambiguous. Cautions against potentially deceptive illusions created by reference frame choice and streaklines in unsteady flows have been published by Hama (1962) and again recently by Kurosaka and Sundaram (1986).

As a result of these experimental difficulties, relatively few references discuss transverse vortices specifically, although they are usually an element of three-dimensional vortex structures. Some of the exceptions are listed in Table 2. For the present purposes, the table does not include the many papers on the large, relatively weakly rotational δ-scale motions, such as those described in, for example, Kovasnay et al (1970), Brown and Thomas (1977), and Antonia et al (1988).

Most of the evidence for strong local transverse vortical motion is from side-view flow-visualization studies such as Kim et al (1971), Clark and Markland (1971), Nychas et al (1973), Praturi and Brodkey (1978), Lian (1986), and Smith and Lu (1988). Probe-based data which imply transverse vortices are included in Nakagawa and Nezu (1981).

The most common reference to transverse vortices is in regard to near-wall hydrodynamic instability (e.g. Einstein and Li, 1956; Kline et al, 1967; Black, 1968; Smith, 1984), in which a local instability occurs at the shear-layer interface of high and low-speed fluid, resulting in a transverse vortex rollup.

Perhaps the earliest extensive description of transverse vortices is included in Clark and Markland (1971), who found them to be the predominant vortex element in the $y^+ > 70$ region. Clark and Markland observed that the streamwise lifetime of transverse vortices increases as distance from the wall increases, and that the diameter grows but the spin-rate slows during the vortex lifetime.

Kim et al (1971) found that transverse vortical motion occasionally appeared during the oscillatory phases of what they defined as the near-wall bursting process, but not as commonly as streamwise vortical motion or "wavy" motion.

Nychas et al (1973) described large-scale transverse vortices (of both rotational signs) that appeared to roll up at the shear-layer interface of high and low-speed fluid for $y^+ > 70$. These vortices were suggested to be the cause of the outer interface bulges described by Blackwelder and Kovasznay (1972), and others. In addition, a close spatial association was observed between the passage of transverse vortices and the occurrence of near-wall ejections of low-speed fluid. Outer-region transverse vortices were therefore suggested by Nychas et al to be the key structural element which connects the near-wall activity with the outer-flow large eddies.

Nychas et al's results were basically confirmed and greatly extended in stereo visualizations of the three-dimensional boundary layer structure by Praturi and Brodkey (1978). These results showed inflows of free-stream potential fluid (entrainment) in the vicinity of the large outer-flow transverse vortices. Contrary to the earlier speculations of several groups, it was stated by Praturi and Brodkey that large-scale bulges in the outer turbulent/non-turbulent interface are not caused by unusually high-momentum ejections of fluid from the near-wall region, but instead by the outer-region transverse vortical motions.

The presence of transverse vortices at the interface of high- and low-speed fluid in the outer-layer was also emphasized by Nakagawa and Nezu (1981). Formation of transverse vortices for $y^+ < 100$ was described by Robinson et al (1988, 1989) as a rollup of near-wall shear layers consisting of locally concentrated spanwise vorticity.

It is fairly well-established that transverse vortices are common in the outer region of turbulent boundary layers, and less so in the near-wall region. It remains unclear whether the common mode is for transverse vortices to form locally in the outer region (Nychas et al, 1973) or in the buffer region and then migrate outward (Smith, 1984).

Hairpin/Horseshoe Vortex Conceptual Models

Horseshoe or hairpin-shaped vortical structures dominate the proposed conceptual models for boundary layer turbulence. Notable alternative (but not necessarily conflicting) concepts are the inclined roller-eddy model of Townsend (1976) (see also Guezennec, 1986), and the vortex ring models of Falco (1983, 1988) and of Kobashi and Ichijo (1986). (See Table 3). In the interest of brevity, we will review only the horseshoe/hairpin models here. Excellent reviews of such models have already been published by Wallace (1982, 1985), so the current section may be considered an update of Wallace's work.

In a landmark paper, Theodorsen (1952) proposed the first vortex model for turbulence production throughout the boundary layer. Theodorsen's model may be considered the ancestor of most vortex structure models proposed in the last 35 years. This model was developed to satisfy the vorticity transport form of the Navier-Stokes equations and consisted of vortices bent into an inclined horseshoe shape (Fig. 2). The vortex structures were described as "tornadoes" which were inclined head-downstream at 45 degrees, with spanwise dimensions proportional to the distance from the wall. This vortical model was proposed as the fundamental structure of transitional and fully turbulent boundary layers, being responsible for both the production and dissipation of turbulence energy. It is notable that extended quasi-streamwise vortex elements (legs) did not play a major role in Theodorsen's model.

Theodorsen also described the outward and downstream growth of a horseshoe vortex after its birth "embracing a region of low velocity medium adjacent to the boundary." The streamwise distance travelled by a mature vortex structure was postulated as approximately equal to the distance from its head to the wall. A useful synopsis of Theodorsen's paper is given in Head and Bandyopadhyay (1981).

Willmarth and Tu (1967) used their space-time correlations between the wall pressure and all three velocity components near the wall to devise a model for the average eddy structure of the near-wall region (Fig. 3). The model describes the deformation of initially two-dimensional transverse vorticity lines into three-dimensional hairpin shapes sloped downstream at about 10 degrees from the wall, with the dominant element being vorticity lines with a streamwise component. Although Willmarth and Tu (1967) proposed their hairpin vortex-line model for the near-wall region only, Willmarth and Lu (1972) suggested that near-wall hairpin vortices may evolve to a larger scale, producing the intermittent bulges in the outer edge of the boundary layer and providing an outward interaction mechanism between the inner and outer regions.

A concept by Lighthill (1963) was invoked by Kline et al (1967) to explain the formation of the sublayer streaky structure. In this idea, any fluctuating velocity normal to the wall stretches (for wallward movement) or compresses (for outward movement) the near-wall spanwise vorticity lines. Since the spanwise vorticity is due mainly to $\partial u/\partial y$, this stretching and compressing would lead to spanwise variation in the near-wall value of u. Kline et al also drew on Stuart's (1965) vortex-stretching concepts from transition research to explain the formation of intense local shear layers above lifted low-speed elements, which are a precursor to the oscillation and breakdown phases of bursting. Kline et al's paper concludes with a diagram of an initially spanwise vorticity line being lifted and stretched into a loop (Fig. 4).

Black (1968) used a simple instability argument to propose a flow model based upon horseshoe vortices which are "shed" from a near-wall instability. In their early formation stages, the vortex structures were described as closed loops, or rings (Fig. 5a). As the outer portions of the vortex evolve outward and downstream, the wallward transverse element of the original ring is left behind to decay in the viscous sublayer, leaving a horseshoe-shaped vortex. The heads of these discrete vortices move outward from the wall, thereby stretching the trailing legs and inclining the horseshoe vortex. The vortex structures induce an inviscid outflow of low-speed fluid from within the vortex loop, creating motions which are seen as sharp, intermittent spikes of Reynolds shear stress by a stationary probe. Instead of individual horseshoe vortices, Black proposed a structure comprised of several horseshoe elements in various stages of growth, which share a common front-like trajectory in space. The vortex structure is maintained for much longer periods than the lifetime of the component vortex elements by the continuous creation of new elements which replace the older members (Fig. 5b).

In a review of boundary layer structure concepts, Hinze (1975) attempted to relate the known coherent elements of near-wall turbulence production to the dynamics of horseshoe-shaped vortices (Fig. 6). In his scenario, Hinze suggests that fluid lifted between the legs of the vortex loop gives rise to a locally unstable shear layer, which then violently breaks down (bursts) into a "blob of fluid of high turbulence intensity," apparently destroying the parent vortex structure in the process. Wallward inrush motions were suggested to be initiated by the tip of the vortex loop on its downstream side, and later aided by pressure waves created during the sudden vortex/shear-layer breakdown.

Offen and Kline (1975) also attempted to synthesize most of the known visual features of near-wall boundary layer structure with a lifted and stretched vortex loop which was essentially the same as that of Kline et al (1967). Offen and Kline describe how the three kinds of oscillatory motion observed during the near-wall bursting process by Kim et al (1971) may be related to the passage of a horseshoe vortex (Fig. 7). Pairing of aligned vortex structures and violent interaction of non-aligned vortices are also postulated.

The most extensive and influential experimental evidence for the existence of loop-shaped vortical structures in turbulent boundary layers was that of Head and Bandyopadhyay (1981). These authors' flow-visualizations of boundary layers over a broad Reynolds number range ($500 < Re_\theta < 17500$) provided images of hairpin-shaped structures virtually dominating the boundary layer. These structures were interpreted as vortices by the authors (Fig. 8). At high Reynolds numbers, the vortices were elongated and hairpin-shaped, forming a characteristic angle of 45° with the wall. Large-scale structures were observed to consist of agglomerations of hairpin-shaped vortices. At low Re_θ, the vortices were less elongated, and more horseshoe-shaped, and the large-scale features were composed of just one or two vortices. Although Head and Bandyopadhyay's visual evidence for the existence of hairpin/horseshoe vortices is compelling, the dynamics that underlie their evolution as well as their contribution to turbulence production and dissipation remain unclear.

Head and Bandyopadhyay's work helped to inspire Perry and Chong's (1982) analysis of a model for the mechanism of wall-bounded turbulence (Fig. 9a). In this model, the boundary layer is represented by a forest of potential-flow Λ-shaped vortices, which were introduced as a candidate form for Townsend's (1976) "attached-eddy" hypothesis (Fig. 9b). Biot-Savart calculations of a geometrical hierarchy of such vortices gave promising reproductions of the mean profile, Reynolds shear-stress, turbulence intensities, and spectra for a turbulent boundary layer, lending further credibility to the idea of vortical loops as the dynamically dominant boundary layer structure.

