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COHERENT MOTIONS IN THE TURBULENT BOUNDARY LAYER[1]

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1. INTRODUCTION

1.1 *Background*

In a turbulent boundary layer, kinetic energy from the free-stream flow is converted into turbulent fluctuations and then dissipated into internal energy by viscous action. This process is continual, such that the turbulent boundary layer is self-sustaining in the absence of strong stabilizing effects.

For as long as these facts have been known, fluid dynamicists have sought to understand just how boundary-layer turbulence is generated at the expense of the mean motion, and just how it is dissipated. These are the objectives of studying the internal "structure" of turbulence. Since boundary-layer flows are the technical driver for so many engineering applications, immense human and financial resources have been brought to bear on the problem over many decades of study. The progress made, however, has not been commensurate with the effort expended, reflecting the fundamental complexity of turbulence phenomena.

Most statistical descriptions and models of boundary-layer turbulence ignore the known presence of quasi-periodic repeating patterns of coherent motion in the flow. Since it is apparently these coherent motions that are actually responsible for the maintenance (production and dissipation) of turbulence in a boundary layer, the study of turbulence structure is of fundamental importance to the understanding of boundary-layer dynamics. This review briefly surveys the history, the major issues, and the current state of the knowledge concerning coherent motions in the turbulent boundary layer.

The vast majority of turbulence-structure knowledge has resulted from investigations of low-Reynolds-number ($Re_\theta < 5000$) boundary layers, where the range of turbulence length scales is limited, but where effective flow visualization, fine-scale experimental probing, and direct numerical simulations are all possible. Accordingly, this review focuses on low-Reynolds-number flows, and the reader is referred to Head & Bandyopadhyay (1981), Murlis et al (1982), Blackwelder & Haritonidis (1983), Alfredsson & Johansson (1984), Willmarth & Sharma (1984), Kim & Spalart (1987), Luchik & Tiederman (1987), Wark (1988), Antonia et al (1989), and Shah & Antonia (1989) for discussions on the important issue of Reynolds-number effects (and the associated questions of scaling laws for coherent motions).

To maintain the general nature of the review, the emphasis here is on descriptions of physical processes rather than on tabulation of numerical values of sizes and frequencies. Since the literature on the subject is extensive, the scope of this review is limited to the simplest and most-studied case: that of the flat-plate turbulent boundary layer in the absence of streamwise pressure gradient.

To the detriment of the field, no generally accepted definition of "coherent motion" for turbulent flows has emerged. For the present paper, a coherent motion is defined as *a three-dimensional region of the flow over which at least one fundamental flow variable (velocity component, density, temperature, etc.) exhibits significant correlation with itself or with another variable over a range of space and/or time that is significantly larger than the smallest local scales of the flow.* A number of different definitions for "coherent motion" or "coherent structure" are available in the literature (e.g. Hussain 1986, Fiedler 1986, Blackwelder 1988). For the purposes of this survey, the above definition is preferred (and may indeed be criticized) for its generality. Specific examples of boundary-layer coherent motions are discussed in Section 2.

1.2 *Motivations and Objectives*

Although Reynolds-averaging techniques do not explicitly account for coherent motions in the turbulence, some sort of instantaneous organization is apparent even in the averaged terms. For example, $-\rho\overline{u'v'}$ (the most important "closure" term for the Reynolds-averaged incompressible Navier-Stokes equations) would be zero if boundary-layer turbulent motions were purely random without preferred intercorrelations between velocity components. (Here ρ is the fluid density, and u' and v' are the fluctuating components of the streamwise and wall-normal velocities, respectively.) The fact that the near-wall region is the source for nearly all of the turbulent kinetic-energy production in a boundary layer (Klebanoff 1954) implies particularly organized motions in the sublayer and buffer regions.

The major *motivations* for investigating coherent motions in turbulent boundary layers are (*a*) to aid predictive modeling of the gross statistics of turbulent flows, (*b*) to guide alteration and control of turbulence by mechanical or chemical means, and (*c*) to shed light on the dynamical phenomena responsible for the statistical properties that we traditionally measure and try to predict through modeling.

With these motivations, there are several main categories for the *objectives* of turbulence-structure research: (*a*) spatial and temporal characteristics and dynamical mechanisms related to the near-wall turbulence-production processes; (*b*) spatial and temporal characteristics of large-scale outer-flow motions and their relation to entrainment; (*c*) causal direction and importance of interactions between outer-flow motions and near-wall turbulence production, including questions of inner vs. outer scaling and Reynolds-number effects; and (*d*) relationship between fluctuating variables at the wall (pressure, wall shear, etc) and the passage of coherent motions in the boundary layer.

2. NOMENCLATURE AND FUNDAMENTAL CONCEPTS

2.1 *Nomenclature*

A common nomenclature for the field of turbulence structure has not evolved. In response to this need, a glossary was recently assembled by members of the research community and is the basis of the following conventions. (This glossary is available from the author).

Names, symbols, and terminology related to the Cartesian coordinate system are shown in Figure 1. The terms "up" and "out" are occasionally used to describe the wall-normal, or $+y$, direction. Wall or "plus" units refer to normalization by the viscous length and velocity scales, ν/u_τ and u_τ, respectively. The term "coherent motion" was defined in Section 1.1 and is used interchangeably with "turbulent structure" in this review. The region $y^+ \leq 100$ is usually considered the "wall region"; this includes the sublayer, the buffer region, and at least part of the logarithmic region. The rest of the layer is commonly referred to as the "outer region."

"Vortex" has no rigorous definition for use in turbulent flows, but a useful working definition is proposed in Section 5. The term "quasi-streamwise vortex" is applied to any vortical element with a predominantly

tensor subscript	axis	axis name	view name
1	x	streamwise (axial) (longitudinal)	end
2	y	wall-normal	plan
3	z	spanwise (transverse) (lateral)	side

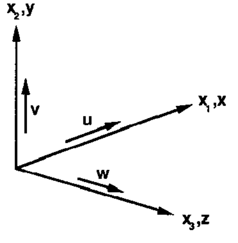


Figure 1 Coordinate system and geometrical terminology.

streamwise (x) orientation, although it may be curved and tilted at a significant angle to the x-axis. "Transverse" and "spanwise" are used interchangeably to refer to vortices (or anything else) with an orientation primarily in the z-direction.

"Sweeps" and "ejections" are defined here as $(u'v')_4$ and $(u'v')_2$ motions, respectively, in accordance with the $u'v'$ quadrant-splitting scheme introduced by Wallace et al (1972) and by Willmarth & Lu (1972) (see Figure 2). There are other interpretations of these terms, especially for sweeps, but the present usage is the most common and has been chosen for its strong association with the Reynolds shear stress.

"Low-speed" and "high-speed" are used as relative terms, referring to perturbations from the mean value at that y-location. These terms are generally used to describe velocities in the streamwise direction, so low-speed implies $-u'$, and high-speed implies $+u'$.

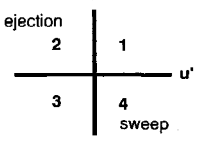


Figure 2 Quadrants of the instantaneous $u'v'$-plane.

The simplest possible turbulent boundary layer is referred to here as the "canonical" case, which describes a flat-plate, smooth-wall boundary layer with a two-dimensional mean flow, in the absence of pressure gradient, large free-stream fluctuations, wall heating, force fields, or compressibility effects. An analogous canonical channel flow is also implied, but with the necessary mean streamwise pressure gradient. This survey restricts itself solely to canonical cases, since the bulk of the research has been performed for such flows.

2.2 *General Description of Coherent Motions in the Turbulent Boundary Layer*

An overview of what is known concerning turbulent boundary-layer coherent motions is appropriate as a preface for surveying the history of the field. Specific and referenced facts are summarized in Section 8.

The streamwise velocity field in the sublayer and buffer regions is organized into alternating narrow streaks of high- and low-speed fluid that are persistent and relatively quiescent most of the time. The majority of the turbulence production in the entire boundary layer occurs in the buffer region during intermittent, violent outward ejections of low-speed fluid and during inrushes of high-speed fluid at a shallow angle toward the wall. This near-wall turbulence-production process is considered to be an intermittent, quasi-cyclic sequence (usually referred to as "bursting"), but there is no consensus as to which observed features of near-wall activity are essential to the continuity of the cycle (see Section 5). A complicating factor is the observation that several of the structural elements apparently arise in more than one way.

In the outer region, three-dimensional bulges on the scale of the boundary-layer thickness form in the turbulent/nonturbulent interface. Deep irrotational valleys occur on the edges of the bulges, through which free-stream fluid is entrained into thc turbulent region. Large, weakly rotational eddies are commonly observed beneath the bulges. Relatively high-speed fluid impacts the upstream sides of these large-scale motions, forming sloping, δ-scale shear layers that are easily detected experimentally.

Although the inner-region production cycle appears to be largely self-sustaining, it is believed that the outer structure has at least a modulating influence on the near-wall events, and that this influence is Reynolds-number dependent. The dynamical relationships between the inner region of intense turbulence production and the larger scale, less active outer layers are poorly understood. As a result, the correct scaling parameters for the near-wall production time and length scales remain controversial.

Embedded tornadolike vortices with a variety of strengths are known to exist in the boundary layer, and they are thought by many to be the central elements in the turbulence-production cycle and also in the transport of momentum between the inner and outer layers. Inclined horseshoes or hairpins are the commonly proposed shapes for the vortex structures. However, three-dimensional vortices are extremely difficult to characterize in the laboratory. Low-Reynolds-number numerical simulations show vortices in the shape of complete loops or horseshoes to be rare, although elements of these vortical structures are common. At this point (1990), the question of vortex geometry in the boundary layer (especially over a significant Reynolds-number range) remains open.

Shear-layer structures are also common in the boundary layer, especially near the wall, and local shear-layer instability arguments are usually invoked to explain the birth of vortices. The details of vortex generation, evolution, interaction, and demise remain under active discussion.

To summarize, the most controversial issues in the field of boundary-layer structure can be grouped as follows:

- Near-wall streak formation
- The bursting process
- Mass and momentum transfer from the inner to the outer layers
- Mass and momentum transfer from the outer to the inner layers
- Reynolds-number effects and appropriate scaling variables for near-wall turbulence-production events
- The existence and role of hairpin/horseshoe/ring vortices

Of these phenomena, the near-wall bursting process of turbulence production (see Section 4.2) has received the most scrutiny. There is now considerable consensus concerning several of the kinematical issues of coherent motions, but the dynamics (including issues of "importance" and relative cause and effect) remains largely unsettled. These points are summarized in Section 8.

2.3 *Taxonomy of Structures*

What is observed in a turbulent boundary layer is strongly dependent upon the tools used to make the observations. As a result, a wide and confusing variety of coherent motions have been reported in the literature. In an attempt to organize this body of knowledge, Kline & Robinson (1989a,b) grouped the various experimentally observed forms of coherent motions into eight classes. This unsorted classification is only one of several possibilities; nevertheless, it provides a useful framework for relating the various structural features.

1. Low-speed streaks in the viscous sublayer

2. Ejections of low-speed fluid outward from the wall, including lifting low-speed streaks
3. Sweeps of high-speed fluid inward toward the wall, including inrushes from the outer region
4. Vortical structures of various forms (Figure 3)
5. Sloping near-wall shear layers, exhibiting local concentrations of spanwise vorticity and $\partial u'/\partial x$
6. Near-wall "pockets," visible in the laboratory as regions swept clean of marked near-wall fluid
7. Large (δ-scale) motions capped by three-dimensional bulges in the outer turbulent/potential interface
8. Shear-layer "backs" of large-scale outer-region motions, consisting of sloping (δ-scale) discontinuities in the streamwise velocity

The characteristics of each of these structural features have been summarized by Kline & Robinson (1989a) and by Robinson (1990). A well-organized collection of known attributes of these structural features has also been compiled by Cantwell (1981).

