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At a recent NSF-AFOSR workshop on self-sustaining mechanisms of wall turbulence several research groups presented their concepts. This paper reviews the idea that were presented. The paper is to distribute this information to fluid dynamieists who are non specialist in turbulence. The production of turbulence and Reynolds stress centers around vortices and "streaks' of low speed fluid near the wall. There are two main categories of self-sustaining mechanisms. In one category parent vortices interact with the wall and produce offspring. In the second category streak velocity profiles are unstable and produce vortices.

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FINAL REPORT

Symposium on Self-Sustaining Mechanisms of Wall Turbulence

June 18, 1998
AIAA Meeting Albuquerque, NM

Sponsored by

National Science Foundation

and

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Organizer

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This workshop was somewhat unique in that most of the participants had already presented papers on the subject. Their presentations were updates and additions to previous work. The papers were chapters in monograph, "Self-Sustaining Mechanisms of Wall Turbulence," was published in August, 1997. This subject is a central issue in the field of turbulence and is important in bringing mathematical modeling methods into closer harmony with nature. Fifteen author groups of international recognition were invited to present their ideas on this subject in articles in the monograph. The purpose of this symposium is to get this group of experts together to discuss and critically review their ideas and the ideas of others. Since publication of the monograph, all parties have had an opportunity to review the ideas of others. Also, since the initial articles have been written, several groups have made significant progress and have new developments to report.

In addition to the original authors, four experts in turbulence, A. J. Smitts, D. G. Bogard, J. Jimenez, and R. Moser, were invited to critique the monograph contributions and add their own ideas. The authors and their titles are shown on the program schedule that is at end of this proposal. Contributions of the four new invited experts are listed as: Summary and Appraisal of Self-Sustaining Mechanisms; I, II, III, and IV. This somewhat unusual format turned out to be very effective in giving focus to the workshop.

NSF-AFOSR Workshop on Self-Sustaining Mechanisms of Wall Turbulence

Thursday, June 18, 1998

8:00 Introduction

Ronald L. Panton, University of Texas

8:05 Tribute to Stephen J. Kline

C. R. Smith, Lehigh University

8:15 Sustaining Mechanisms of Turbulent Boundary Layers: The Role of Vortex Development and Interactions

C. R. Smith and J. D. A. Walker, Lehigh University (invited speaker)

8:35 An Experimental Model for Near-Wall Structure

R. F. Blackwelder, University of Southern California (invited speaker)

8:55 The Role of Wall Vortices in Producing Turbulence

T. J. Hanratty and D. V. Papavassiliou, University of Illinois (invited speaker)

9:15 Open Form

Ronald L. Panton, University of Texas

9:30 Coffee Break

10:00 Formation of Coherent Hairpin Packets in Wall Turbulence

J. Zhou, C.D. Meinhart, S. Balachandar, & R.J. Adrian, University of Illinois (invited speaker)

10:20 Connecting Vortex Regeneration with Near-Wall Stress Transport

J. C. Klewicki, University of Utah (invited speaker)

10:40 Summary and Appraisal of Self-Sustaining Mechanisms; I

A. J. Smitts (invited speaker)

11:05Summary and Appraisal of Self-Sustaining Mechanisms; II

D. G. Bogard, University of Texas (invited speaker)

11:30 Lunch

1:00 Wall Layer Microturbulence Phenomenological Model and a Semi-Markov Probability Predictive Model for Active Control of Turbulent Boundary Layers

J. C. S. Meng, Naval Undersea Warfare Center (invited speaker)

1:20 Hierarchical, Self-sustained Energy Cascade to Small Scales in Wall-bounded Shear Turbulence