Perry, Henbest, and Chong (1986) extended both the attached-eddy hypothesis of Townsend (1976) and the Λ-vortex model of Perry and Chong (1982) to include the entire turbulent boundary layer rather than just the wall (log) region. The updated Perry et al model for wall turbulence is based upon the existence of hierarchies of attached coherent eddies. The first hierarchy of attached eddies forms at the outer edge of the sublayer, then stretch and grow with a fixed orientation to the wall (e.g. 45° for hairpin vortices). Eddies that do not die through viscous diffusion or vorticity cancellation merge to form eddies of a larger length scale, which comprise the second hierarchy. This continual process creates a "hierarchy of geometrically similar hierarchies" of attached eddies, which are responsible for the mean vorticity, Reynolds shear stress, and most of the energy-containing motions.

Perry et al propose that the attached eddies are immersed in a soup of detached isotropic small-scale motions which are responsible for the Kolmogoroff spectral region and most of the turbulent energy dissipation. Thus, in the model, energy is extracted from the mean flow by coherent motions and dissipated into heat by incoherent, small-scale motions. The model involves energy flow to low wave numbers through eddy-merging, and energy flow to high wave numbers through the unattached, dissipative motions. The assumptions involved in Perry et al's model lead to a logarithmic law of the wall, a constant Reynolds shear stress region, and an inverse power law

u' spectrum near the wall for a variety of attached eddy shapes and distributions. This indifference of the statistics to the geometry of the eddy structure tends to de-focus the attention being paid to the exact form of coherent eddy structure dominant in the boundary layer.

Falco (1982) observed the formation of short-lived, near-wall hairpin vortices on the downstream edge of sublayer "pocket" modules, which are created from the impact of relatively high-speed fluid upon the sublayer. These hairpin vortex structures were found to be associated with outward ejections of low-speed fluid, in agreement with the hypotheses of Kline et al (1967), and others.

Wallace (1982; updated in 1985) convincingly reviewed the quantitative evidence for hairpin/horseshoe vortices in boundary layers (Fig. 10). To explain the birth of the horseshoe vortices, Wallace invokes the Navier-Stokes equations at the wall, which show that local wall-pressure gradients are equivalent to an outward diffusion of vorticity from the wall. Although the equations predict the generation of strongly kinked vorticity lines near the wall, the concept is not necessarily applicable to the the formation of true vortices, which can be quite distinct from vorticity lines. This issue will be revisited in the following section.

Working from the many vortex models in the literature as well as from his own extensive visualization studies, Smith (1984) described the most complete conceptual model yet proposed for hairpin-shaped vortices in the wall region ($y^+ < 100$) (Fig. 11). The model describes both the kinematics and dynamics of hairpin vortices and their relations to low-speed streaks, the bursting process, near-wall shear layers, ejections, and sweeps. Smith proposes that the "bursting" of a low-speed streak is the visual and probe signature of vortex roll-up (one or a packet) in the unstable shear layer formed on the top and sides of the streak. Once formed, a vortex loop moves outward by self-induction and downstream due to the streamwise velocity gradient. The trailing legs of the loop remain in the near-wall region but are stretched, forming counter-rotating quasi-streamwise vortices which serve to pump fluid away from the wall (ejection) and to accumulate low-speed fluid between the legs. Coalescence of the stretched legs of multiple "nested" hairpins is postulated as a mechanism by which low-speed streaks are preserved or redeveloped during the bursting process, leading to observed streak lengths considerably greater than the streamwise extent of any particular hairpin vortex. The streamwise array of vortices which comprises a burst grows outward and may agglomerate into large-scale rotational outer-region bulges.

Although elements of Smith's scenario may be traced to the literature cited above, his model is the most complete in its schematic of vortex structure evolution and its description of the relationship of hairpin vortices to the stages of the bursting process.

Acarlar and Smith (1987a,b) extended the investigation of hairpin vortex dynamics with a pair of papers in which vortices were generated in a laminar boundary layer by shedding from a wall-mounted hemisphere or by rollup on an artificial low-speed streak at the wall (Fig. 12). The results support the concept of three-dimensional vortex formation through the rollup of an unstable shear layer wrapped over the top and/or sides of a low-speed streak. Low-speed regions in the laminar layer were observed to lift, oscillate, and break into small-scale motions during the passage of a hairpin vortex.

Smith and Lu (1988) have applied digital image processing techniques to detect hydrogen-bubble patterns in side-views of a turbulent boundary layer, using pattern-recognition templates obtained from bubble patterns surrounding artificially-generated hairpin vortices in a laminar boundary layer. The resulting distribution of detected hairpin patterns is skewed toward the wall, with a peak in the distribution centered at $y^+ \approx 40$.

Since direct experimental evidence for the existence of horseshoe/hairpin vortices in turbulence has been so limited, Moin and Kim have analyzed their Large-Eddy and direct numerical simulations of turbulent channel flow to locate, identify, and characterize hairpin vortices in the simulated turbulent channel flow.

In the first of two papers, Moin and Kim (1985) analyzed the vorticity field, employing vorticity vector angle histograms, two-point vorticity correlations, and vorticity line tracing in individual flow-fields. A hairpin vortex was defined as "an agglomeration of vortex lines in a compact region (with higher vorticity than the neighboring points) that has a hairpin or horseshoe shape." (A definition of this form can be utilized only by numerical simulation researchers, who have complete access to the three-dimensional vorticity vector field.)

In their results, Moin and Kim showed that for the outer region of the flow, the vorticity vectors tend to be inclined at about 45 degrees to the wall. Two-point velocity and vorticity correlations in the 45 and 135 degree planes provided additional evidence for 45 degree vortical structures. These data described only single, *inclined* vortical structures, with unknown connection to hairpins themselves. To investigate the three-dimensional nature of the vortical structures, instantaneous vorticity lines (everywhere parallel to the vorticity vector) were traced through the flow, and were commonly found in horseshoe shapes, though usually asymmetric (Fig. 13). The horseshoe-shaped vorticity lines appeared to coalesce from deformed vortex sheets, and generally did not exhibit elongated streamwise legs. From these results, Moin and Kim concluded that 45 degree, hairpin-shaped vortices are statistically relevant features of turbulent channel flow structure.

In the follow-on paper, Kim and Moin (1986) applied variants of the VITA and $u'v'$ quadrant-splitting technique to detect turbulence-producing events in the LES channel flow. Although the objective was to isolate the structures associated with the near-wall bursting process, the detection points were placed in the outer regions of the flow ($y^+ = 100, 200, 300$) to avoid triggering by near-wall sweep motions. The resulting conditionally-averaged fields were then visualized by vorticity line tracing. The results exhibited horseshoe-shaped vorticity lines in both the conditionally averaged and selected instantaneous fields. The bunched instantaneous vorticity line structures were interpreted as true vortices (with pronounced circular motion about the axis). Upright horseshoe-shaped vorticity lines were found to be associated with ejection ($(u'v')_2$) motions, while inverted horseshoes were found in conjunction with sweep ($(u'v')_4$) motions. Since the horseshoe vortex structures were detected well away from the wall, it was argued that horseshoe vortices are a result of only vortex stretching, and are thus characteristic of all turbulent shear flows, whether or not there is a wall. (The argument that vortex stretching is a sufficient condition for the generation of horseshoe vortices was also the fundamental premise of Theodorsen's paper). Quasi-streamwise vortices were rarely found in the simulation results, and were generally of limited ($\Delta x^+ < 100$) streamwise extent. The major results of this paper were also confirmed in a new direct simulation without a subgrid model.

In a general review of coherent structures in turbulent flows, Fiedler (1986) included a sketch of hairpin vortices which suggests a phase relationship between the vortex structures and the large-scale motions associated with bulges in the outer interface of the boundary layer (Fig. 14). The figure depicts hairpins with 45 degree heads and nearly horizontal near-wall legs, and shows the hairpins residing on the backs of the outer-flow large-scale motion.

A dramatic example of the advantages of modern digital image-processing techniques as applied to coherent structure research is the work of Utami and Ueno (1987). These authors used successive pictures of particles in $x - z$ cross-sections at several y-values to obtain instantaneous distributions in the $x - z$ plane of the three components of velocity and vorticity, and of various associated spatial statistics. (This work has probably come the closest to producing experimental data approaching the detail provided by direct numerical simulations.) The results were interpreted by the authors with vortical structures in mind, and a horseshoe vortex model with coalesced legs (reminiscent of Smith, 1984) is proposed which exhibits causal relationships to low- and high-speed streaks, ejections and sweeps (quadrant 2 and 4 $u'v'$ motions, respectively), longitudinal vortices, and internal shear layers (Fig. 15).

Adrian (1988) has suggested that the topological distinction between near-wall hairpin vortices and a ring vortex plus two trailing quasi-streamwise vortices may not be necessary (Fig. 16). This proposal (as well as Black's, 1968) provides a conceptual link between hairpin vortices and the vortex ring structures documented by Falco (1983, 1988).

Kasagi (1988) presented a model of the near-wall region which featured alternating streamwise vortices with accumulated regions of low-speed fluid. Included in the paper was a figure illustrating the connections between streamwise vortices in hairpin shapes (Fig. 17).

Robinson et al (1988, 1989) analyzed Spalart's (1988) numerically-simulated boundary layer to educe the character and evolution of three-dimensional vortical structures, as well as their relationships to other coherent motions. Vortices were identified in the simulation by their elongated low-pressure cores. The results showed a strong spatial correspondence between vortical structures and both $(u'v')_2$ and $(u'v')_4$ motions (Fig. 18). Although hairpin-shaped vortices were occasionally sighted, long trailing legs were observed to be rare and fleeting, compared to the relatively common occurrance of long-lived vortical arches without extended legs.