3. INVESTIGATIVE TECHNIQUES

3.1 *Experimental Techniques*

Flow visualization employing dye, particles, bubbles, and smoke has played a major role in the study of turbulent coherent motions. Flow-

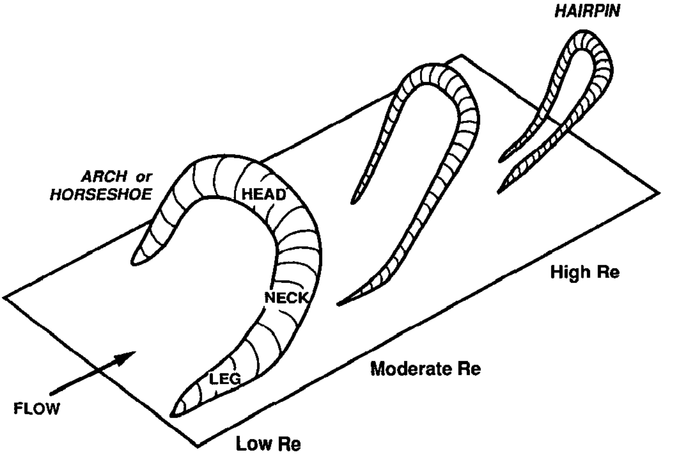


Figure 3 Geometry and nomenclature for arch- and hairpin-shaped vortical structures (after Head & Bandyopadhyay 1981).

visualization methods offer much higher information density than do probes for a given area or volume; these methods, however, are susceptible to varying degrees of embedded history in the marker patterns and are generally limited to low Reynolds numbers, making conclusions drawn from visual studies at least partially ambiguous. Although some flow-visualization techniques can be made quantitative (e.g. image-processing of particle or bubble displacements), this quantification has been successful so far only in two-dimensional planes of turbulent flows.

The most successful probe techniques for characterizing coherent motions have employed multiple sensors separated in space, as suggested by the definition in Section 1.1 Highly resolved temporal sequences are also required for most forms of conditional signal processing. As a result, more advanced single-point instrumentation such as laser-Doppler anemometry (LDA) is rarely used for structure measurements, compared with the widespread use of multisensor hot-wire and hot-film arrays.

The active length of the sensing element is of major concern when probing for compact, near-wall motions; Blackwelder & Haritonidis (1983) suggested a maximum length of 20 viscous length units for hot wires. This physical constraint, combined with the requirement of hot-wire length-to-diameter ratios that are greater than 150, has limited nearly all turbulence-structure experiments to low Reynolds numbers ($Re_\theta < 5000$) and low Mach numbers. The few data available for high-Reynolds-number supersonic flows concern only the large-scale boundary-layer structures (Robinson 1986, Spina & Smits 1987, Smith & Smits 1988).

3.2 *Statistical-Analysis Techniques*

A rich variety of statistical-analysis tools has emerged from the study of turbulent coherent motions, ranging from the simple turbulent/nonturbulent discriminator circuits of Corrsin & Kistler (1954) to stochastic estimations of multipoint conditional averages in numerical channel flow (Adrian 1989). These techniques are used to detect and characterize the four-dimensional (space plus time) structure of organized turbulent motions and to quantify the contributions of the structures to the gross statistical properties of the flow.

A number of conditional-sampling techniques have evolved to educe turbulence events with certain predefined characteristics. Among the most popular are the variable-interval time average (VITA) method (Gupta et al 1971, Blackwelder & Kaplan 1976), the $u'v'$ quadrant method (Figure 2; Wallace et al 1972, Willmarth & Lu 1972), and the u-level method (Lu & Willmarth 1973). Since each sampling criterion extracts a different feature of the flow, some confusion has arisen from comparisons between the results from different techniques. Also, it has proven difficult to relate probe-detected flow events to visually identified turbulence structures. For example, the VITA technique has often been applied to the u' signal as a "burst" detector; however, VITA actually triggers on the passage of shear layers, which are known to have a nonunique phase relationship with turbulence-producing motions. Recently, Bogard & Tiederman (1986) provided a welcome comparison of several event-detection criteria with simultaneous flow visualization. Additional key aspects of conditional-sampling methods for turbulence structures are reviewed by Antonia (1981), Subramanian et al (1982), Alfredsson & Johansson (1984), Luchik & Tiederman (1987), and Morrison et al (1989).

More sophisticated statistical techniques employed to educe the structure of organized turbulence motions include proper orthogonal decomposition (Bakewell & Lumley 1967, Herzog 1986, Moin & Moser 1989) and stochastic estimation of the single-point (Moin et al 1987) and two-point correlation tensors (Adrian et al 1987). These tools have been especially valuable in characterizing the streamwise-vortical nature of the near-wall Reynolds-stress-producing events.

3.3 *Numerical Simulations*

Computer simulation of wall-bounded turbulent flows has been underway for 20 years, and the cumulative results from the relatively few numerical investigations has created a modern renaissance in turbulence knowledge. Two approaches to turbulent simulation have been utilized in the investigation of turbulent structure: large-eddy simulation and direct simulation.

In large-eddy simulation (LES), the smallest scales of the flow are modeled, while the remaining scales are computed directly with the three-dimensional, time-dependent Navier-Stokes equations, which are averaged over the small scales (Rogallo & Moin 1984). This approach is based upon the observation that the small scales in turbulent flows are nearly universal, whereas the turbulent behavior at larger scales is a strong function of the flow geometry and gross flow parameters. Direct numerical simulation (DNS) dispenses with the subgrid-scale model at the expense of greatly increased computational cost in order to accurately resolve the turbulent motions at *all* relevant scales. Quantitative turbulence-structure investigations require DNS simulations because of the inadequate spatial resolution of near-wall features by LES methods.

Direct numerical simulations of turbulence are extremely demanding of computational resources (Reynolds 1990) and are thus currently limited to low-Reynolds-number flows with simple geometries, such as channel flows (Kim et al 1987, Lyons et al 1989) and boundary layers (Spalart 1988). Most DNS computations have utilized the accuracy and efficiency of spectral methods, but these require periodic boundary conditions on the computational domain, which severely restrict flow geometries. Research on high-order finite-difference techniques for DNS is now under way (Rai & Moin 1989) in order to enable simulation of flows with more complex geometries, such as steps and expansions.

4. HISTORY

The literature on turbulent boundary-layer structure is much too extensive to review here, but a detailed bibliography and history of the field is available from the author (Robinson & Chacin 1990). In addition, a number of previous review papers (e.g. Kovasznay 1970, Willmarth 1975a, Laufer 1975, Hinze 1975, Saffman 1978, Cantwell 1981, Fiedler 1986, Blackwelder 1988) have summarized the characteristics and statistics of the various structural features. The following subsections briefly outline the historical progress of the field, with a summary of the current state of the knowledge given in Section 8.

4.1 *Four Eras of Turbulent Boundary-Layer Structure Research*

Over the years, the study of turbulent boundary-layer coherent motions has progressed along several intricately connected paths. To help organize the literature, it is useful and appropriate to divide the history of the field into four eras (1932–59, 1960–71, 1972–79, 1980–present). Each era has been referred to here according to an appropriate enabling technology or focus.

THE DISCOVERY ERA (1932–59) The realization that turbulent boundary layers were populated with repeating, coherent motions that significantly affect the classical statistics came only gradually as nonrandom phenomena were discovered in both the outer and near-wall regions. During this first era, ground-breaking investigations were performed on (*a*) intermittency in the turbulent/potential interface at the edge of turbulent flows (Corrsin 1943, Corrsin & Kistler 1954); (*b*) the large-eddy motions in the outer regions of the boundary layer (Townsend 1956, Favre et al 1957, Grant 1958); and (*c*) coherent features in the near-wall region, including the sublayer streaky structure and violent ejections of near-wall fluid (Einstein & Li 1956, Kline & Runstadler 1959). Flow visualization, two-point space-time correlations, and rudimentary conditional-sampling schemes were employed to analyze experimental flows. Many findings during this period were counter to the "common wisdom" of the times, such as the presence of continual three-dimensional and unsteady motions in the supposedly laminar viscous sublayer.

THE FLOW-VISUALIZATION ERA (1960–71) The discovery of coherent motions in the turbulent boundary layer ignited considerable controversy over their dynamical and statistical relevance, prompting researchers to attempt to quantify the characteristics and contributions of the coherent motions. The dominant experimental technique during this period was flow visualization, often combined with quantitative probe anemometry. The major focus was the buffer region, where turbulence production is maximized, and the viscous sublayer, with its streaky and peculiarly nonlaminar nature. Extensive experimentation was conducted at Stanford (Runstadler et al 1963, Kline et al 1967, Kim et al 1971, Offen & Kline 1974, 1975) and at Ohio State (Corino & Brodkey 1969), with important contributions by Grass (1971) and Clark & Markland (1971). Outer-flow structures were characterized by Kovasznay et al (1970), and wall-pressure studies were conducted by Willmarth & Woolridge (1962). The work performed during this period confirmed that coherent motions do indeed play critical roles in the production of new turbulence near the wall, in the transport of momentum across the mean velocity gradient in both directions, and in the growth of the boundary layer through entrainment.

THE CONDITIONAL-SAMPLING ERA (1972–79) The availability in the early 1970s of inexpensive digital laboratory computers completely changed the nature of turbulence-structure research. The year 1972 is chosen for the beginning of this era because, although analog techniques still prevailed, it was then that quadrant splitting of the $u'v'$ signal came into use (Wallace et al 1972, Willmarth & Lu 1972), triggering a community-wide concentration on conditional-sampling methods.

Much of the conditional-sampling work during this period was fueled by controversy over the unknown scaling parameters for the frequency of "bursts" detected by a stationary probe. This question was in turn motivated by the unresolved issue of whether near-wall events dominated a self-regenerative cycle of near-wall turbulence generation, or if the production processes were instead triggered by the passage of outer-flow motions. This appears to be a Reynolds-number-dependent issue, and the lack of detailed results at even moderate Reynolds numbers, and the uncertainty in detection methods have prevented satisfactory closure of this scaling question even today.

THE COMPUTER-SIMULATION ERA (1980–PRESENT) Although large-eddy simulations (LES) had been available throughout the 1970s, it wasn't until almost 1980 that numerically simulated turbulence began to be probed in depth for answers to the questions that had eluded the experimentalists for several decades (Grotzbach & Schumann 1979, Kim & Moin 1979). As structural features of the three-dimensional pressure, vorticity, and velocity fields emerged from the numerical data bases, the experimental community found its focus shifting away from ad hoc digital conditional-sampling schemes to pursuit of deeper physical understanding of the three-dimensional coherent motions. Today, the simulations function as both complement and competition to experiments, and they are propelling the laboratory community beyond the low-Reynolds-number flat-plate boundary layer.

4.2 *Definitions of "Bursting"*

"Bursting" is the term popularly used since the work of Runstadler et al (1963) to refer to the production of turbulence in the boundary layer via violent outward eruptions of near-wall fluid. This concept is commonly invoked in the literature of turbulence physics, but the definition and usage of the term "bursting" have long been a source of confusion and miscommunication. The meaning of the term has evolved over the years, but in an accumulative sense, such that several meanings are now ascribed to "bursting," without universal agreement as to the proper one. A partial history of the usage is as follows:

- Violent breakup of a low-speed streak after lifting (Runstadler et al 1963, Kline et al 1967)
- Three-stage process of low-speed streak lift-up, oscillation, and breakup (Kim et al 1971, Blackwelder 1989)
- Shear-layer interface sandwiched between an upstream, high-speed "sweep" and a downstream, low-speed "ejection" (numerous authors, early 1970s–present)
- Occurrence of a single-point event found by a specified detection criterion, usually VITA or quadrant splitting (numerous authors, mid-1970s–present)
- One or more $(u'v')_2$ ejections emanating from a single low-speed streak (Bogard & Tiederman 1986, Talmon et al 1986)

In addition to these definitions of bursting, there are many hypothesized *causes* of the bursting process, most of which involve a vortical structure of some type (see Robinson 1989). The nonunique meanings associated with the term have prompted Kline & Robinson (1989a) to exclude "bursting" from the taxonomy of Section 2.2 in favor of more tightly defined structural elements of the turbulence-production processes.

Most definitions of the bursting process describe a highly intermittent, explosive event, which is an intuitively satisfying concept for the production of turbulent motion. However, a significantly different picture has emerged from recent experimental and numerical investigations. In this alternate scenario, the manner in which turbulence is produced in the near-wall region is not actually "burst"-like and appears to be much more intermittent in space than in time. In other words, turbulence-production regions (ejections and sweeps) in the buffer layer appear spotty in the instantaneous x-z plane but persist for significant temporal durations. The passage of such a production region past a stationary probe or aggregation of fluid marker would produce sudden velocity excursions at the measurement station over a limited time without making clear the passage of an associated vortical structure.