N. Aubry, New Jersy Institute of Technology (invited speaker)

1:40 How Streamwise Rolls and Streaks Self-Sustain in a Shear Flow

J. Kim and F. Waleffe, UCLA and MIT (invited speaker)

2:00 Mechanisms of Turbulent Wall Bounded Flows

L. Sirovich and Ahmet Ormutag, CUNY/Mount Sini School of Medicine (invited speaker)

2:20 On the Dynamics of Turbulent Boundary Layers

B. J. Cantwell, J. M. Chacin, and P. Bradshaw, Stanford University (invited speaker)

2:40 Dynamics and Control of Near-Wall Vortical Structures in Turbulent Boundary Layers

Wade Schoppa and Fazle Hussain, University of Houston (invited speaker)

3:00 Coffee Break

3:30 Summary and Appraisal of Self-Sustaining Mechanisms; III

J. Jimenez, Universidad Polytecnica de Madrid (invited speaker)

4:00 Summary and Appraisal of Self-Sustaining Mechanisms; IV

R. Moser, University of Illinois (invited speaker)

4:30 Open Form

Ronald L. Panton

5:30 End

AIAA 99-0552

Self-Sustaining Mechanisms of Wall Turbulence - A Review

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Self-Sustaining Mechanisms of Wall Turbulence - A Review

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Abstract

At a recent NSF-AFOSR workshop on self-sustaining mechanisms of wall turbulence several research groups presented their concepts. This paper reviews the idea that were presented. The paper is to distribute this information to fluid dynamicists who are non specialist in turbulence. The production of turbulence and Reynolds stress centers around vortices and "streaks' of low speed fluid near the wall. There are two main categories of self-sustaining mechanisms. In one category parent vortices interact with the wall and produce offspring. In the second category streak velocity profiles are unstable and produce vortices.

Introduction

The term "turbulent structure" or "coherent structure" is used to indicate a fluid motion that has coherence over a spatial region and lasting for a reasonable period of time. Turbulent Eddy is an older term. The study of these structures, their relationships and interactions is essential to define simplified mechanisms that give turbulence its self-sustaining characteristic.

Physicists can study something for the sake of intellectual curiosity. Engineers, first because they are engineers and second on order to get funding, must show an application that benefits society. Study of the self-sustaining mechanisms is justified for two purposes. The first is to construct mathematical models for predicting turbulent flows. The second is to guide in the construction of flow control technology either to enhance or moderate turbulence.

For some time there have been informal gatherings of workers in this field to discuss results and issues. A couple of meetings held at Ohio State University in the 1960-70's were called Delta Conferences. In 1985 a workshop was held at the University of Texas. More formal conferences were the Zaric Memorial International Seminar on Near Wall Turbulence in 1988 and the NASA Langley Conference on Turbulent Boundary Layer Structure in 1990. More recently a monograph "Self-Sustaining Mechanisms of

Wall Turbulence," (Panton (1997)) contained the thoughts of 16 author groups on the subject. Finally, a NASA-AFOSR workshop was held at last June 18th in conjunction with the 29th AIAA Fluid Dynamics Conference. For the workshop all authors in the monograph were invited to update their work. In addition, four noted researchers were invited to critique the papers (D. G. Bogard, A. J. Smits, R. Moser and J. Jimenez). These critiques have been very valuable in preparing this review. Workshop presentations are available in AIAA papers 98-2959 through 98-3002. The NSF-AFOSR workshop grant monitors, Roger Arnt and Steven Walker, requested a wider distribution of the proceedings. This paper is to serve that purpose.

My goal here is to provide an introduction the subject and the current state of development. The reader should obtain a survey of the nomenclature and sketch of proposed mechanisms. I assume that the reader is not a specialist in turbulence, but has a knowledge of fluid dynamics.