Literature Summary

The existence of vortical elements in turbulent boundary layers is well established. However, experimental and even computational detections of horseshoe/hairpin vortical structures are outnumbered by the theoretical arguments for their existence. Most critically, the role and statistical relevance of vortical structures as a dynamical element of boundary-layer turbulence is mostly hypothesis. Quasi-streamwise vortices are the most thoroughly documented of the vortex elements, but distributions of the diameters, distance from the wall, strength, and population of all types of boundary-layer vortices are scarce.

In some ways, this lack of information may not be surprising, since we are in need of both a general definition and a set of useful detection techniques for vortices. Nevertheless, there is almost universal agreement that some form of vortical structures play a key role in the creation and maintenance of turbulence in boundary layers.

THE USE OF VORTICITY LINES

The use of vorticity lines (often called vortex lines) in numerically-simulated turbulence has proven useful for detecting vortical structures in the simulation databases (e.g. Moin and Kim, 1985; Kim and Moin, 1986). However, vorticity lines can be misleading unless the distinction between vortex and vorticity is maintained. In the literature of coherent vortical motions, this distinction has not always been made clear. Therefore, as a reminder, this section briefly outlines the causes and implications of horseshoe-shaped vorticity lines in turbulent shear flows. A more thorough discussion of the use of vorticity lines is included in Moin and Kim (1985).

A vorticity line is defined as a line everywhere parallel to the instantaneous vorticity vector, and its location in space is defined by

$$\frac{d\vec{x}}{ds} = \frac{\vec{\omega}}{|\vec{\omega}|} \qquad (1)$$

where $\vec{x}$ is the position vector of the vorticity line, s is the distance measured along the vorticity line, and $\vec{\omega}(\vec{x})$ is the vorticity field. In the absence of viscous diffusion, vorticity lines cannot end within the flow, and must travel with the fluid particles.

In a shear flow, it is a kinematical necessity that upright, downstream-leaning, loop-shaped vorticity lines surround a region of fluid which is lifted upwards from the lower speed region into the higher speed flow. If we consider outward movement of a low-speed fluid parcel of limited spanwise extent (like a $(u'v')_2$ ejection), and ignore viscous diffusion effects, initially spanwise vorticity lines will be lifted outward in the region of the upward-moving fluid, and carried downstream by the higher speed flow above. The result is a sloping upright loop in the vorticity lines, without the existence of a vortex. This is illustrated in Figure 19, in which a vorticity line has been integrated through a localized region of lifting, low-speed $(+v', -u')$ fluid within an otherwise two-dimensional, linear shear flow. Similar arguments describe the formation of inverted, upstream-leaning vorticity-line loops for parcels of high-speed, wallward-moving fluid (sweeps).

Vortices consist of "bundles" of vorticity lines, with rotational motion about the bundle axis, so single vorticity lines cannot be construed as vortices. Thus, arrays of "horseshoe"-shaped vorticity lines must always accompany ejections and sweeps, but the association of vortices with these motions is not necessary from a kinematic point of view. To carry the point a bit further, any shear flow with a mean Reynolds shear stress (and hence $(u'v')_2$ and $(u'v')_4$ motions) must possess horseshoe-shaped vorticity lines, whether or not vortices are present.

When vorticity lines are traced in the vicinity of true vortices, the results can be surprisingly misleading. Consider, for example, a streamwise vortex in a shear flow (a common occurrence in the near-wall region of turbulent boundary layers). Unless the starting point for the integration of equation (1) is chosen almost precisely within the vortex core, the vorticity lines will trace out well-defined upright hairpins on the outward-rotating side of the streamwise vortex, and inverted hairpins on the wallward-rotating side. This is demonstrated in Figure 20, which is schematic drawing of vorticity lines computed by the author on both sides of a near-wall quasi-streamwise vortex found in Spalart's (1988) numerically-simulated boundary layer.

These points are not made to denigrate the method of vorticity line tracing, but to raise a warning that horseshoe or hairpin-shaped vorticity lines are vastly more common than similarly shaped vortices. This is a crucial dynamic issue, since isolated vorticity lines play a different role than true vortices with regard to induced motions and propagation of pressure disturbances.

Other than direct observation of rotational motions, no vortex detection technique has yet been found that is free of ambiguities of interpretation. For instance, the static pressure field available in the numerical simulations has been found to be useful for identifying the low-pressure cores of vortices (Robinson et al. 1989). Most low-pressure regions in the simulated boundary layer are observed to be elongated, and every elongated low-pressure region checked so far has corresponded to a vortex, under the definition set forth earlier in this paper. However, non-elongated low-pressure regions in the simulation apparently are not vortices, and are created through other types of local motions. Unambiguous vortex detection awaits improved experimental and computational detection methods as well as a more widely accepted definition of a vortex.

VORTICES IN THE NUMERICALLY-SIMULATED BOUNDARY LAYER

As part of a larger-scale research project, Spalart's (1988) direct Navier-Stokes simulation of a flat-plate, zero pressure gradient boundary layer has been analyzed extensively to clarify the kinematics of all detectable forms of coherent motions (Robinson et al, 1988, 1989; Robinson, 1989). In this section, new statistical results concerning the size, locations, and strength of vortices in the numerical boundary layer are presented.

The results presented here are for a momentum thickness Reynolds number of approximately 670. This is very low, so the results are directly indicative of the character of a very low Reynolds number boundary layer only, with unknown extensibility to higher Reynolds numbers.

Spalart's spectral code has been used to compute and save 104 time-steps ($\Delta t^+ = 3$) beyond the initial 1200 timesteps required to achieve statistical equilibrium. These 104 time-steps represent nearly 54 gigabytes of turbulence information, and comprise the database utilized for all of the analyses in the project. Each time-step is computed on a 384 x 288 x 85 grid, comprising 9.4 million nodes. At each node, for each time-step, pressure and all three components of velocity (and thus vorticity) are available. Grid resolution is is 12.8 viscous lengths in the streamwise (x) direction, and 4.3 viscous lengths in the spanwise (z) direction. Resolution in the wall-normal (y) direction varies from 0.03 to 16.0 viscous lengths, with 14 grid points between the wall and $y^+ = 10$. The grid spacing for the $Re_\theta = 670$ case gives a computational domain with streamwise, spanwise, and wall-normal dimensions of 4900, 2500, and 1100 viscous units, respectively. The boundary layer is approximately 300 viscous units thick at this Reynolds number. Further details concerning the computational method and the results are included in Spalart (1988). (The simulation used for the present study has been computed with a finer grid than the results reported in Spalart, 1988.)

In accordance with the working definition of a vortex stated above, vortices in the end-view ($y - z$) and side-view ($x - y$) planes have been identified by plots of instantaneous streamlines or vectors. For quasi-streamwise vortices, streamlines were plotted in 25 $y - z$ planes with dimensions $\Delta z^+ = 418$ by $\Delta y^+ = 250$. For spanwise vortices instantaneous vectors constructed with the fluctuating velocity (u', v') components were found to display all vortices identifiable from any moving reference frame. (This suggests that transverse vortices travel downstream at velocities not too different from the local mean velocity.) Dimensions of the 15 $x - y$-plane views used for the transverse vortex counting were $\Delta x^+ = 845$ by $\Delta y^+ = 250$. All data-planes were chosen at widely different and unrelated spatial and/or temporal locations in the simulation database. Examples of the $y - z$ and $x - y$ planes are given in Figure 21, in which vortices are clearly visible in the streamlines, but less obvious in the vectors.

For each vortex visually identified in the plots, the diameter, distance from the wall, core area, and approximate circulation was recorded. For the streamlines in the end-view planes, the diameter was estimated by measuring the extent of the bounding streamline of a group of closed concentric streamlines, and the area was estimated as the area of a circle with that diameter. Transverse vortices were more difficult to identify in the side-view vector plots, although strong (high circulation) vortices with significant perturbation velocities tended to be fairly obvious. For this reason, there may be a bias towards stronger transverse vortices in the data presented below, and this effect is accentuated near the wall. Though tedious, hand-counting of the "visual vortices" was considered preferable to more sophisticated, but less reliable vortex identification methods, at least for a first set of control data.

Quasi-Streamwise Vortex Results

Statistics were computed for a sample of 229 quasi-streamwise vortices identified visually in the simulated boundary layer. Recall that vortices visible in end-plane ($y - z$) views need not be (and usually are not) strictly streamwise but may possess significant spanwise and/or wall-normal components, and are thus referred to as "quasi-streamwise."

The distribution of distances of the vortex centers to the wall is shown in Figure 22. In agreement with experimental results, quasi-streamwise vortices are more commonly found in the wall region, with 72% of the total occurring for $y^+ < 100$. The diameter distribution in Figure 23 shows that 73% of the visual quasi-streamwise vortices have diameters between 10 and 40 viscous lengths, and 90% between 10 and 60 viscous lengths. The average diameter of the quasi-streamwise vortices in the sample is 34 viscous lengths.

The variation of quasi-streamwise vortex diameters with distance from the wall is plotted in Figure 24. Larger vortices generally reside further from the wall, but the data is broadly scattered between the $d^+ = 2y^+$ line and the lower bound of $d^+ \approx 10$.