Results from direct numerical simulations of turbulence show clearly that the low-Reynolds-number near-wall turbulence process is dominated by tilted quasi-streamwise vortices. Thus, in several recent papers (Kim 1987b, Guezennec et al 1989, Robinson 1990), the bursting process as seen from a stationary location is interpreted as the passage of a relatively long-lived, single, quasi-streamwise vortex, which ejects low-speed fluid away from the wall by vortex induction. Near-wall arches and transverse vortices also generate strong ejection motions but are outnumbered by quasi-streamwise vortices in the buffer region, where the bursting process is observed to originate.

There is so far little quantitative evidence to support this alternative view of bursting, although descriptive reference to vortex passage has been made by Black (1968), Clark & Markland (1971), Kim et al (1971), Acarlar & Smith (1987), and others. Explicit experimental agreement has been provided by Nakagawa & Nezu (1981), who state in their conclusions that "the bursting motion is a kind of large-scale eddy structure, and its coherent structure is fairly inclined downstream toward the wall. It is convected downstream with a longer lifetime than the bursting passing-period. . . ."

In summary, there are currently two general concepts in use for the term "bursting": (*a*) a violent, temporally intermittent eruption of fluid away from the wall, in which a form of local instability is often implied; (*b*) a localized ejection of fluid from the wall, caused by the passage of one or more tilted, quasi-streamwise vortices, which persist for considerably longer time scales than do the observed ejection motions. Since both concepts usually involve vortical structures, the main differences between them are the degree of temporal intermittency and whether or not an instability is involved.

5. VORTICES AND VORTICAL STRUCTURES

A significant portion of the boundary-layer-structure literature is devoted to detection and characterization of vortical elements and structures. The study of vortices appears to lie at the heart of turbulent boundary-layer-structure research, for several reasons: First, in a boundary layer, any vortex with an orientation other than wall normal has the potential to function as a "pump" that transports mass and momentum across the mean velocity gradient. Second, the concept of a vortex is invaluable as a conceptual shorthand for a complex class of three-dimensional motions. Given the definition presented in Section 1.1, vortices are among the most coherent of turbulent motions and tend to be persistent in the absence of destructive instabilities. Finally, strong vortices function as a source for pressure disturbances by virtue of their low-pressure cores and the high-pressure regions they can induce in the nearby flow.

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. In analyzing Spalart's (1988) numerically simulated boundary layer, Robinson et al (1989) adopted the following working definition: *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. A number of other vortex definitions exist (e.g. Lugt 1979, Blackwelder & Swearingen 1989), and the issue cannot be considered closed.

Three-dimensional vortices are extremely difficult to characterize in the laboratory, and only moderate success has been attained with visual methods (e.g. Smith & Lu 1989) or with vorticity measurements (Foss & Wallace 1989). In numerically simulated turbulence, a wide variety of techniques has been brought to bear, but unambiguous vortex detection remains elusive even here. Among the numerical methods for identifying vortical structures are vorticity lines (Moin & Kim 1985), vorticity magnitudes (Kim 1987a), complex eigenvalues of the deformation-rate tensor (Hunt et al 1988, Chong et al 1990), and elongated regions of low pressure (Robinson et al 1989). None of these methods are based on criteria that are both necessary and sufficient for the presence of a vortex, and the debate over vortex-detection techniques continues in parallel with the debate over the definition of a vortex.

A distinction must be made between vortices and vorticity. Vorticity is a point function, whereas most descriptions of a vortex require coherence over an area or volume in space. Thus, in the turbulent boundary layer, the association between regions of strong vorticity and actual vortices can be rather weak, especially in the near-wall region (Robinson et al 1989). The distinction is especially important in the use of vorticity lines, which are defined as being everywhere parallel to the instantaneous-vorticity vector field. According to the definition above, vortices need not obey the Helmholtz laws for vorticity lines; thus, vortices may end within the flow field and may propagate at speeds other than the local fluid velocity, whereas vorticity lines (in the inviscid limit) can do neither.

When vorticity lines are traced in the vicinity of true vortices, the results can be surprisingly misleading. Consider, for example, a strong 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 the vorticity line 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 wall-ward-rotating side. This is demonstrated in Figure 4, which is a schematic drawing of vorticity lines computed on both sides of a near-wall quasi-streamwise vortex found in Spalart's (1988) numerically simulated boundary layer. Hairpin-shaped vorticity lines are common in any turbulent shear flow, whether or not hairpin-shaped vortices are present.

A number of different shapes and topologies have been proposed for boundary-layer vortices. Quasi-streamwise (outward-tilted) vortices are visible in near-wall end views (e.g. Smith & Schwartz 1983, Kasagi et al 1986), while transverse vortices are visible in convecting and stationary side views of the outer region (Clark & Markland 1971, Kim et al 1971, Nychas et al 1973, Praturi & Brodkey 1978, Smith & Lu 1989). Three-dimensional vortical structures are generally described as loops or rings. A

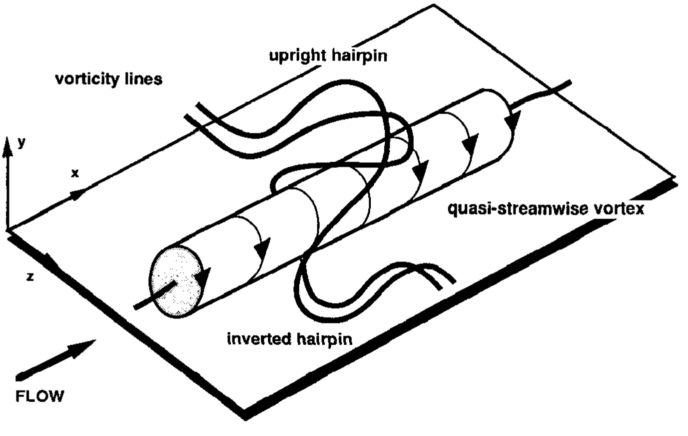


Figure 4 Vorticity lines traced from either side of a quasi-streamwise vortex in a boundary layer, showing upright- and inverted-hairpin shapes.

distinction is commonly made between vortical "arches" or "horseshoes," which are approximately as wide as they are high, and "hairpin" vortices with elongated trailing legs (e.g. Head & Bandyopadhyay 1981; Figure 3). Recent low-Reynolds-number studies suggest that arches or hairpins may be predominantly one sided rather than symmetrical (Moin & Kim 1985, Robinson et al 1989), and that near-wall quasi-streamwise vortices occur singly more often than in side-by-side pairs (Moin 1987, Nishino et al 1988, Guezennec et al 1989). Robinson (1989) has surveyed the accumulated knowledge concerning boundary-layer vortical structures and has provided distributions of size, location, and strength (circulation) for quasi-streamwise and transverse vortex elements identified in Spalart's (1988) numerically simulated boundary layer.

6. CONCEPTUAL MODELS

A conceptual model is an idealized description of the physical processes underlying the observed behavior of turbulent boundary layers; conceptual models are generally distinct from predictive models. Only a few of the many published ideas are represented here. Horseshoe- or hairpin-shaped vortex models are the dominant theme, but variations occur in the applicable domains of the model (near-wall or outer flow), in distinctions between vorticity lines and vortices, and in whether the model is meant to represent an average or instantaneous eddy structure.

Theodorsen (1952) proposed a hairpin vortex model for boundary-layer turbulence production and dissipation that was developed from the vorticity-transport form of the Navier-Stokes equations. In this model, vortical "tornadoes" form astride near-wall regions of low-velocity fluid and grow outward with heads inclined downstream at 45°, and with spanwise dimensions proportional to the distance from the wall (Figure 5). Theodorsen's model was proposed as an instantaneous description of near-wall turbulence dynamics.

Willmarth & Tu (1967) used 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 (Figure 6). The model describes hairpin-shaped vorticity lines sloped downstream at about 10° from the wall, with the dominant element being trailing, nearly streamwise vorticity lines. Although Willmarth & Tu (1967) proposed their model for the near-wall region only, Willmarth & 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 thus providing an outward interaction mechanism between the inner and outer regions.

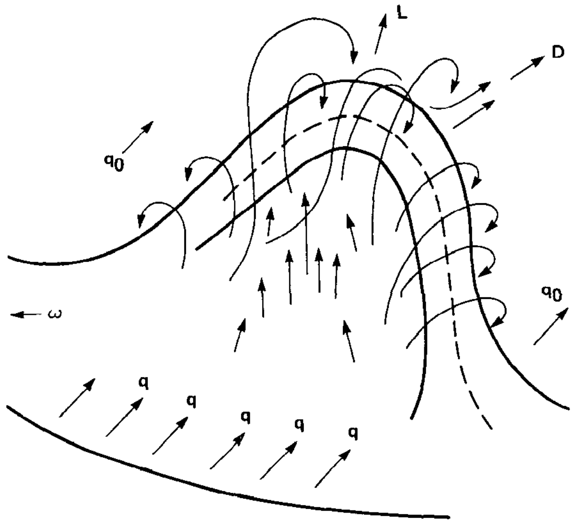


Figure 5 Primary structure of wall-bound turbulence (from Theodorsen 1952).

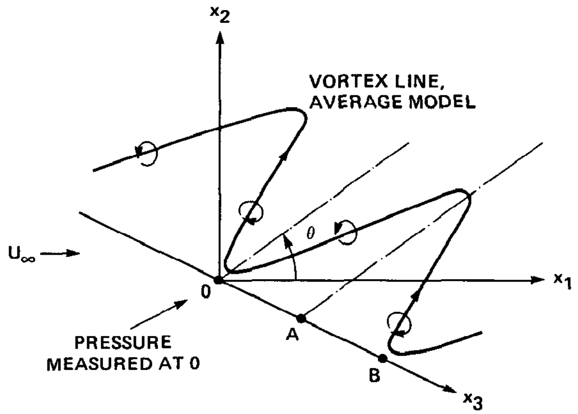


Figure 6 Structure of an average model of a vortex line near the wall (from Willmarth & Tu 1967).

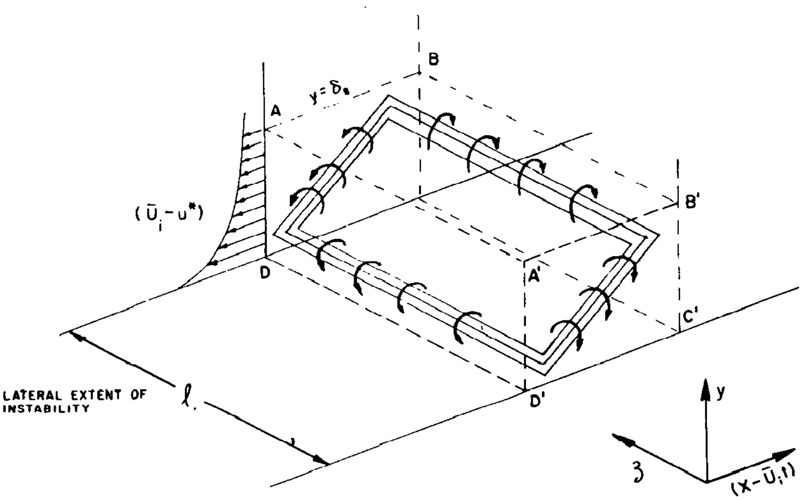
Black (1968) proposed a conceptual boundary-layer model based upon outward-migrating horseshoe vortices that are "shed" from a near-wall instability. The vortex structures induce an inviscid outflow of low-speed fluid from within the vortex loop, creating motions that are seen as sharp, intermittent 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 frontlike 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 that replace the older members (Figure 7).

The key features of the extensive near-wall studies by the Stanford group (Runstadler et al 1963, Kline et al 1967, Kim et al 1971, Offen & Kline 1974) were synthesized by Offen & Kline (1975) in a model featuring a lifted and stretched horseshoe-shaped vortex loop. Offen & Kline describe how the three kinds of oscillatory motion that were observed by Kim et al (1971) during the near-wall bursting process are consistent with the passage of a horseshoe vortex (Figure 8). Pairing of aligned vortex structures and violent interaction of nonaligned vortices are also postulated.

Hinze (1975) also attempted to relate the many observed features of near-wall turbulence production to the dynamics of horseshoe-shaped vortices (Figure 9). 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.

Praturi & Brodkey (1978) summarized the Ohio State visualization studies of turbulent pipe and boundary-layer flows (Corino & Brodkey 1969, Nychas et al 1973) with a conceptual model that explicitly relates coherent motions in the outer region to the near-wall turbulence production. The main causative element in Praturi & Brodkey's model is a δ-scale shear-layer interface between high- and low-speed fluid, upon which large-scale transverse vortices roll up. In the model, these outer-region transverse vortices induce near-wall ejections and streamwise vortices, as well as bulges in the outer turbulent/potential interface and entrainment of new free-stream fluid (Figure 10). Several aspects of Praturi & Brodkey's two-dimensional idealization were extended to three dimensions by Nakagawa & Nezu (1981), who studied space-time correlations of ejections and sweeps with twin $u'v'$ probes in a channel.