Review of Mean Flow Trends and Regions

A brief review of elementary concepts follows. Turbulent flows over walls in pipes, channels, and boundary layers have some common features. The flows have two overlapping regions where different physical processes dominate. The region immediately next to the wall is the same in each instance while the outer regions of pipes, channels, and boundary layers are different but qualitatively similar. The common coordinate system is x in the flow direction, y measured from the wall, and z in the transverse direction. Parameters that describe the flow are the centerline or free-stream velocity U_o , the boundary layer thickness or channel half-height δ, the fluid viscosity ν, and the friction velocity $u_* . \equiv (\tau/\rho)^{1/2}$ (ρ = fluid density, τ = wall shear stress). The important Reynolds number is $Re_* = u_* h/\nu$ or $Re = U_o h/\nu$. Re is a factor of 20-30 larger than Re_*. Ultimately one is interested in the distribution of mean velocity $U(y)$and Reynolds stress $\langle uv\rangle(y)$ across the flow.

The outer region distance variable is

$$Y = \frac{y}{\delta}$$

while the inner distance scale ν/u_* (called a *viscous unit*) yields variables

$$y^+ = \frac{u_* y}{\nu} = Y\,Re_* \,; \quad x^+ = \frac{u_* x}{\nu}\,; \quad z^+ = \frac{u_* z}{\nu}$$

with inner time

$$t^+ = \frac{t}{u_*^2/\nu}$$

Theory indicates that for high Reynolds numbers the mean velocity can be represented by a composite of two functions

$$\frac{U(y)}{u_*} = f_o(y^+) + W(Y) \quad \text{where } Y = y^+/Re_*$$

In the inner region $W(Y)$ is negligible and the law-of-the-wall $f_o(y^+)$ describes the velocity. The inner region consists of a viscous sublayer, $0<y^+<7$, where $f_o = y^+$, a buffer region, $7<y^+<50$, where the production of turbulent energy reaches a maximum, and an overlap or log region, $y^+>50$, where the velocity is

$$\frac{U(y)}{u_*} = f_o(y^+) = \frac{1}{\kappa}\ \ln y^+ + C_i$$

In the outer region the law-of-the-wake W(Y) is qualitatively the same for pipes, channels, and boundary layers.

Figure 1 plots the mean velocity profiles in a pipe for Re_* from 200 to 100,000. Empirical functions were used for $f_o(y^+)$and $W(Y)$. It is somewhat amassing that these functions fit the experiments from Re_* =100,000 down to Reynolds numbers as low as say $Re_* = 800$. Some adjustments in the coefficients are needed to get to the Reynolds number $Re_* = 200$, the lowest value for which turbulence is developed.

The Reynolds stress is also given by a composite expression

$$-\frac{\langle uv\rangle(y)}{u_*^2} = g_o(y^+) + G(Y) - 1$$

Here $g_o(y^+)$ is the inner region stress distribution and G(Y) that for the outer region. Figure 2 is a plot of the composite expansion for the Reynolds stress with Re* values from 200 to 100,000. The empirical relation used has been fitted to pipe and channel data from experiments and DNS (Panton(1997)). These data seem to fit very nicely for all Reynolds numbers of known experiments and DNS (Re* values from 170 to 1650).

It is of interest to look at the production of turbulent kinetic energy. This is given by the product of mean shear and Reynolds stress

$$P = -\frac{\langle uv \rangle}{u_*^2} \frac{d\,U/u_*}{dy^+}$$

The curves in Fig. 3 shows little Reynolds number variation for Re* values from 200 to 100,000. The maximum production is well within the inner region at $y^+ = 12$. One can appreciate that modeling this region for LES calculations is an extremely difficult problem.

A very encouraging aspect is the fact that the mean velocity and Reynolds stress show theoretical Re trends. One could imply that physical processes producing $\langle uv \rangle$ discovered at low Reynolds numbers are likely to also be relevant at higher values. This is not to say there will not be modifications or new events, however, it is likely that the dominant process are roughly similar.

The Reynolds stress is caused by x-direction velocity fluctuations u and y-direction fluctuations v having a non zero correlation $\langle uv \rangle$. Wallace et al. (1972) provided a major conceptual tool when they divided the contributions to $\langle uv \rangle$ into quadrants according to the signs of u and v. Events where u and v are + are quadrant one, Q1 events. Similarly $u-$ and $v+$ are Q2 events, $u-$ and $v-$ are Q3 events, and $u+$ and $v-$ are Q4 events. They experimentally determined the distribution of events that compose the Reynolds stress, Fig. 4. Although there is significant cancellation, the results have caused workers to concentrate on Q2 and Q4 events as the major turbulence producing motions.