Since visual identification of vortices cannot easily determine their potential as significant momentum transport "pumps," the circulation of each visual vortex was also computed. Following Pearson and Abernathy (1984), the circulation is described in terms of a vortex Reynolds number defined as

$$R_V \equiv \Gamma/2\pi\nu, \tag{2}$$

where Γ is the circulation computed by integrating the streamwise vorticity ω_x over the vortex area. As a reference value for evaluating the strengths of vortices, the vortex Reynolds number of a δ by δ box in the $x-y$ plane may be computed. For the numerically simulated boundary layer, this reference circulation is

$$R_{V_\delta} = \frac{U_e\delta}{2\pi\nu} \approx 955. \tag{3}$$

Since Γ is computed as an area integral, very large vortices are likely to contain high values of circulation. To estimate the intensity of the vortices, the vortex Reynolds number R_V may be divided by the area of the vortex, non-dimensionalized by viscous units. Using the δ by δ box, a reference intensity for the simulated boundary layer is ≈ 0.011, which may be taken as a mean circulation intensity for the boundary layer.

The vortex Reynolds number and intensity distributions for visually-identified quasi-streamwise vortices are shown in Figures 25 and 26, respectively. The average value of R_V is 22, but the distribution has a long tail toward much higher values. However, the intensity distribution (Figure 26) shows that about 90% of the quasi-streamwise vortices have a higher intensity than the boundary layer reference value of 0.011. The most intense quasi-streamwise vortices have intensity values up to nearly 10 times the reference value, and nearly all of the very intense vortices occur for $y^+ < 75$. Vortices with higher intensities than the average circulation intensity in the boundary layer may be expected to have sufficient strength to induce significant momentum transport through induction.

Spanwise Vortex Results

The sample used for transverse vortex statistics was 85 "visual vortices." From the wall-distance distribution in Figure 27, it is seen that transverse vortices tend to be located outside the near-wall region, with over 80% of the population occurring for $80 < y^+ < 180$, in a boundary layer with $\delta^+ \approx 300$. The broad, outer-region distribution of transverse vortices differs significantly from the near-wall preference of quasi-streamwise vortices (Figure 22).

Transverse vortices also tend to exhibit larger diameters than quasi-streamwise vortices. The distribution in Figure 28 shows 74% of transverse vortex diameters measuring between 30 and 70 viscous lengths, with an average value of 51. The variation of transverse vortex diameter with distance from the wall (Figure 29) exhibits wide scatter, but the data is fit reasonably well by a $d^+ = \kappa y^+$ line, where $\kappa = 0.41$ is the Karman constant. This apparent agreement with the boundary-layer mixing-length distribution is not surprising, and suggests that transverse vortices do indeed play a statistically significant role in determining the average statistics within a turbulent boundary layer.

Since transverse vortices are embedded in a mean velocity gradient, their circulation was computed with the fluctuating component $(\omega_z'(x,y) = \omega(x,y) - \overline{\omega}(y))$ of spanwise vorticity. This approach may be criticized on the grounds that the transverse vortices may themselves be the mean vorticity, but it was desired to compare the circulation intensities between quasi-streamwise and transverse vortices.

The distribution of vortex Reynolds number (Figure 30) shows that transverse vortices tend to have higher circulation values than quasi-streamwise vortices (comparing again to the boundary-layer reference value of 955), which is to be expected given their generally larger diameter. The R_V distribution peaks at about 30 for transverse vortices, and at about 12 for streamwise. About 17% of the transverse vortices were found to have positive values of circulation, i.e. containing lower total circulation than the local mean, which is negative.

The circulation intensity (R_V/A^+) distribution for transverse vortices is plotted in Figure 31. Transverse vortices are significantly less intense than quasi-streamwise vortices, with the peak in the distribution appearing at just above the reference intensity value of 0.011. However, occasional intense transverse vortices do occur and are generally found below $y^+ = 75$, as in the case of quasi-streamwise vortices.

If circulation intensity is assumed to determine the potential of a vortex for producing contributions to $-\overline{u'v'}$, the clustering of high-intensity quasi-streamwise vortices near the wall, and the distribution of low-intensity transverse vortices in the outer flow are consistent with the shape of the turbulence production $(-\overline{u'v'}\frac{\partial \overline{U}}{\partial y})$ profile in a boundary layer. Further statistics of vortices in Spalart's simulated boundary layer may be found in Robinson (1989).

Vortical Structure Results

To identify three-dimensional vortical structures in the numerically-simulated boundary layer, advantage is taken of the fact that the pressure is low within the cores of vortices with significant circulation. When isobaric surfaces of constant low pressure are plotted, elongated tubular structures emerge which exhibit circular streamlines (from a reference frame moving with the low-pressure region) in any cross-section. As mentioned above, not all low-pressure regions are elongated, and those which are not apparently do not correspond to vortices. An example of a subvolume from the simulation database is shown in Figure 18, in which several vortical structures are clearly evident. Figure 18 contains a large, assymetric loop-shaped structure with a single long, trailing leg, as well as a smaller horseshoe-shaped structure with a secondary transverse vortex visible just upstream. Regions of significant $(u'v')_2$ and $(u'v')_4$ are seen to have a close spatial association with the vortical structures in Figure 18 (Robinson et al, 1989).

The low-pressure regions in the simulated boundary layer exhibit a wide variety of shapes and sizes, as seen in the top-view of the computational domain in Figure 32. In this picture, the low-pressure isobaric surfaces corresponding to $p'/\rho u_\tau{}^2 = -4.2$ are plotted in three dimensions in a volume measuring 4900 by 1225 viscous lengths in the streamwise and spanwise directions, respectively. (The subvolume of Figure 18 is in the upper, far-right portion of Figure 32.)

The most striking impression gained from Fig. 32 is the wide variety of shapes of the elongated low-pressure regions. A number of arch-like structures are visible, with spanwise dimensions similar to the height of their heads from the wall. (This was determined through stereo top-views combined with selected side-view slices.) Hairpins with two elongated legs are rare, as are quasi-streamwise vortices longer than 200 viscous lengths; this observation is not dependent upon the pressure value chosen for the contour surfaces. The stereo versions of Figure 32 also confirm that the most common near-wall vortical structure has a mostly streamwise orientation, while most outer-region structures are arches with well-defined transverse elements. Although many arches can be found without trailing legs, it also true that many quasi-streamwise vortices exist without a clear connection to arches. This suggests that although a symmetric hairpin may be a reasonable idealized conceptual model for the vortical structures, predictive modeling might be successfully approached by treating the transverse and streamwise vortex elements separately. This scheme should be sufficient for a kinematic/statistical picture of the flow, but would not be appropriate for a dynamically accurate model.

For vortices with significant circulation, the radial pressure gradient at the edge of the core is relatively strong. As a result, small changes in the pressure contour level used to compute the isobaric surfaces in Fig. 32 do not significantly affect the overall picture of the vortical structures. The most noticeable effect of varying the contour level is to alter the topological connectivity between adjacent low-pressure regions.

CONCLUSIONS

From the brief literature review presented, the following general conclusions may be drawn regarding vortices as coherent motions in turbulent boundary layers:

The major vortex elements (quasi-streamwise "legs," transverse "heads," and "necks") all exist within the boundary layer. However, vortex structures of a wide variety of shapes also apparently exist, and the evidence for the prevalence of particular forms (horseshoes, hairpins, rings, etc.) is not yet conclusive.

The near-wall region ($y^+ < 100$) is dominated by quasi-streamwise vortices with an outward tilt. These vortices appear to be kinematically associated with $(u'v')_2$ and $(u'v')_4$ motions, and are probably related to the near-wall streaky structure, although the specific cause-and-effect relationships for the latter remain unclear. Spanwise and 45-degree vortices are more commonly found in the outer region ($y^+ > 100$). These vortices have a consistent kinematical relation to a large fraction of the Reynolds stress production outside the buffer zone.

Horseshoe/hairpin vortex models and simulations are consistent with many forms of experimental data, but actual evidence of such vortical structures existing in turbulent boundary layers is limited. As a result, much of the kinematic and dynamic behavior of horseshoe/hairpin vortices is postulated or inferred from measurable statistics. For example, the following issues (a partial list) concerning boundary-layer vortical structures may all be considered unresolved from the standpoint of a community consensus:

- Formation: shear-layer instability or vortex stretching alone?
- Growth: self-induction, circulation lift, or wall-normal pressure-gradient?
- Destruction: short or long life? dissipation or destructive instability?
- Regeneration: pairing? secondary rollup? bifurcations?
- Contribution to the gross statistics: rare, significant, or dominant?

The arguments and evidence for the existence of horseshoe/hairpin vortices, at least in the near-wall region, are convincing (e.g. Wallace, 1985). The relationship of such vortices to the "bursting" process is quite unclear, however. Among the vortex-structure interpretations of bursting are:

1) Rollup of a locally unstable shear layer atop a low-speed streak into a vortex (e.g. Kim et al, 1971; Smith, 1984; Blackwelder and Swearingen, 1989)
2) Instability breakdown of lifted fluid between the legs of a hairpin vortex (e.g. Hinze, 1975).
3) Direct induction during passage of a relatively long-lived vortex structure past a measuring or observing station (e.g. Black, 1968; Acarlar and Smith, 1986; Robinson et al, 1989).
4) Indirect influence from the passage of an outer-region transverse vortex (e.g. Nychas et al, 1977; Praturi and Brodkey, 1979).
5) Violent eruption due to local pressure fields generated by near-wall vortical motion (e.g. Walker and Herzog, 1987).

Clearly, a considerable body of work needs to be done before the kinematics, dynamics, statistical contribution, and Reynolds number dependence of vortical structures in turbulent boundary layers is agreed upon. The recent development of direct numerical turbulence simulations should help accelerate the learning pace by suggesting new experimental techniques as well as by providing direct information on low Reynolds-number vortical structures. Cautions are in order for the simulated turbulence too, however, since their spatial resolution is finite and thus may be insufficient to capture all viscous interactions between vortices. For example, the "pinch-off" of a hairpin vortex loop into a ring-shaped vortex is dynamically possible (Falco, 1983; Moin, Leonard, and Kim, 1986), but has not yet been observed in channel-flow (Kim, Moin, Moser, 1987) or boundary layer (Spalart, 1988) simulations. In addition, vorticity-line tracing as well as low-pressure marking in the simulations must be interpreted with care, as discussed in the present paper.