Head & Bandyopadhyay's (1981) smoke flow visualizations of boundary



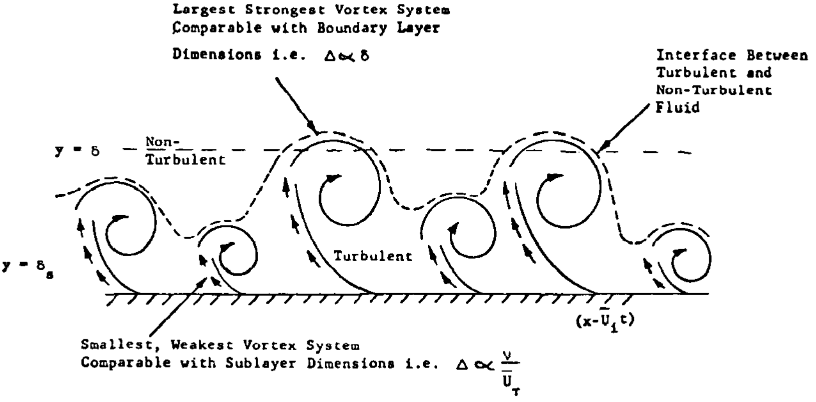


Figure 7 (*top*) Generation of ring-vortices by instability in the actual shear layer. (*bottom*) Intermittency explained by random variation in the strength of consecutive vortex systems (from Black 1968).

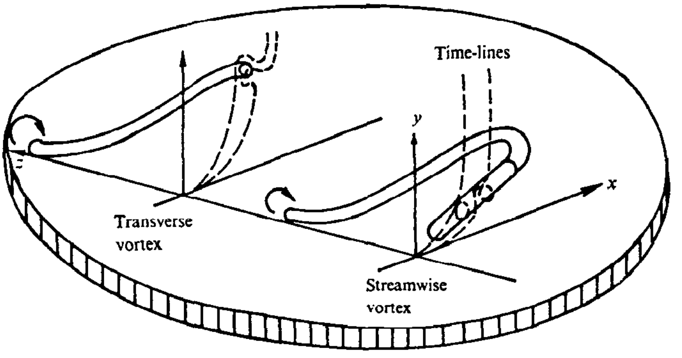


Figure 8 Time-line patterns at different locations of a lifted and stretched vortex element (from Offen & Kline 1975).

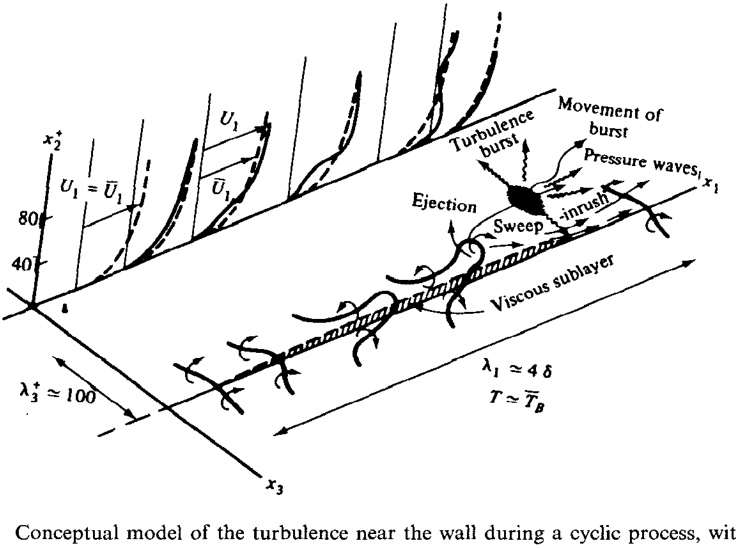


Figure 9 Conceptual model of the turbulence near the wall during a cyclic process, with average spacings λ_1 and λ_2 (from Hinze 1975).

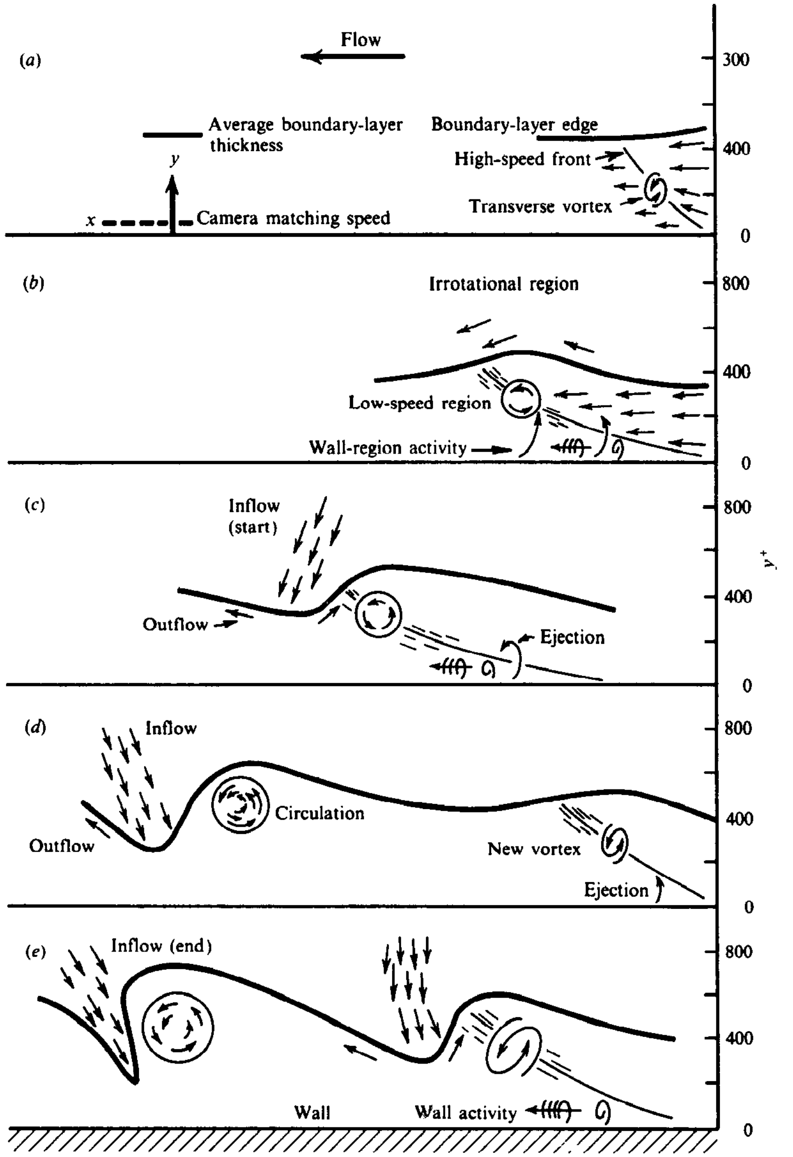


Figure 10 Conceptual model of outer-flow motions and interactions with the wall region, as seen from a downstream-convecting frame of reference (from Praturi & Brodkey 1978).

layers over a Reynolds number range of $500 < Re_\theta < 17{,}500$ provided images of hairpin-shaped structures virtually dominating the boundary layer; these structures were interpreted as vortices by the authors. 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 [similar to Black's (1968) model]. 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 (Figure 3).

Simultaneous flow visualization and hot-wire anemometry have been employed by the Michigan State group to study the near-wall region (Falco 1980b) and the interactions between the near-wall and the large-scale motions (Falco 1983). The results suggest that the large-scale outer motions affect, but do not govern, the near-wall production processes. Falco (1983) outlined a comprehensive conceptual model of the boundary-layer turbulence production cycle, which involved ringlike vortices that scale on the wall variables, ejections, sweeps, "pockets" of sublayer fluid free of marker, near-wall streamwise vortices, hairpin vortices, and streaky structures. Falco associated most of these features with the movement of the ringlike vortices and the pocket wall-region disturbances.

Thomas & Bull (1983), in a combined extension of previous efforts (Brown & Thomas 1977, Bull 1967), studied the relationships between wall-pressure fluctuations, wall-shear fluctuations, near-wall shear layers, and the "burst-sweep" cycle in the buffer region. Thomas & Bull showed that characteristic high-pressure regions associated with the burst-sweep cycle are due to the passage of inclined shear layers that occur on the upstream side of the bursting process and that may traverse most of the boundary layer. The authors conclude that streamwise pressure gradients of either sign do not play an active role in the near-wall turbulence-production process. Side-view diagrams (Figure 11) show the phase relationships between large-scale outer motions and their inclined backs, near-wall bursting activity, and fluctuations in wall-shear stress and wall pressure. The Thomas & Bull results provide extensive quantitative evidence concerning a kinematical relationship between the turbulence-generation processes and pressure fluctuations at the wall.

Working from the many vortex models in the literature as well as from his own extensive visualization studies, Smith (1984) proposed a relatively complete conceptual model for hairpin-shaped vortices in the wall region ($y^+ < 100$) (Figure 12). 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

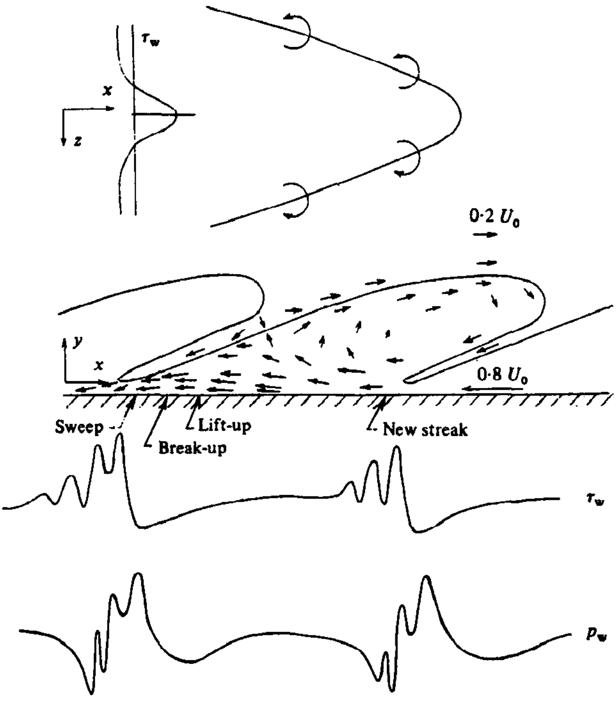


Figure 11 Large structure, associated pressure and shear distributions, and location of events in the burst-sweep cycle in a frame of reference moving with the large structure (from Thomas & Bull 1983).

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 owing to the streamwise velocity gradient. The trailing legs of the loop remain in the near-wall region but are stretched, forming counterrotating quasi-streamwise vortices that 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 that comprises a burst grows outward and may agglomerate into large-scale rotational outer-region bulges. Smith's symmetric model is drawn in

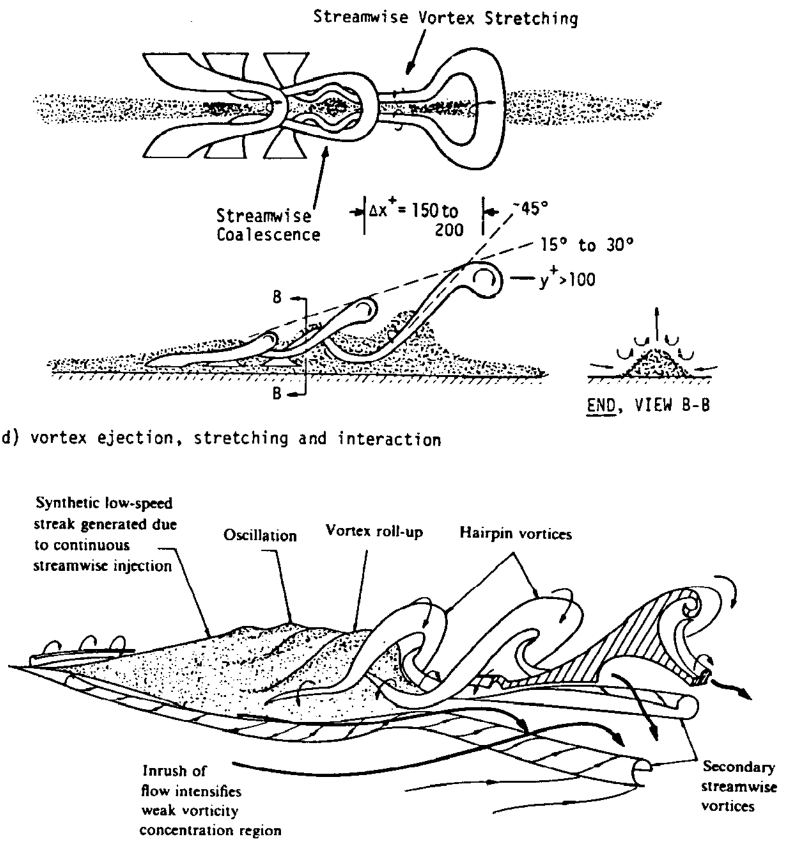


Figure 12 (*top*) Illustration of the breakdown and formation of hairpin vortices during a streak-bursting process. Low-speed streak regions indicated by shading (from Smith 1984). (*bottom*) Schematic of breakup of a synthetic low-speed streak generating hairpin vortices. Secondary streamwise vortical structures are generated owing to inrush of fluid (from Acarlar & Smith 1987).

part from studies of laminar boundary layers in which symmetry across an *x-y* plane is forced by the flow geometry (Acarlar & Smith 1987).