Simple Structures and Events

It is natural in the quest to understand turbulence that we use elemental flow patterns. The purpose of this section is to define and describe these elements in a historical context.

One of the first elements or turbulent molecules was proposed by the aerodynamicists
Theodore Theodorsen (1952). He proposed that *horseshoe (hairpin) vortices* arose from the wall to transport fluid and produce Reynolds stress. The ends were attached to the wall. Fig. 5 was drawn by his daughter and appears in Theodorsen (1955). Jim Wallace has the original drawing in his laboratory. As an addition, the picture shows secondary and tertiary vortices spring from the main structure.

Townsend, without any reference to Theordorsen proposed an *attached eddy* ; Townsend (1956). Figure 6 is taken from the 1976 version of Townsend's book. The double cone vortices were envisioned to be attached to the wall along a line and extend into the log layer. My impression is that the vortices are fixed in space. Townsend (p178) states" Our concept of an attached eddy is of a flow pattern which is of finite size, mechanically coherent and resistant to disintegration. If energy is supplied to or removed in one part of the pattern, energy flows to or from that part to preserve the structure,..."

A considerable amount of detail has been added to our knowledge by examining DNS data. Robinson(1991), examining the boundary layer DNS results of Spalart (1988), found it convenient to divide the horseshoe vortex into three parts *legs, neck,* and *arch,* as shown in Fig. 7. He also found that the majority of horseshoes were incomplete or one sided. The are then referred to as *arches.* As the legs become elongated and they become *streamwise vortices.*

Streamwise, *quasi streamwise vortices,* (also *rolls)* are a very important element in turbulence and can terminate by a divergence of the vortex lines without being part of a horseshoe.

One of the events that stimulated work in the turbulent structure area was the discovery of *streaks* or *low speed streaks.* Streaks were discovered, Kline(1967), when dye was allowed to seep from a transverse slot in the wall and enter the flow. Streaks from a hydrogen bubble wire are shown in Fig. 8 (courtesy of David Bogard and Steven Truejillo; University of Texas, unpublished). Kline(1967) and co-workers went on to determine that the streaks are caused by weak streamwise vortices close to the wall that bring wall fluid up to positions further from the wall. Since this fluid has a low speed characteristic of its former location, the term low speed streaks is often used. On the other side of the vortex fluid from a higher speed is being brought closer to the wall. The high speed regions are devoid of dye because the fluid comes from further distances from the wall. The streaks are about $\Delta z^+ = 80\text{-}100$ wide and can be $\Delta x^+ = 1000$ in length. They are not observed above $y^+ > 40\text{-}50$. The current concept is that relatively short, $\Delta x^+ = 100$ streamwise vortices are convected over the wall, bring up the low speed fluid and leave it behind in the long trails. Streaks are thus somewhat distinct from their method of formation The term *streak* is also used to mean a *U(y,z)* velocity profile that has an oscillation in the *z* direction as well as a profile in *y*. This profile has no roll or streamwise vortex component.

The Kline group observed that the dye would gradually lift up, oscillate and the abruptly "burst". Figure 9 shows the process. Later Bogard and Tiederman(1984) showed that one streak had several *ejections*, which were grouped together to be called a *burst* . Some estimates are that bursting comprises 80% of the Reynolds stress. *Burst* as a single event has been dropped from the vocabulary in favor of the term *bursting process* (or simply the old term burst) to cover the complete sequence of events. *Shear layers* have bee observed in several locations in both inner and outer regions of the boundary layer . One important place is above and to the side of the low speed streaks.