The obvious need is for the development of more robust experimental methods for vortex identification in turbulent flows. For this reason, recent advances in multi-sensor hot-wire anemometry (Antonia et al, 1988), scanning two-component laser-doppler anemometry (Williams and Economou, 1987), particle-displacement imagery (Landreth et al, 1988), and digital image pattern recognition (Corke, 1984; Smith and Lu, 1988) may hold the promise of the most productive era yet in turbulence structure research.

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Categories:
A: Conceptual model (description of physics only)
B: Analytical model (predictive in some sense)
C: Probe data evidence (quantitative)
D: Visual evidence (qualitative)
E: Laminar boundary layer simulation
F: Numerical simulation (LES or DNS)

Table 1: Quasi-Streamwise Vortex References

Authors	Year	Category
Bakewell and Lumley	1967	B,C
Kline et al	1967	D
Kim et al	1971	C,D
Grass	1971	D
Clark and Markland	1971	D
Willmarth and Lu	1972	C
Brown and Thomas	1977	A,C
Kastrinakis et al	1978	C,D
Praturi and Brodkey	1978	D
Kreplin and Eckelmann	1979	C
Blackwelder & Eckelmann	1979	A,C
Nakagawa and Nezu	1981	A,C
Falco	1982	A,D
Falco	1983	A,D
Smith and Schwartz	1983	D
Kim	1983	C,F
Pearson and Abernathy	1984	B
Moin	1984	B,C,F
Moin and Kim	1985	C,F
Herzog	1986	B,C
Jang et al	1986	B
Kasagi et al	1986	B,C,D
Kim and Moin	1986	C,F
Ersoy and Walker	1986	B
Swearingen & Blackwelder	1987	C,D,E
Acarlar and Smith	1987	A,D
Lian	1987	D
Utami and Ueno	1987	C
Moin	1987	C,F
Moin, Adrian, Kim	1987	C,F
Aubrey et al	1988	B,C
Hanratty	1988	B
Kasagi	1988	B,C,D
Guezennec et al	1989	C,F
Robinson et al	1989	D,F

Table 2: Spanwise Vortex References

Authors	Year	Category
Clark and Markland	1971	D
Kim et al	1971	C,D
Nychas et al	1973	D
Praturi and Brodkey	1978	D
Nakagawa and Nezu	1981	A,C
Lian	1987	D
Smith and Lu	1988	C,D
Robinson et al	1988	D,F
Robinson et al	1989	D,F

Table 3: Vortex Structure References

Authors	Year	Category
Theodorsen	1952	A
Willmarth and Tu	1967	A,C
Kline et al	1967	A,C,D
Black	1968	A,B
Hinze	1975	A
Offen and Kline	1975	A
Townsend	1976	A,B
Smith	1978	A,D
Head & Bandyopadhyay	1981	A,D
Wallace	1982	A
Perry and Chong	1982	B
Falco	1982	A,D
Falco	1983	A,C,D
Smith and Metzler	1983	A,C
Smith	1984	A
Wallace	1985	A
Moin and Kim	1985	C,F
Kim and Moin	1986	C,F
Guezennec	1986	A,C
Kobashi and Ichijo	1986	A,C
Fiedler	1986	A
Perry et al	1986	B
Acarlar and Smith	1987	A,C,D,E
Utami and Ueno	1987	A,C
Chu and Falco	1988	A,D,E
Smith and Lu	1988	C,D
Kasagi	1988	A,B,C
Robinson et al	1988	D,F
Robinson et al	1989	D,F

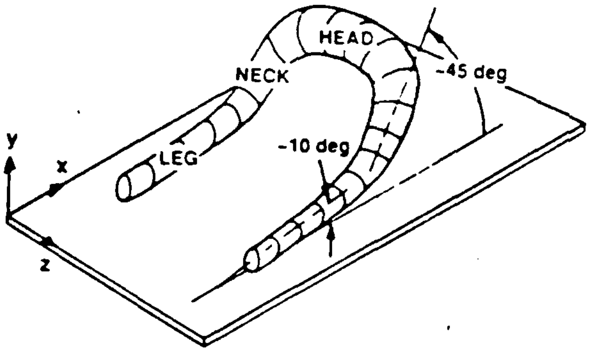

Fig.1. Nomenclature for schematic hairpin vortex.

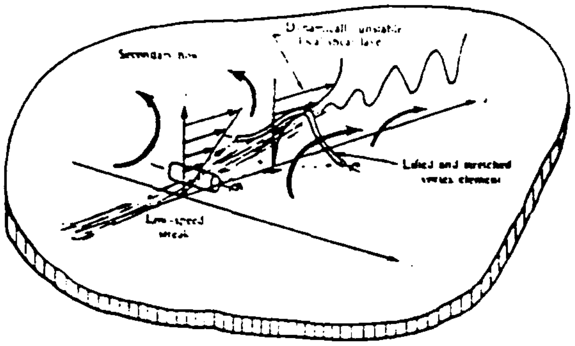

Fig. 4. Kline et al (1967). "The mechanics of streak breakup."

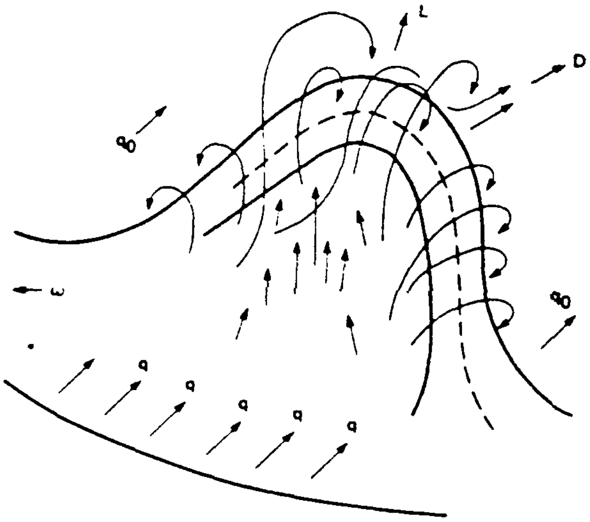

Fig. 2. Theodorsen (1952). "Primary structure of wallbound turbulence."

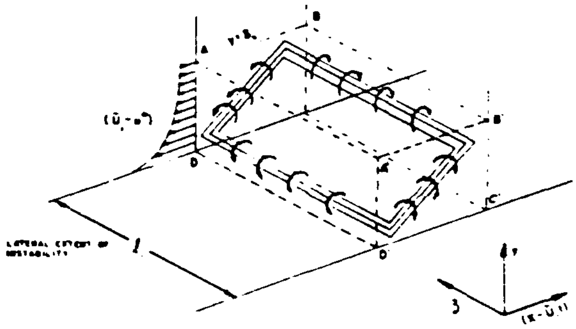

Fig. 5a. Black (1968). "Generation of ring-vortices by instability in actual shear layer."

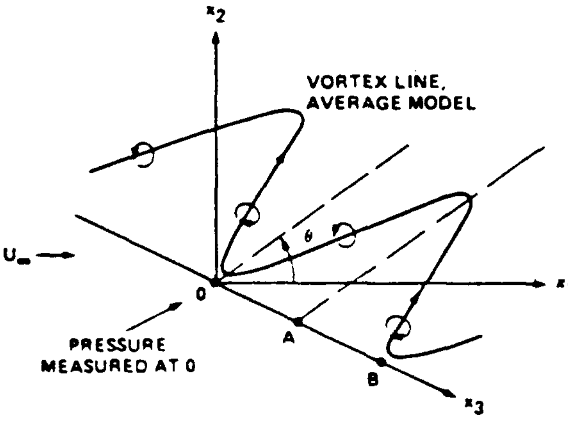

Fig. 3. Willmarth and Tu (1967). "Structure of an average model of vortex line near the wall..."

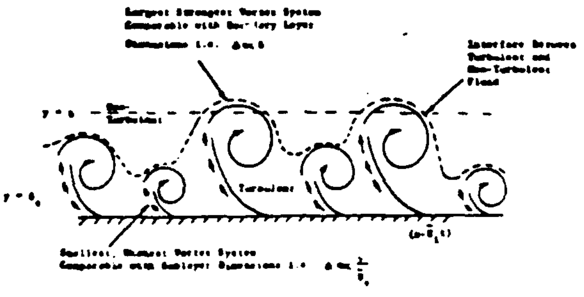

Fig. 5b. Black (1968). "Intermittency explained by random variation in strength of consecutive vortex systems."

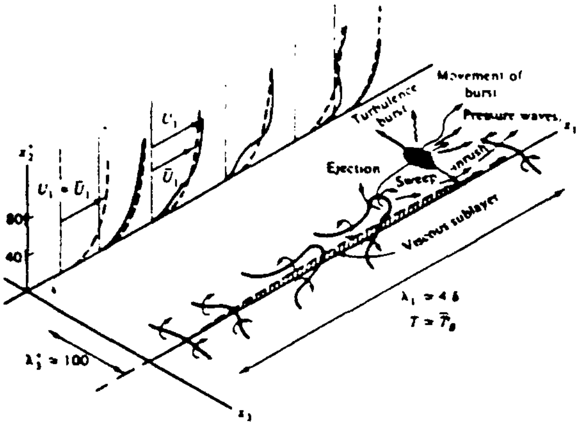

Fig. 6. Hinze (1975). "Conceptual model of the turbulence near the wall during a cyclic process, with average spacings λ_1 and λ_2.