Robinson (1990) also proposed an idealized model for low-Reynolds-number boundary layers based on vortical structures (Figure 13*a*). In this model, quasi-streamwise vortices dominate the buffer region, while archlike vortices are the most common vortical structure in the wake region. In the logarithmic, or overlap, region, both arches and quasi-streamwise vortices exist, often as elements of the same vortical structure. Symmetry of vortical structures is not required in this concept, reflecting

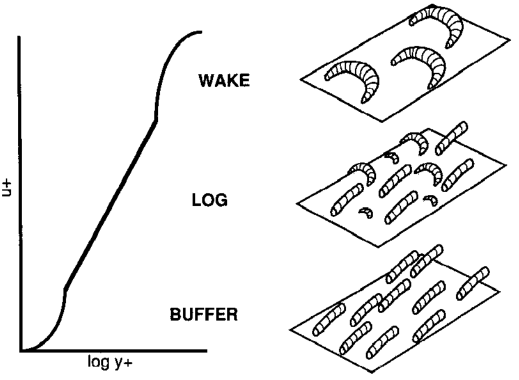


Figure 13a Idealized schematic of vortical-structure populations in different regions of the turbulent boundary layer (from Robinson 1990).

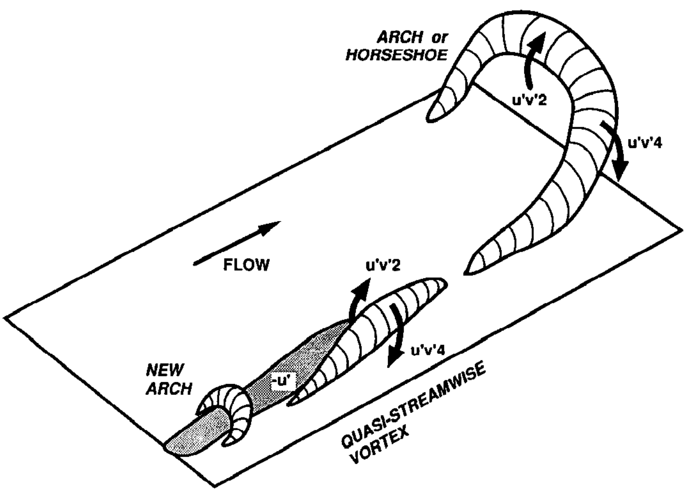


Figure 13b Conceptual model of the kinematical relationships between (1) ejection/sweep motions and quasi-streamwise vortices in the near-wall region and (2) ejection/sweep motions and arch-shaped vortical structures in the outer region. Model proposed for low-Reynolds-number boundary layers (from Robinson 1990).

the numerical results that vortical arches are often lopsided, and that near-wall quasi-streamwise vortices occur only rarely as equal-strength, counterrotating pairs. In Robinson's model, most structural elements are related to vortical structures, including turbulence production through sweeps and ejections throughout the boundary layer, sloping near-wall and δ-scale shear layers, and pressure fluctuations at the wall and within the flow field (Figure 13*b*). Several aspects of this conceptual model are listed in Section 8.2.

A number of additional conceptual models are proposed in the literature, including those of Kovasznay (1970), Laufer (1975), Blackwelder & Eckelmann (1979), Dinkelacker (1982), Wallace (1982, 1985), Fiedler (1986), Utami & Ueno (1987), Adrian et al (1987), Jimenez et al (1987), Choi (1988), and Kobashi & Ichijo (1986, 1989). Many of these models are similar in their inclusion of a three-dimensional vortical structure, but most models do not account for the existence of all the structural features enumerated in Section 2.3. Also, not all models are described in terms of dynamic relationships among coherent motions, and a wide variety of concepts exists among those models that do address dynamics. It is not possible to conclusively accept or reject any of the above models based on currently available data.

7. PREDICTIVE MODELS

Turbulence-structure knowledge has found only limited application to the development of predictive models for boundary-layer properties. The few models that have emerged either have utilized structural information to predict statistical profiles or have used a simplified form of the governing equations to model the dynamics of the near-wall turbulence-production process. Space limitations do not allow more than a brief mention of these important contributions.

Townsend (1956) proposed one of the earliest statistical models based on boundary-layer coherent motions. Townsend's original model of the large-eddy structure consisted of large inclined vortices, with their plane of rotation normal to the principal axis of strain. He later (Townsend 1970, 1976) modified this concept into a double-cone roller eddy model and was able to reproduce turbulence-intensity profiles and two-point correlation functions with reasonable accuracy. Some conditionally averaged experimental results resemble Townsend's model (e.g. Guezennec 1985, Choi 1988).

Perry et al (1986) extended Perry & Chong's (1982) model in which the boundary layer is represented by a forest of Λ-shaped vortices, which were introduced as a candidate form for Townsend's (1976) "attached-eddy" hypothesis. 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 credibility to the idea of vortical loops as the dynamically dominant boundary-layer structure. (Another type of hairpin-vortex predictive model has been proposed by Kasagi 1989.) Recently, Perry et al (1989) have extended the attached-eddy hypothesis to formulate a rudimentary closure scheme for the prediction of turbulent boundary layers with streamwise pressure gradients.

Considerable effort has been expended to explain theoretically the experimentally observed mean spanwise streak spacing of 100 viscous lengths (e.g. Landahl 1967, 1980, Bank 1975, Jang et al 1986). Although a number of these approaches have resulted in near-wall spanwise scales similar to the streak spacing, the formation dynamics of low-speed streaks remain poorly understood. Landahl (1990) used linear theory to construct an idealized model of the streaky structure during the quiescent period between bursting events. Landahl's model exhibits many of the attributes of laboratory low-speed streaks, including persistence, irregular waviness, and formation of near-wall shear layers, but the model is not formulated to replicate the bursting phenomenon itself.

A number of dynamical models for the near-wall flow in the y-z plane have also been developed—for example, by Hanratty (1989) and by Walker & Herzog (1988), who solve the three-dimensional Navier-Stokes equations in a two-dimensional cross-flow plane in the near-wall region. Both models replicate key aspects of the quasi-streamwise vortex (or "closed-eddy") structure in the buffer and lower log layers. An eruptive event reminiscent of the bursting process is observed in Walker & Herzog's computations.

Berkooz et al (1990), building on earlier work by Bakewell & Lumley (1967), Herzog (1986), and Aubry et al (1988), utilized proper orthogonal decomposition to identify and then model near-wall coherent motions (arrays of streamwise vortices, in this case) associated with Reynolds-stress and kinetic-energy production. The resulting dynamic model displays a "burstlike" tendency to transition abruptly from one mode to another, with accompanying ejection and sweep motions.

Future developments of statistical/structural models will offer alternative methods for the prediction of turbulent boundary-layer statistical profiles, while dynamical models such as those mentioned above are beginning to show promise for the optimization of turbulence-control methodologies. Recent results are encouraging, but considerable progress remains to be made on both research fronts before knowledge of coherent motions may be considered of practical use.

8. CONCLUSIONS

8.1 *Summary of Points of Consensus*

An extraordinarily large body of knowledge is represented by the literature of turbulence structure. Although progress in the field has been punctuated by numerous controversies, there exists today a growing consensus concerning many of the fundamental structural features in low-Reynolds-number canonical flows. This has been due in part to numerical simulations, which have served to filter and unify many of the discrete bits of information produced from 40 years of experimentation.

For the most part, quantitative tabulations of lengths, durations, and frequencies are avoided here, since such numerical values may find limited applicability to practical ($Re_\theta \gg 5000$) Reynolds numbers; see Cantwell (1981) for quantitative data. The key points of current qualitative consensus can be summarized in brief form as follows (the references cited here are representative but not exhaustive):

- The sublayer is not laminar, and the buffer region is not transitional in the laminar-to-turbulent sense (many references).
- The sublayer, buffer region, and outer region (log plus wake) each have coherent motions with different structural characteristics. In most cases, the variance of the structures' measurable attributes about their mean values is very large (many references).
- The sublayer consists of elongated, unsteady regions of high- and low-speed streamwise velocity. The mean spanwise spacing between low-speed streaks in the sublayer is approximately 100 viscous lengths, up to Reynolds numbers of at least $Re_\theta \approx 6000$. (Kline & Runstadler 1959, Reiss & Hanratty 1963, Runstadler et al 1963, Smith & Metzler 1983.)
- The thin, near-wall buffer region is the most important zone of the boundary layer in terms of turbulence energy production and dissipation (Laufer 1953, Klebanoff 1954). Buffer-region activity is characterized by a bursting process, during which low-speed fluid (provided in the form of streaks) is flung outward from the wall, generating most of the turbulence production in the boundary layer (Kline et al 1967, Corino & Brodkey 1969, Kim et al 1971, Grass 1971, and many others).
- Both outward $(u'v')_2$ ejections of low-speed fluid and wallward $(u'v')_4$ sweeps of high-speed fluid occur intermittently throughout the layer. Ejection motions are the major contributor to $-\overline{u'v'}$ in the region beyond $y^+ \approx 12$, while sweep motions dominate the Reynolds stress nearer the wall (Wallace et al 1972, Willmarth & Lu 1972, Brodkey et al 1974, Kim et al 1987).
- Wall-normal velocity fluctuations in the near-wall region are narrow and slightly elongated, and they tend to appear in side-by-side pairs. Strong wallward motions are not broad, outer-scale motions (Grass 1971, Moin 1987, Robinson et al 1989). Wallward motions in the buffer and sublayer are redirected by the wall, giving rise to the visual appearance of "pockets" (Falco 1980b, Kim et al 1987).

- Instantaneously inflectional velocity profiles [in both $u(y)$ and $u(z)$] are common near the wall and may "roll up" into vortices through a mechanism often interpreted as a local shear-layer instability. (Note, however, that classic inviscid inflectional stability analysis assumes steady, two-dimensional flow; Kline et al 1967, Grass 1971, Kim et al 1971, Willmarth & Lu 1972, Blackwelder & Swearingen 1989).
- Thin shear layers (with $\partial u'/\partial x$, $\partial u'/\partial y$, and/or $\partial u'/\partial z$) exist throughout the boundary layer at interfaces between upstream high-speed fluid and downstream low-speed fluid. These sloping shear layers are very common below $y^+ \approx 100$ and often occur on the upstream side of lifted or kinked low-speed streaks. A region of high wall pressure is found directly beneath the convecting stagnation point of a near-wall shear layer (Corino & Brodkey 1969, Kim et al 1971, Burton 1974, Blackwelder & Kaplan 1976, Brown & Thomas 1977, Kreplin & Eckelmann 1979, Johansson & Alfredsson 1982, Dinkelacker & Langeheineken 1983, Kobashi & Ichijo 1986, Bogard & Tiederman 1986, Johansson et al 1987a,b,c).
- The intermittent region of the boundary layer is dominated by large-scale motions (also called entrainment eddies) that exist beneath bulges in the outer interface. These bulges are three-dimensional (δ-scale in both x and z), and they are characterized by slow rotational motion in the direction of the mean strain and by deep crevasses of high-speed potential fluid around the edges. Shear layers form on the upstream side of large-scale outer motions; these shear layers can span most of the boundary layer, even at high Reynolds numbers (Kovasznay et al 1970, Blackwelder & Kovasznay 1972, Nychas et al 1973, Hedley & Keffer 1974, Falco 1977, Brown & Thomas 1977, Chen & Blackwelder 1978, Spina & Smits 1987, Antonia et al 1989).
- Entrainment of potential fluid occurs in valleys in the turbulent/nonturbulent interface that exist at the edges of bulges (Kovasznay et al 1970, Townsend 1970, Falco 1977, Bevilaqua & Lykoudis 1977, Praturi & Brodkey 1978, Robinson 1990).
- Instantaneous wall-pressure patterns are rounded, not elongated, and contain regions of high-amplitude, high-frequency fluctuations (Willmarth 1975b, Dinkelacker et al 1977, Grotzbach & Schumann 1979, Schewe 1983, Thomas & Bull 1983, Moin 1984, Johansson et al 1987a).
- Loop-shaped vortical structures (horseshoes, hairpins, Λ-eddies) exist and play some role in the dynamics of turbulence production, but spatial and evolutionary details as well as statistical relevance is controversial [many references; see Robinson (1989) for a survey].
- Transverse vortices exist in the outer (log and wake) region. These are

associated with entrainment and with the bulges in the outer interface (Clark & Markland 1971, Nychas et al 1973, Praturi & Brodkey 1978, Nakagawa & Nezu 1981, Smith & Lu 1989, Robinson 1989).