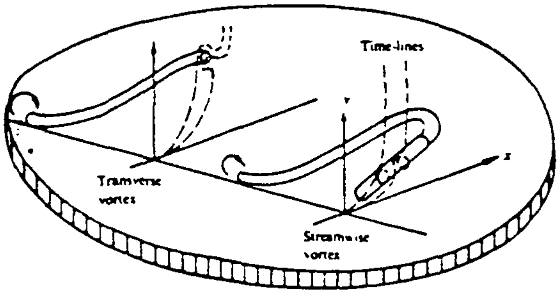

Fig. 7. Offen and Kline (1975). "Time-line patterns at different locations of a lifted and stretched vortex element."

Fig. 8. Head and Bandyopadhyay (1981). "Effect of Reynolds number on features composing an outer region of turbulent boundary layer. (a) *Very* low *Re* (loops); (b) low-moderate *Re* (elongated loops or horseshoes); (c) moderate-high *Re* (elongated hairpins or vortex pairs).

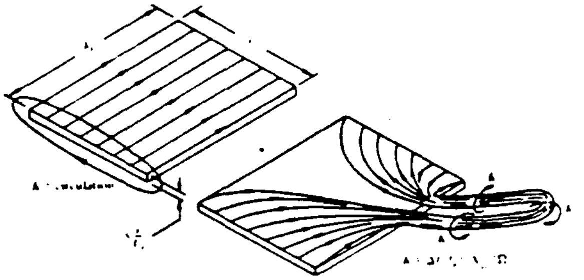

Fig. 9a. Perry and Chong (1982). "Carpet of vorticity being wrapped into vortex (schematic)."

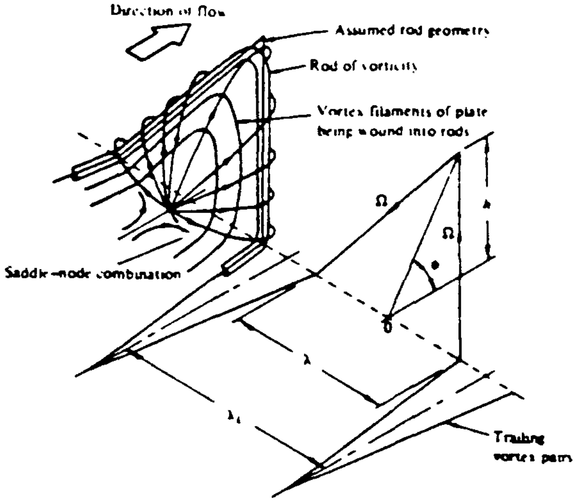

Fig. 9b. Perry and Chong (1982). "Λ-vortex configuration".

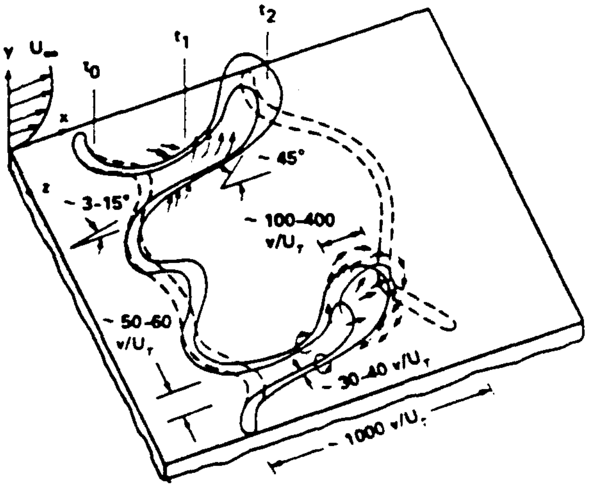

Fig. 10. Wallace (1982, 1985). "Conceptual model of hairpin vortices from warped sheets of vorticity."

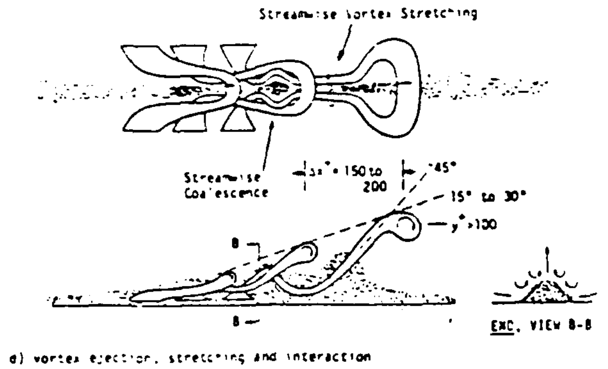

Fig. 11. Smith (1984). "Illustration of the breakdown and formation of hairpin vortices during a streak bursting process. Low-speed streak regions indicated by shading."

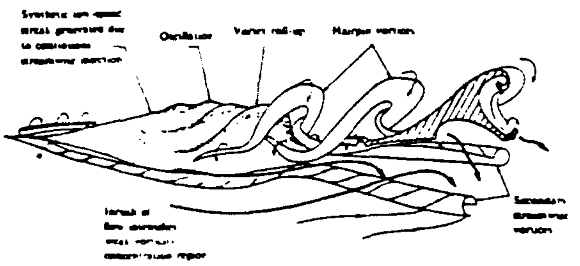

Fig. 12. Acarlar and Smith (1987b). "Schematic of breakup of a synthetic low-speed streak generating hairpin vortices. Secondary streamwise vortical structures are generated owing to inrush of fluid."

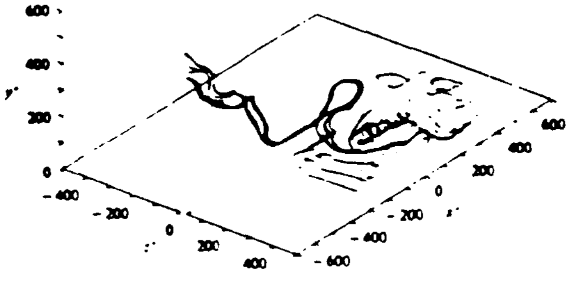

Fig. 13 Kim and Moin (1986). "Vortex lines showing an instantaneous structure detected by QD-2."

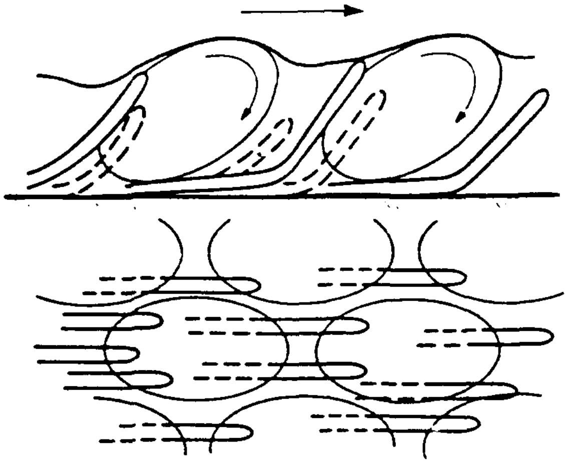

Fig. 14. Fiedler (1986). "Boundary layer structure."

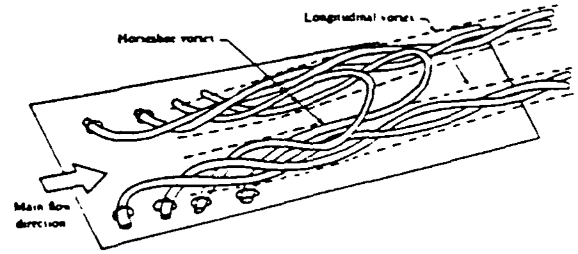

Fig. 15. Utami and Ueno (1987). "Conceptual model representing the overall structure of turbulence in the wall region in the fully developed stage. Solid lines denote vortex tubes."

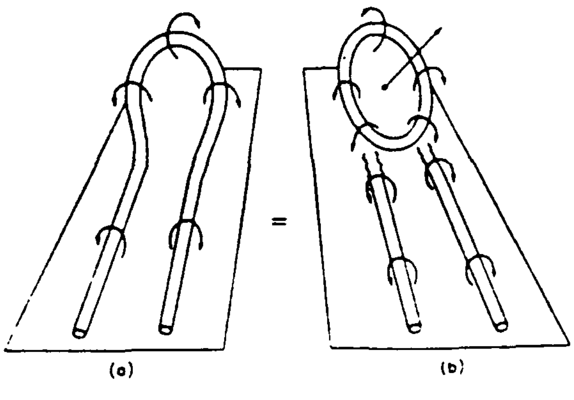

Fig. 16. Adrian (1988). "(a) Hairpin vortex close to the wall, (b) decomposition of a wall hairpin into a vortex ring plus mean shear plus two streamwise vortices."

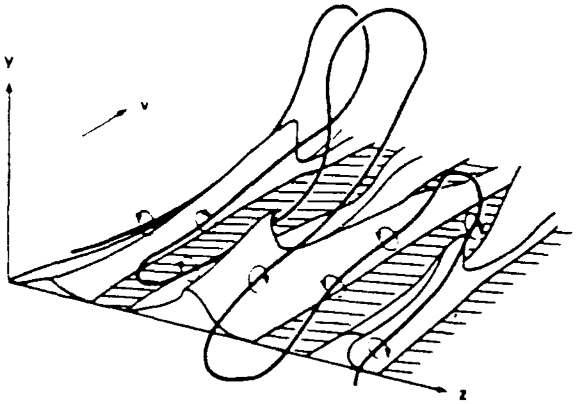

Fig. 17. Kasagi (1988). "Conceptual model of the wall-layer structure."

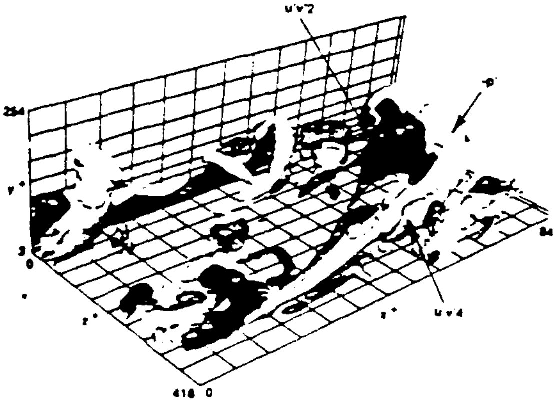

Fig. 18. Robinson et al (1989). "Spatial relationship between elongated low-pressure regions, strong ejections ($u'v'_2$), and strong sweeps ($u'v'_4$)."

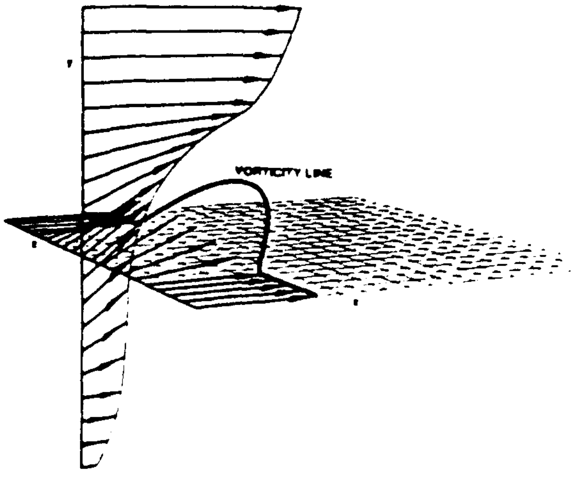

Fig. 19. Vorticity line computed for a localized region of lifting, low-speed ($+v', -u'$) fluid within an otherwise two-dimensional, linear shear flow.

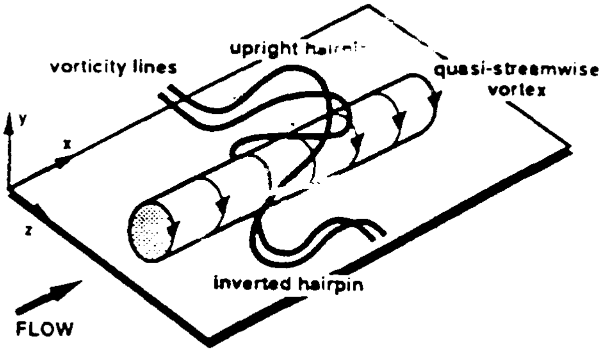

Fig. 20. Vorticity lines traced from either side of a quasi-streamwise vortex in a boundary layer, showing upright and inverted hairpin shapes.

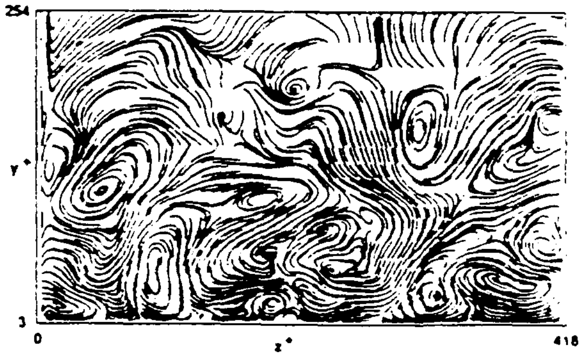

Fig. 21a. Example from Spalart's (1988) numerically simulated boundary layer: instantaneous streamlines in an end-view ($y-z$) plane.

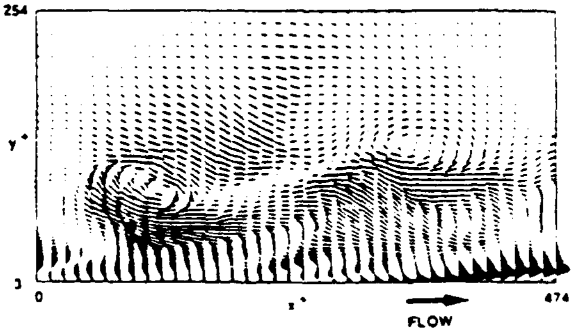

Fig. 21b. Example from Spalart's (1988) numerically simulated boundary layer: instantaneous $u'v'$ perturbation velocity vectors in a side-view ($x-y$) plane.

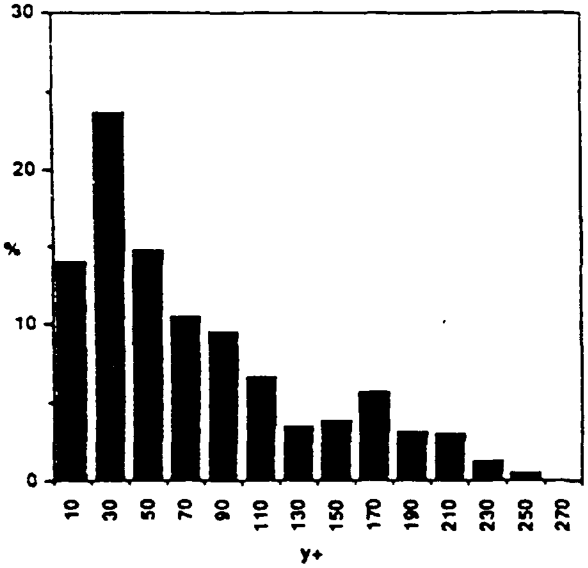

Fig. 22. Distribution of distances from the wall for visually-identified quasi-streamwise vortices.

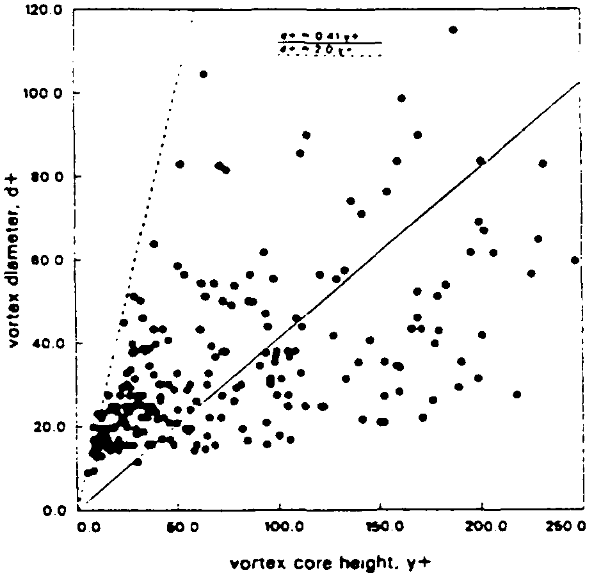

Fig. 24. Variation of vortex diameter with distance from the wall for visually-identified quasi-streamwise vortices.

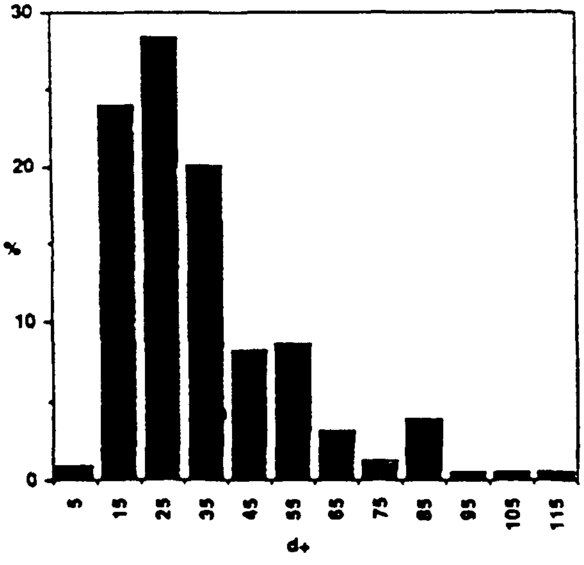

Fig. 23. Distribution of vortex diameters for visually-identified quasi-streamwise vortices.

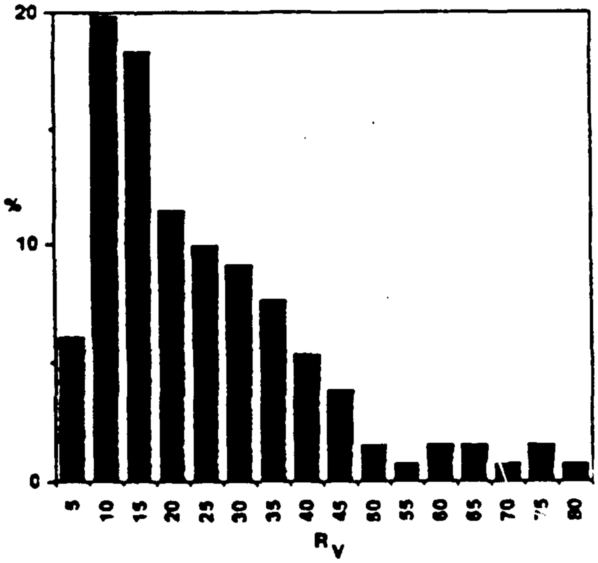

Fig. 25. Distribution of vortex Reynolds number R_V (circulation) for visually-identified quasi-streamwise vortices.