- The wall region is well populated by relatively strong quasi-streamwise vortices, with an upward tilt that increases with distance from the wall. These quasi-streamwise vortices are closely associated with both ejections and sweeps, and they are major contributors to the Reynolds shear stress in the near-wall region. Buffer-layer vortices apparently play a role in the formation of low-speed streaks but are an order of magnitude shorter than streaks in the sublayer. A popular inference is that vortices "drag" through the wall region, leaving elongated trails of low-speed fluid from the upward-rotating sides of the vortices [many references; see Robinson (1989) for survey].
- Information from the wall region is transferred to the outer region both directly (through mass transfer from near-wall ejections) and indirectly (through the outward growth of vortical structures). The former process is rapid and possibly less important at high Reynolds number. The latter process is much slower and may be associated with vortex interactions at higher Reynolds numbers (Clark & Markland 1971, Kim et al 1971, Nychas et al 1973, Offen & Kline 1974, Praturi & Brodkey 1978, Nakagawa & Nezu 1981, Head & Bandyopadhyay 1981, Smith 1984)
- Outer-flow events have a definite, but not a controlling, effect on the near-wall production process and, therefore, on the wall shear stress and surface heat transfer. However, the precise mechanisms through which the outer-region eddies influence the wall zone are not agreed upon and are expected to be Reynolds-number dependent (Townsend 1956, 1961, 1976, Offen & Kline 1974, Praturi & Brodkey 1978, Brown & Thomas 1977, Chen & Blackwelder 1978, Falco 1983, Thomas & Bull 1983, Guezennec 1985, Wark 1988).

8.2 *Recent Developments*

The field of turbulence structure has enjoyed new vitality in the past decade, due largely to the influence of direct numerical simulations of turbulent flows. As a result, a number of findings have been published that confirm, extend, and occasionally contradict conclusions of previous experimental studies. Some of these recent results establish kinematic associations between various structural elements, helping to form a more unified picture of the turbulence-maintenance process. Many of these items lack confirmation by more than one lab or differ from previous conclusions, so community consensus cannot yet be claimed for them. Again, these conclusions are all drawn from low-Reynolds-number flows.

- In the buffer region, sweeps and ejections are closely associated with quasi-streamwise vortices and so tend to occur in a side-by-side orientation (Moin 1987) rather than with a sweep directly upstream of an ejection, contrary to several published structural models. This apparent conflict between instantaneous observations and single-point conditional averages may result from making two-dimensional measurements of three-dimensional structures; a slight skewing of the sweep/ejection pair in the x-z plane would cause a fixed probe to detect one, followed closely in time by the other. [Note, however, that high-speed fluid with little or no wallward component often exists upstream of an ejection. This "gusting" motion is sometimes called a "sweep" in the literature, but it does not constitute a significant $(u'v')_4$ contribution to the Reynolds stress.]
- In the buffer and lower log regions, quasi-streamwise vortices most often occur singly, with only occasional instances of counterrotating pairs (Moser & Moin 1987, Nishino et al 1988, Guezennec et al 1989). Single vortices produce both ejections and sweeps, without the need for an equal-strength twin. Most early conclusions that near-wall vortices occur primarily in counterrotating pairs were based upon conditional averaging methods that *prescribe* a spanwise symmetry in the results (e.g. Bakewell & Lumley 1967, Blackwelder & Eckelmann 1979, Kim 1983, Moin 1984).
- In the sublayer, regions of high-speed fluid tend to be considerably shorter (in the streamwise direction) and wider (in the spanwise direction) than the elongated streaks of low-speed fluid. This variation may become more pronounced at higher Reynolds numbers (Robinson et al 1989).
- In the upper log and wake regions, much of the contribution to the Reynolds shear stress is associated with vortical structures: Most strong ejections are found on the upstream side of transverse vortices, which often form "head" elements of one- or two-sided vortical arches. This observation is generally consistent with most hairpin-vortex models of turbulence production. Strong sweeps occur primarily on the outboard side of tilted necks; weak sweeps often occur on the downstream side of heads. The local length scales of both ejections and sweeps in the outer region are modulated by the diameter of the associated vortex (Robinson 1990).
- Transverse vortices (predominantly found in the outer region) have relatively long lifetimes compared with quasi-streamwise vortices, which form, evolve, and dissipate rapidly in the near-wall region (Clark & Markland 1971, Praturi & Brodkey 1978). This may be due in part to the much higher level of viscous dissipation present in the rapidly

stretching near-wall quasi-streamwise vortices. These vortices are more populous than transverse vortices (Robinson 1989), which suggests that not all quasi-streamwise vortices are the legs of arches or hairpins, and/or that any one vortical arch may spawn several legs during its lifetime (Acarlar & Smith 1987).

- Most low-pressure regions within the field are elongated, and most elongated low-pressure regions correspond to vortex cores. High-pressure regions within the field occur whenever high-speed fluid impacts low-speed fluid, thus forming a convecting stagnation point. This occurs both near the wall and in the outer flow, often involving motions directly induced by vortical structures. These results were largely expected, but they were not confirmed until the advent of numerically simulated turbulence, for which the pressure field within the flow is accessible (Kim 1983, 1987a, Johansson et al 1987c, 1989).
- Pressure structures (especially high-pressure regions) tend to span much of the layer, but the majority of the wall-pressure mean-square fluctuation is provided by local, near-wall motions (Kim 1989).
- The entrainment process is highly three dimensional, in that irrotational flow from the free-stream is entrained alongside the necks of large vortical arches, as well as on the downstream side of transverse vortical elements. The length scales of the "inrushes" are related to the diameters of the associated vortices. Most studies of the outer-flow structure have examined *x-y* planes, in which the association of entrainment with tilted vortical structures is not evident (see also Townsend 1970, Hedley & Keffer 1974, Falco 1980a).
- Near-wall shear layers are created when relatively high-speed fluid impacts low-speed fluid lifted by a quasi-streamwise vortex (see Stuart 1965), and when high-speed fluid impacts the kinked upstream side of a low-speed streak. In the former case, ejections are closely associated with shear-layers, but this is not necessarily true in the latter case. Thus, the relation between near-wall shear layers and ejections is not unique. Spanwise asymmetry is a common and possibly dynamically significant characteristic of the local flow surrounding a near-wall shear layer (Alfredsson et al 1988).
- The most common near-wall coherent motions (quasi-streamwise vortices, shear layers, and $u'v'$ peaks) are relatively persistent, often traveling significant downstream distances (on the order of 1000 viscous lengths) during their lifetimes (Nakagawa & Nezu 1981, Johansson et al 1987a,b, Alfredsson et al 1988). This observation supports the second of the two interpretations of bursting discussed in Section 4.2.

All of the above findings are further explored by Robinson (1990).

8.3 *Research Issues as of 1990*

For canonical boundary layers, progress in the past decade has been rapid and gratifyingly convergent when compared with the widely disparate conclusions drawn in the earlier years. However, major open issues remain; these research needs can be organized into five categories:

1. *Kinematics*: Further characterize vortical structures and internal shear layers, including their relationships to turbulence production and dissipation, temporal longevity, rates of growth and decay, strength, topologies and shapes, passage frequencies. Also, strengthen knowledge of feedback between wall-pressure fluctuations and near-wall events.
2. *Dynamics*: Further characterize vortex and shear-layer formation dynamics, growth mechanisms, interaction modes, and their sensitivity to Reynolds-number variations. Increase understanding of unsteady, three-dimensional shear-layer instabilities, as well as of inward and outward interactions and their Reynolds-number dependencies. Clarify scaling laws for near-wall production events. Improve understanding of near-wall streak formation and reasons for constant mean transverse spacing.
3. *Links between numerical simulations and experiments*: Simulate experimental techniques, such as flow visualization, particle-tracking, and hot-wire probes, in numerical turbulence. Use simulation results to develop experimental methods for detecting and quantifying vortices in laboratory flows. Use simulations to develop event-detection and control schemes for turbulence modification in the laboratory. Extend numerical results to higher Reynolds numbers with experiments.
4. *Noncanonical boundary layers*: Study effects of pressure gradients, compressibility, density stratification, wall roughness, three dimensionality, nonequilibrium, unsteadiness, free-stream turbulence, and combinations of the above.
5. *Links to modeling*: Provide physical insight for Reynolds-averaged modeling efforts. Eventual development of "structural/statistical" model for predictive use.

The unsolved dynamical issues are clearly the most important in terms of "understanding" boundary-layer coherent motions; the key dynamics questions may be identified as (*a*) vortex formation and evolution, and (*b*) interaction between coherent motions in the inner and outer regions of the boundary layer. [Cantwell (1990) provides an additional viewpoint concerning future research directions in turbulent boundary-layer structure.]

8.4 *Final Discussion*

Most of the causative coherent motions in the canonical turbulent boundary layer may be characterized as either a vortex or a shear layer. Kinematical combinations and dynamical relationships between these two fundamental classes of structure comprise the foundation physics of the momentum-transport and mixing properties of the boundary layer. Observations show that shear layers may give birth to vortices, and that vortical structures may create shear layers, but there are apparently nonunique formation mechanisms for each. To gain the depth of understanding required to improve practical modeling and control methodologies will require focused study of these basic three-dimensional structural features, which in turn requires improved experimental/numerical techniques for their detection.

Several decades of intense academic study have provided an extensive knowledge base of the simple canonical case. The immediate need is to learn to utilize this store of information in the context of boundary-layer modeling and control methodologies, with the eventual goal of practical application to engineering problems involving real-world, noncanonical boundary layers.

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Literature Cited

Acarlar, M. S., Smith, C. R. 1987. A study of hairpin vortices in a laminar boundary layer. Part II: hairpin vortices generated by fluid injection. *J. Fluid Mech.* 175: 43–83

Adrian, R. J. 1989. Linking correlations and structure: stochastic estimation and conditional averaging. In *Near Wall Turbulence. Proc. Zaric Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 420–36. New York: Hemisphere

Adrian, R. J., Moin, P., Moser, R. D. 1987. Stochastic estimation of conditional eddies in turbulent channel flow. *Proc. 1987 Summer Program Cent. Turbul. Res.*, pp. 7–19. Stanford, Calif: Cent. Turbul. Res.

Alfredsson, P. H., Johansson, A. V. 1984. Time scales in turbulent channel flow. *Phys. Fluids* 27: 1974–81

Alfredsson, P. H., Johansson, A. V., Kim, J. 1988. Turbulence production near walls: the role of flow structures with spanwise asymmetry. *Proc. 1988 Summer Program Cent. Turbul. Res.*, pp. 131–41. Stanford, Calif: Cent. Turbul. Res.