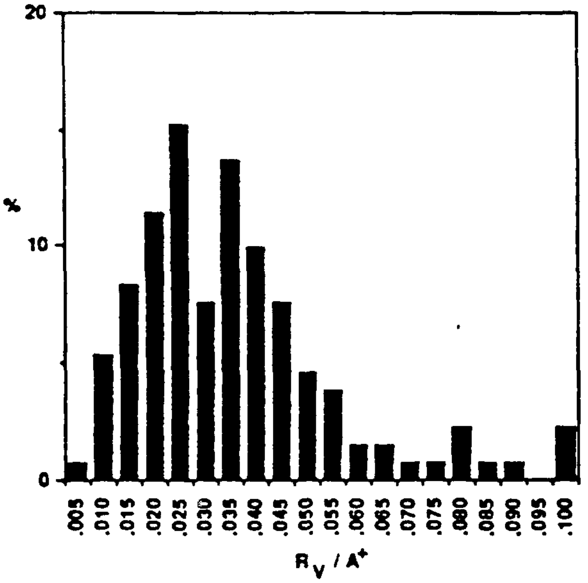

Fig. 26. Distribution of vortex intensity (R_V/A^+) for visually-identified **quasi-streamwise vortices.**

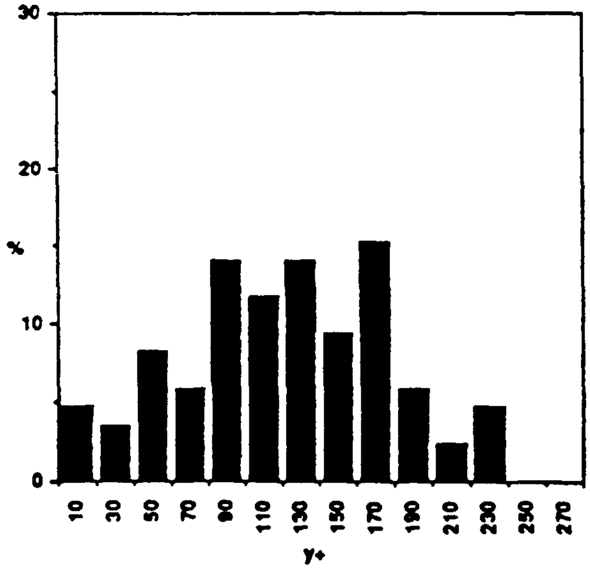

Fig. 27. Distribution of distances from the wall for visually-identified **transverse vortices.**

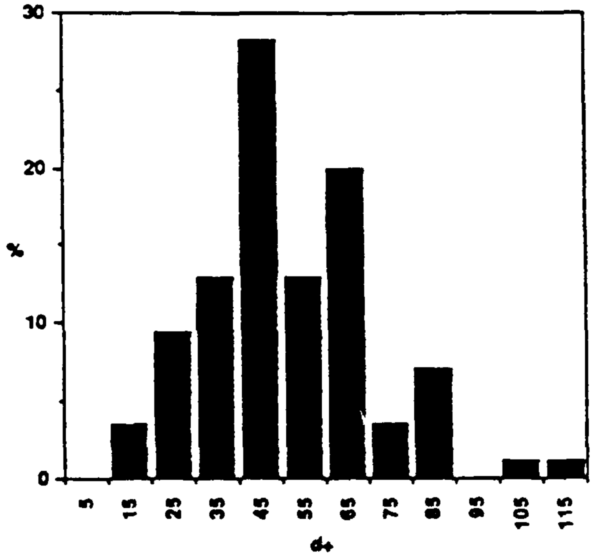

Fig. 28. Distribution of vortex diameters for visually-identified **transverse vortices.**

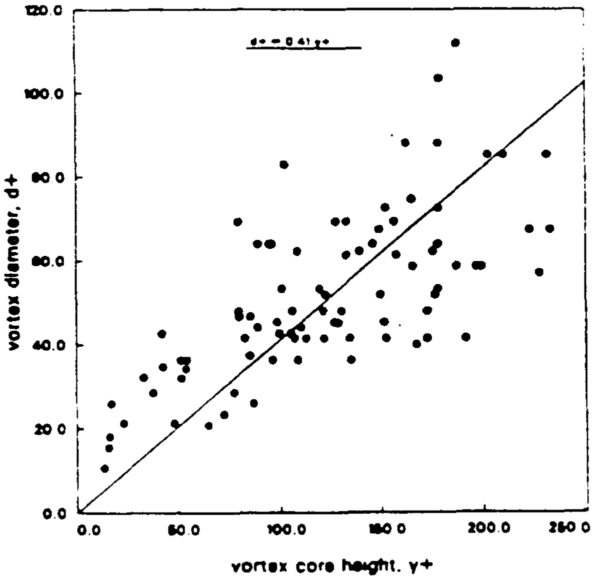

Fig. 29. Variation of vortex diameter with distance from the wall for visually-identified **transverse vortices.**

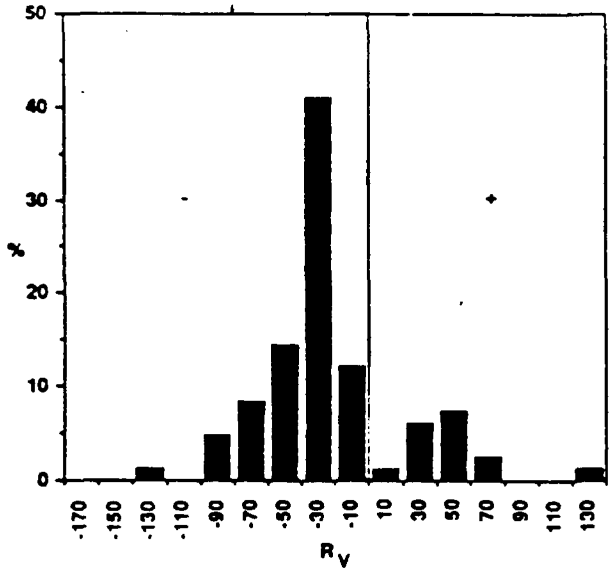

Fig. 30. Distribution of vortex Reynolds number R_V (circulation) for visually-identified transverse vortices.

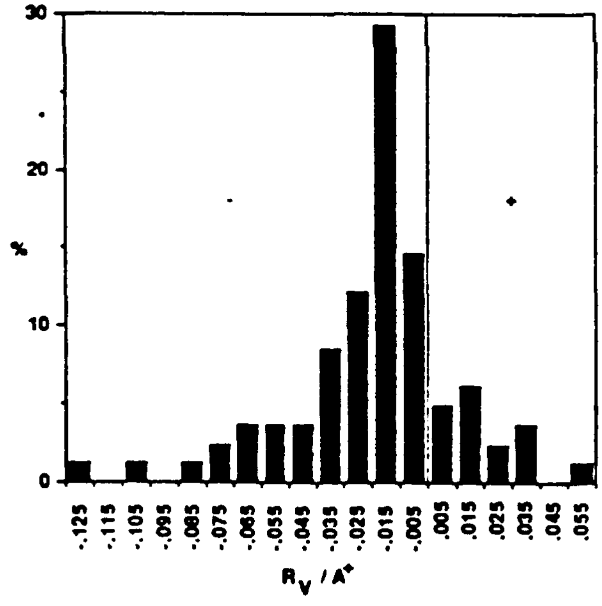

Fig. 31. Distribution of vortex intensity (R_V/A^+) for visually-identified **transverse vortices.**

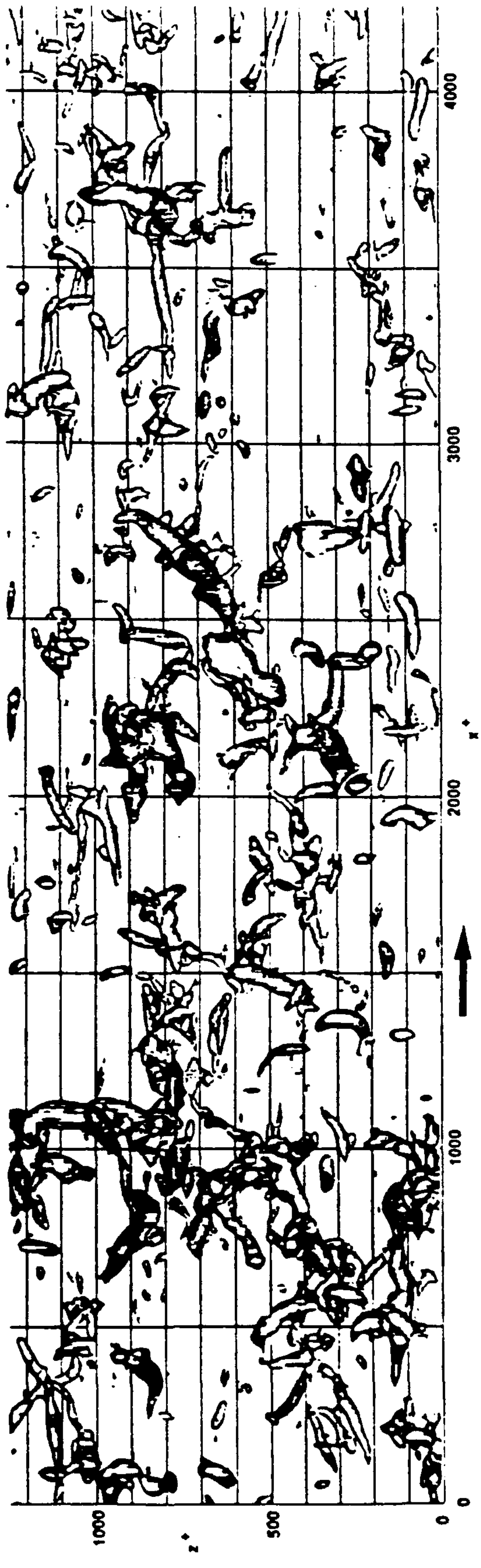

Fig. 32. Top-view of instantaneous three dimensional low-pressure structures in numerically-simulated turbulent boundary layer. Isobaric surfaces computed for $p' = -4.2\rho u_\tau^2$.