Antonia, R. A. 1981. Conditional sampling in turbulence measurement. *Annu. Rev. Fluid Mech.* 13: 131–56

Antonia, R. A., Browne, L. W. B., Bisset, D. K. 1989. Effect of Reynolds number on the organised motion in a turbulent boundary layer. In *Near Wall Turbulence. Proc. Zaric Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 488–506. New York: Hemisphere

Aubry, N., Holmes, P., Lumley, J. L., Stone, E. 1988. The dynamics of coherent structures in the wall region of a turbulent boundary layer. *J. Fluid Mech.* 192: 115–73

Bakewell, H. P., Lumley, J. L. 1967. Viscous sublayer and adjacent wall region in turbulent pipe flow. *Phys. Fluids.* 10(9): 1880–89

Bark, F. H. 1975. On the wave structure of the wall region of a turbulent boundary layer. *J. Fluid Mech.* 70: 229–50

Berkooz, G., Guckenheimer, J., Holmes, P., Lumley, J. L., Marsden, J., et al. 1990. Dynamical-systems-theory approach to the wall region. *AIAA Pap. No. 90–1639*

Bevilaqua, P. M., Lykoudis, P. S. 1977. Some observations on the mechanism of entrainment. *AIAA J.* 15(8): 1194–96

Black, T. J. 1968. An analytical study of the measured wall pressure field under supersonic turbulent boundary layers. *NASA CR-888*

Blackwelder, R. F., Kovasznay, L. S. G. 1972. Time scales and correlations in a turbulent boundary layer. *Phys. Fluids* 15(9): 1545–54

Blackwelder, R. F., Kaplan, R. E. 1976. On the wall structure of the turbulent boundary layer. *J. Fluid Mech.* 76: 89–112

Blackwelder, R. F. 1988. Coherent structures associated with turbulent transport. In *Transport Phenomena in Turbulent Flows*, ed. M. Hirata, N. Kasagi, pp. 69–88. New York: Hemisphere

Blackwelder, R. F. 1989. Some ideas on the control of near-wall eddies. *AIAA Pap. No. 89–1009*

Blackwelder, R. F., Eckelmann, H. 1979. Streamwise vortices associated with the bursting phenomenon. *J. Fluid Mech.* 94: 577–94

Blackwelder, R. F., Haritonidis, J. H. 1983. Scaling of the bursting frequency in turbulent boundary layers. *J. Fluid Mech.* 132: 87–103

Blackwelder, R. F., Swearingen, J. D. 1989. The role of inflectional velocity profiles in wall-bounded flows. In *Near Wall Turbulence. Proc. Zaric Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 268–88. New York: Hemisphere

Bogard, D. G., Tiederman, W. G. 1986. Burst detection with single-point velocity measurements. *J. Fluid Mech.* 162: 389–413

Brodkey, R. S., Wallace, J. M., Eckelmann, H. 1974. Some properties of truncated turbulence signals in bounded shear flows. *J. Fluid Mech.* 63: 209–24

Brown, G. L., Thomas, A. S. W. 1977. Large structure in a turbulent boundary layer. *Phys. Fluids* 20(10): S243–51 (Suppl.)

Bull, M. K. 1967. Wall-pressure fluctuations associated with subsonic turbulent boundary layer flow. *J. Fluid Mech.* 28: 719–54

Burton, T. E. 1974. The connection between intermittent turbulent activity near the wall of a turbulent boundary layer with pressure fluctuations at the wall. *Tech. Rep. No. 70208-10*, Mass. Inst. Technol., Cambridge

Cantwell, B. J. 1981. Organized motion in turbulent flow. *Annu. Rev. Fluid Mech.* 13: 437–515

Cantwell, B. J. 1990. Future directions in turbulence research and the role of organized motion. *Proc. Whither Turbul. Workshop*, Ithaca, N.Y. Berlin: Springer-Verlag. In press

Chen, C.-H. P., Blackwelder, R. F. 1978. Large-scale motion in a turbulent boundary layer: a study using temperature contamination. *J. Fluid Mech.* 89: 1–31

Choi, K. 1988. On physical mechanisms of turbulent drag reduction using riblets. In *Transport Phenomena in Turbulent Flows*, ed. M. Hirata, N. Kasagi, pp. 185–98. New York: Hemisphere

Chong, M. S., Perry, A. E., Cantwell, B. J. 1990. A general classification of three-dimensional flow fields. *Phys. Fluids A.* In press

Clark, J. A., Markland, E. 1971. Flow visualization in turbulent boundary layers. *J. Hydraul. Div. ASCE* 97: 1653–64

Corino, E. R., Brodkey, R. S. 1969. A visual investigation of the wall region in turbulent flow. *J. Fluid Mech.* 37: 1–30

Corrsin, S. 1943. Investigation of flow in an axially symmetric heated jet of air. *NACA Adv. Conf. Rep. 3123*

Corrsin, S., Kistler, A. L. 1954. The free-stream boundaries of turbulent flows. *NACA TN-3133*

Dinkelacker, A. 1982. Do tornado-like vortices play a role in the turbulent mixing process? *Proc. IUTAM/ICHMT Symp.* New York: Hemisphere

Dinkelacker, A., Hessel, M., Meier, G. E. A., Schewe, G. 1977. Investigation of pressure fluctuations beneath a turbulent boundary layer by means of an optical method. *Phys. Fluids* 20(10): S216–24 (Suppl.)

Dinkelacker, A., Langeheineken, T. 1983. Relations between wall pressure fluctuations and velocity fluctuations in turbulent flow. *Proc. IUTAM Symp., Marseilles, Fr.*, pp. 1–9. Berlin: Springer-Verlag

Einstein, H. A., Li, H. 1956. The viscous sublayer along a smooth boundary. *J. Eng. Mech. Div. ASCE* 82(EM2): Pap. No. 945

Falco, R. E. 1977. Coherent motions in the outer region of turbulent boundary layers. *Phys. Fluids* 20(10): S124–32 (Suppl.)

Falco, R. E. 1980a. Combined simultaneous flow visualization/hot-wire anemometry for the study of turbulent flows. *J. Fluids Eng.* 102: 174–83

Falco, R. E. 1980b. The production of turbulence near a wall. *AIAA Pap. No. 80-1356*

Falco, R. E. 1983. New results, a review and synthesis of the mechanism of turbulence production in boundary layers and its modification. *AIAA Pap. No. 83-0377*

Favre, A. J., Gaviglio, J. J., Dumas, R. 1957. Space-time double correlations and spectra in a turbulent boundary layer. *J. Fluid Mech.* 2: 313–41

Fiedler, H. E. 1986. Coherent structures. In *Advances in Turbulence* pp. 320–36. Berlin: Springer-Verlag

Foss, J. F., Wallace, J. M. 1989. The measurement of vorticity in transitional and fully developed turbulent flows. In *Frontiers in Experimental Fluid Mechanics*. Berlin: Springer-Verlag

Grant, H. L. 1958. The large eddies of turbulent motion. *J. Fluid Mech.* 4: 149–90

Grass, A. J. 1971. Structural features of turbulent flow over smooth and rough boundaries. *J. Fluid Mech.* 50: 233–55

Grotzbach, G., Schumann, U. 1979. Direct numerical simulation of turbulent velocity-, pressure-, and temperature-fields in channel flows. In *Turbulent Shear Flows I*, ed. F. Durst, B. E. Launder, F. W. Schmidt, J. H. Whitelaw, pp. 370–85. Berlin: Springer-Verlag

Guezennec, Y. 1985. *Documentation of large coherent structures associated with wall events*. PhD thesis. Ill. Inst. Technol., Chicago

Guezennec, Y. G., Piomelli, U., Kim, J. 1989. On the shape and dynamics of wall structures in turbulent channel flow. *Phys. Fluids A* 1(4): 764–66

Gupta, A. K., Laufer, J., Kaplan, R. E. 1971. Spatial structure in the viscous sublayer. *J. Fluid Mech.* 50: 493–512

Hanratty, T. J. 1989. A conceptual model of the viscous wall region. In *Near Wall Turbulence. Proc. Zaric Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 81–103. New York: Hemisphere

Head, M. R., Bandyopadhyay, P. 1981. New aspects of turbulent boundary layer structure. *J. Fluid Mech.* 107: 297–338

Hedley, T. B., Keffer, J. F. 1974. Some turbulent/non-turbulent properties of the outer intermittent region of a boundary layer. *J. Fluid Mech.* 64: 645–78

Herzog, S. 1986. *The large-scale structure in the near-wall region of turbulent pipe flow*. PhD thesis. Cornell Univ., Ithaca, N.Y.

Hinze, J. O. 1975. *Turbulence*. New York: McGraw-Hill

Hunt, J. C. R., Wray, A. A., Moin, P. 1988. Eddies, streams, and convergence zones in turbulent flows. *Proc. 1988 Summer Program Cent. Turbul. Res.*, pp. 193–207. Stanford, Calif: Cent. Turbul. Res.

Hussain, A. K. M. F. 1986. Coherent structures and turbulence. *J. Fluid Mech.* 173: 303–56

Jang, P. S., Benney, D. J., Gran, R. L. 1986. On the origin of streamwise vortices in a turbulent boundary layer. *J. Fluid Mech.* 169: 109–23

Jimenez, J., Moin, P., Moser, R. D., Keefe, L. R. 1987. Ejection mechanisms in the sublayer of a turbulent channel. *Proc. 1987 Summer Program Cent. Turbul. Res.*, pp. 37–47. Stanford, Calif: Cent. Turbul. Res.

Johansson, A. V., Alfredsson, P. H. 1982. On the structure of turbulent channel flow. *J. Fluid Mech.* 122: 295–314

Johannsson, A. V., Alfredsson, P. H., Eckelmann, H. 1987a. On the evolution of shear-layer structures in near-wall turbulence. In *Advances in Turbulence*, pp. 383–90. Berlin: Springer-Verlag

Johansson, A. V., Alfredsson, P. H., Kim, J. 1987b. Shear-layer structures in near-wall turbulence. *Proc. 1987 Summer Program Cent. Turbul. Res.*, pp. 237–51. Stanford, Calif: Cent. Turbul. Res.

Johansson, A. V., Her, J. Y., Haritonidis, J. H. 1987c. On the generation of high-amplitude wall pressure peaks in turbulent boundary layers and spots. *J. Fluid Mech.* 175: 119–42

Johansson, A. V., Alfredsson, P. H., Kim, J. 1989. Velocity and pressure fields associated with near-wall turbulence structures. In *Near Wall Turbulence. Proc. Zaric Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 368–80. New York: Hemisphere

Kasagi, N. 1989. Structural study of near-wall turbulence and its heat transfer mechanism. In *Near Wall Turbulence. Proc. Zaric Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 596–619. New York: Hemisphere

Kasagi, N., Hirata, M., Nishino, K. 1986. Streamwise pseudo-vortical structures and associated vorticity in the near-wall region of a wall-bounded turbulent shear flow. *Exp. Fluids* 4: 309–18

Kim, H. T., Kline, S. J., Reynolds, W. C. 1971. The production of turbulence near a smooth wall in a turbulent boundary layer. *J. Fluid Mech.* 50: 133–60

Kim, J. 1983. On the structure of wall-bounded turbulent flows. *Phys. Fluids* 26: 2088–97

Kim, J. 1987a. Evolution of a vortical structure associated with the bursting event in a channel flow. In *Turbulent Shear Flows 5*, pp. 221–33. Berlin: Springer-Verlag

Kim, J. 1987b. Overview of research by the Turbulence Structure Group. *Proc. 1987 Summer Program Cent. Turbul. Res.*, pp. 231–35. Stanford, Calif: Cent. Turbul. Res.

Kim, J. 1989. On the structure of pressure fluctuations in a simulated turbulent channel flow. *J. Fluid Mech.* 205: 421–51

Kim, J., Moin, P. 1979. Large-eddy simulation of turbulent channel flow. *NASA TM 78619*. Also in *AGARD Symp. Turbul. Boundary Layers* (1979)

Kim, J., Moin, P., Moser, R. 1987. Turbulence statistics in fully-developed channel flow at low Reynolds number. *J. Fluid Mech.* 177: 133–66

Kim, J., Spalart, P. R. 1987. Scaling of the bursting frequency in turbulent boundary layers at low Reynolds numbers. *Phys. Fluids* 30: 3326–28

Klebanoff, P. S. 1954. Characteristics of turbulence in a boundary layer with zero pressure gradient. *NACA TN-3178*

Kline, S. J., Reynolds, W. C., Schraub, F. A., Runstadler, P. W. 1967. The structure of turbulent boundary layers. *J. Fluid Mech.* 30: 741–73

Kline, S. J., Robinson, S. K. 1989a. Quasi-coherent structures in the turbulent boundary layer. Part I: status report on a community-wide summary of the data. In *Near Wall Turbulence. Proc. Zaric Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 200–17. New York: Hemisphere

Kline, S. J., Robinson, S. K. 1989b. Turbulent boundary layer structure: progress, status, and challenges. *Proc. IUTAM Symp. Struct. of Turbul. and Drag Reduct., 2nd, Zurich*

Kline, S. J., Runstadler, P. W. 1959. Some preliminary results of visual studies of the flow model of the wall layers of the turbulent boundary layer. *Trans. ASME, Ser. E* 2: 166–70

Kobashi, Y., Ichijo, M. 1986. Wall pressure and its relation to turbulent structure of a boundary layer. *Exp. Fluids* 4: 49–55

Kobashi, Y., Ichijo, M. 1989. Relation between wall pressure and turbulent structure. In *Near Wall Turbulence. Proc. Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 361–67. New York: Hemisphere

Kovasznay, L. S. G. 1970. The turbulent boundary layer. *Annu. Rev. Fluid Mech.* 2: 95–112

Kovasznay, L. S. G., Kibens, V., Blackwelder, R. F. 1970. Large-scale motion in the intermittent region of a turbulent boundary layer. *J. Fluid Mech.* 41: 283–325

Kreplin, H.-P., Eckelmann, H. 1979. Propagation of perturbations in the viscous sublayer and adjacent wall region. *J. Fluid Mech.* 95: 305–22

Landahl, M. T. 1967. A wave-guide model for turbulent shear flow. *J. Fluid Mech.* 29: 441–59

Landahl, M. T. 1980. A note on an algebraic instability of inviscid parallel shear flows. *J. Fluid Mech.* 98: 243–51

Landahl, M. T. 1990. On sublayer streaks. *J. Fluid Mech.* 212: 593–614

Laufer, J. 1953. The structure of turbulence in a fully developed pipe. *NACA TN 2954*

Laufer, J. 1975. New trends in experimental turbulence research. *Annu. Rev. Fluid Mech.* 7: 307–26

Lu, S. S., Willmarth, W. W. 1973. Measurements of the structure of the Reynolds stress in a turbulent boundary layer. *J. Fluid Mech.* 60: 481–511

Luchik, T. S., Tiederman, W. G. 1987. Timescale and structure of ejections and bursts in turbulent channel flows. *J. Fluid Mech.* 174: 529–52

Lugt, H. J. 1979. The dilemma of defining a vortex. In *Recent Developments in Theoretical and Experimental Fluid Mechanics*, ed. V. Muller, K. G. Roesner, B. Schmidt, pp. 309–21. Berlin: Springer-Verlag

Lyons, S. L., Hanratty, T. J., McLaughlin, N. C. 1989. Turbulence-producing eddies in the viscous wall region. *AIChE. J.* 35: 1962–74

Moin, P. 1984. Probing turbulence via large eddy simulation. *AIAA Pap. No. 84-0174*

Moin, P. 1987. Analysis of turbulence data generated by numerical simulations. *AIAA Pap. No. 87-0194*

Moin, P., Adrian, R. J., Kim, J. 1987. Stochastic estimation of conditional eddies in turbulent channel flow. *Proc. Symp. Turbul. Shear Flows, 6th Toulouse, Fr.*

Moin, P., Kim, J. 1985. The structure of the vorticity field in turbulent channel flow. Part 1: analysis of instantaneous fields and statistical correlations. *J. Fluid Mech.* 155: 441–64

Moin, P., Moser, R. D. 1989. Characteristic-eddy decomposition of turbulence in a channel. *J. Fluid Mech.* 200: 471–509

Morrison, J. F., Tsai, H. M., Bradshaw, P. 1989. Conditional-sampling schemes for turbulent flow, based on the variable-interval time averaging (VITA) algorithm. *Exp. Fluids* 7: 173–89

Moser, R. D., Moin, P. 1987. The effects of curvature in wall-bounded turbulent flows. *J. Fluid Mech.* 175: 479–510

Murlis, J. Tsai, H. M., Bradshaw, P. 1982. The structure of turbulent boundary layers at low Reynolds numbers. *J. Fluid Mech.* 122: 13–56

Nakagawa, H., Nezu, I. 1981. Structure of space-time correlations of bursting phenomena in an open-channel flow. *J. Fluid Mech.* 104: 1–43

Nishino, K., Kasagi, N., Hirata, M. 1988. Study of streamwise vortical structures in a two-dimensional turbulent channel flow by digital image processing. In *Transport Phenomena in Turbulent Flows*, ed. M. Hirata, N. Kasagi, pp. 157–70. New York: Hemisphere

Nychas, S. G., Hershey, H. C., Brodkey, R. S. 1973. A visual study of turbulent shear flow. *J. Fluid Mech.* 61: 513–40

Offen, G. R., Kline, S. J. 1974. Combined dye-streak and hydrogen-bubble visual observations of a turbulent boundary layer. *J. Fluid Mech.* 62: 223–39

Offen, G. R., Kline, S. J. 1975. A proposed model of the bursting process in turbulent boundary layers. *J. Fluid Mech.* 70: 209–28

Perry, A. E., Chong, M. S. 1982. On the mechanism of wall turbulence. *J. Fluid Mech.* 119: 173–217

Perry, A. E., Henbest, S., Chong, M. S. 1986. A theoretical and experimental study of wall turbulence. *J. Fluid Mech.* 165: 163–99

Perry, A. E., Li, J. D., Henbest, S., Marusic, I. 1989. The attached eddy hypothesis in wall turbulence. In *Near Wall Turbulence. Proc. Zaric Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 715–35. New York: Hemisphere

Praturi, A. K., Brodkey, R. S. 1978. A stereoscopic visual study of coherent structures in turbulent shear flow. *J. Fluid Mech.* 89: 251–72

Rai, M. M., Moin, P., 1989. Direct simulations of turbulent flow using finite difference schemes. *AIAA Pap. No. 89-0369*

Reiss, L. P., Hanratty, T. J. 1963. An experimental study of the unsteady nature of the viscous sublayer. *AIChE J.* 9(2): 154–60

Reynolds, W. C. 1990. The potential and limitations of direct and large eddy simulations. *Proc. Whither Turbul. Workshop, Ithaca, N.Y.* Berlin: Springer-Verlag. In press

Robinson, S. K. 1986. Space-time correlation measurements in a compressible turbulent boundary layer. *AIAA Pap. No. 86-1130*

Robinson, S. K. 1989. A review of vortex structures and associated coherent motions in turbulent boundary layers. *Proc. IUTAM Symp. Struct. Turbul. and Drag Reduct., 2nd*, Zurich

Robinson, S. K. 1990. *Kinematics of turbulent boundary layer structure*. PhD dissertation. Stanford Univ., Stanford, Calif. Also, *NASA TM*. In press

Robinson, S. K., Chacin, J. 1990. A history, review, and bibliography of coherent motions in turbulent boundary layers. *NASA TM*. In press

Robinson, S. K., Kline, S. J., Spalart, P. R. 1988. Spatial character and time evolution of coherent structures in a numerically simulated boundary layer. *AIAA Pap. No. 88-3577*

Robinson, S. K., Kline, S. J., Spalart, P. R. 1989. A review of quasi-coherent structures in a numerically simulated turbulent boundary layer. *NASA TM-102191*

Rogallo, R. S., Moin, P. 1984. Numerical simulation of turbulent flows. *Annu. Rev. Fluid Mech.* 16: 99–137

Runstadler, P. G., Kline, S. J., Reynolds, W. C. 1963. An experimental investigation of flow structure of the turbulent boundary layer. *Rep. No. MD-8*, Dep. Mech. Eng., Stanford Univ., Stanford, Calif.

Saffman, P. G. 1978. Problems and progress in the theory of turbulence. In *Structure and Mechanisms of Turbulence II*, pp. 274–316. Berlin: Springer-Verlag

Schewe, G. 1983. On the structure and resolution of wall-pressure fluctuations associated with turbulent boundary-layer flow. *J. Fluid Mech.* 134: 311–28

Shah, D. A., Antonia, R. A. 1989. Scaling of the "bursting" period in turbulent boundary layer and duct flows. *Phys. Fluids A* 1(2): 318–25

Smith, C. R. 1984. A synthesized model of the near-wall behavior in turbulent boundary layers. *Proc. Symp. Turbul., 8th, Rolla, Mo.*

Smith, C. R., Lu, L. J. 1989. The use of a template-matching technique to identify hairpin vortex flow structures in turbulent boundary layers. In *Near Wall Turbulence. Proc. Zaric Meml. Conf., 1988*, ed. S. J. Kline, N. H. Afgan, pp. 248–67. New York: Hemisphere

Smith, C. R., Metzler, S. P. 1983. The characteristics of low-speed streaks in the near-wall region of a turbulent boundary layer. *J. Fluid Mech.* 129: 27–54

Smith, C. R., Schwartz, S. P. 1983. Observation of streamwise rotation in the near-wall region of a turbulent boundary layer. *Phys. Fluids* 26: 241–52

Smith, M. W., Smits, A. J. 1988. Cinematic visualization of coherent density structures in a supersonic turbulent boundary layer. *AIAA Pap. No. 88-0500*

Spalart, P. R. 1988. Direct simulation of a turbulent boundary layer up to $Re_\theta = 1410$. *J. Fluid Mech.* 187: 61–98

Spina, E. F., Smits, A. J. 1987. Organized structures in a compressible, turbulent boundary layer. *J. Fluid Mech.* 182: 85–109

Stuart, J. T. 1965. The production of intense shear layers by vortex stretching and convection. *AGARD Rep. No. 514*

Subramanian, C. S., Rajagopalan, S., Antonia, R. A., Chambers, A. J. 1982. Comparison of conditional sampling and averaging techniques in a turbulent boundary layer. *J. Fluid Mech.* 123: 335–62

Talmon, A. M., Kunen, J. M. G., Ooms, G. 1986. Simultaneous flow visualization and Reynolds-stress measurement in a turbulent boundary layer. *J. Fluid Mech.* 163: 459–78

Theodorsen, T. 1952. Mechanism of turbulence. *Proc. Midwest. Conf. Fluid Mech., 2nd, Columbus, Ohio*, pp. 1 18

Thomas, A. S. W., Bull, M. K. 1983. On the role of wall-pressure fluctuations in deterministic motions in the turbulent boundary layer. *J. Fluid Mech.* 128: 283–322

Townsend, A. A. 1956. *The Structure of Turbulent Shear Flow*. Cambridge: Univ. Press. 315 pp. 1st ed.

Townsend, A. A. 1961. Equilibrium layers and wall turbulence. *J. Fluid Mech.* 11: 97–120

Townsend, A. A. 1970. Entrainment and the structure of turbulent flow. *J. Fluid Mech.* 41: 13–46

Townsend, A. A. 1976. *The Structure of Turbulent Shear Flow*. Cambridge: Univ. Press. 429 pp. 2nd ed.

Utami, T., Ueno, T. 1987. Experimental study on the coherent structure of turbulent open-channel flow using visualization and picture processing. *J. Fluid Mech.* 174: 399–40

Walker, J. D. A., Herzog, S. 1988. Eruption mechanism for turbulent flows near walls. In *Transport Phenomena in Turbulent Flows*, ed. M. Hirata, N. Kasagi. New York: Hemisphere

Wallace, J. M. 1982. On the structure of bounded turbulent shear flow: a personal view. In *Developments in Theoretical and Applied Mechanics*, 11: 509–21. Huntsville: Univ. Ala.

Wallace, J. M. 1985. The vortical structure of bounded turbulent shear flow. *Lect. Notes Phys.* 235: 253–68

Wallace, J. M., Eckelmann, H., Brodkey, R. S. 1972. The wall region in turbulent shear flow. *J. Fluid Mech.* 54: 39–48

Wark, C. E. 1988. *Experimental investigation of coherent structures in turbulent boundary layers*. PhD thesis. Ill. Inst. Technol., Chicago

Willmarth, W. W. 1975a. Structure of turbulence in boundary layers. *Adv. Appl. Mech.* 15: 159–254

Willmarth, W. W. 1975b. Pressure fluctuations beneath turbulent boundary layers. *Annu. Rev. Fluid Mech.* 7: 13–38

Willmarth, W. W., Lu, S. S. 1972. Structure of the Reynolds stress near the wall. *J. Fluid Mech.* 55: 65–92

Wilmarth, W. W., Sharma, L. K. 1984. Study of turbulent structure with hot wires smaller than the viscous length. *J. Fluid Mech.* 142: 121–49

Willmarth, W. W., Tu, B. J. 1967. Structure of turbulence in the boundary layer near the wall. *Phys. Fluids* 10: S134–37 (Suppl.)

Willmarth, W. W., Woolridge, C. E. 1962. Measurements of the fluctuating pressure at the wall beneath a thick turbulent boundary layer. *J. Fluid Mech.* 14: 187–210

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