About the same time that Kline was looking at the near wall region Brodkey was using seeded particles in the bulk flow (Corino and Brodkey(1969)). Among the events which he added to the picture were a *sweep* ; the burst process ended when a packet of fluid from the outer region came close to the wall. This brought forth a possible inner-outer interaction into the process.

The ejection event is a Q2 Reynolds stress contribution. As a result people sometimes call any coherent event that produces a Q2 contribution an *ejection.* Similarly, people frequently call any coherent event that produces a Q4 contribution an *sweep.*

Other events that occur in the outer region include the growth and bundling of horseshoe vortices. Head and Bandyopadhyay(1981) observed that the vortices extended from the wall to the edge of the boundary layer, but maintained a constant size in inner units 100 viscous units.

In flow visualization of the wall layer *pockets* clear of marking fluid were observed, Falco (1977). Pockets are formed by outer fluid moving to the wall and scale on viscous units

Configuration of Turbulent Structures

Experimental researchers have measured many characteristics of the turbulent events by conditional averaging; for instance Wark and Nagib (1991). When DNS data bases became available much more information was at hand. The problem of identifying spatially coherent vortices became important. First attempts at defining a vortex by bundles of vortex lines was unsuccessful. Likewise looking for instantaneous circular streamlines in a transverse plane proved inadequate. Robinson (1991) made a detailed analysis of a DNS boundary layer data base. He identified vortices by an elongated low pressure region that coincides roughly with the core.

One of the many general results of his work is the conclusion that streamwise vortices populate the inner region and transverse vortices populate the outer region. The overlap layer contains a mixture as shown in

Fig. 10. Cantwell, Chacin and Bradshaw (1998) have started to reexamine DNS data bases using the vortex definition of Chong *et al.*(1990). For every point in the flow they compute the discriminate of the strain rate tensor **S**. This can indicate if the flow has a local spiral structure. Although the work is still in progress one interesting result is that they do not think that the low pressure criteria of Robinson picks up all vortices. Shoppa and Hussain(1997) have also looked at the near wall of a DNS data base using a criteria involving strain and vorticity. It is thought that the vortex criteria of Hussain's group gives the same result as with the Chong method. A schematic of the educed and phase adjusted coherent structures in the wall are given in Fig. 11. Note the overlapping of the head and tails of vortices and the location of quadrant events.

Comment on Vorticity

The vorticity transport equation for incompressible flow is

$$\frac{D\omega}{Dt} = \omega \bullet \mathbf{S} + \mu \nabla^2 \omega$$

where **S** is the strain rate tensor; $S_{ij} = \frac{1}{2}\left(\frac{\partial v_j}{\partial x_i} + \frac{\partial v_i}{\partial x_j}\right)$. Researchers frequently use the concept that vortex lines follow the material particles in discussing the physics of turbulence. This is valid in inviscid situations or in viscous flows for time scales that are short compared to the viscous diffusion time. Bursting is usually so fast that viscous events are secondary. However, when one talks about a cycle longer times are involved. If one assumes the Rayleigh diffusion distance scale, $\delta = 3.6\sqrt{\nu t}$, then the viscous diffusion time to go to $y^+ = 10$ is only $t^+ = 7.7$ To cross the inner layer, $y^+ = 50$, requires a time $t^+ = 190$.

Vortex lines have only an instantaneous identity when viscous effects are important.

Another issue involves the intensification of vorticity by straining and turning, $\omega \bullet \mathbf{S}$. Neglecting viscosity the x-component of the vorticity equation is

$$\frac{D\omega_x}{Dt} = \omega_x S_{xx} + \omega_y S_{yx} + \omega_y S_{yx}$$

All textbooks that I know (including my own) interpret the term $\omega_x S_{xx}$ as vortex line stretching and the second and third terms as vortex line turning. This is actually incorrect as pointed out to me by L. Ong and J. Wallace. Stretching a vortex line is given by the projection of $\omega \bullet \mathbf{S}$ in the ω direction. If the vorticity direction is given by the unit vector α, ie. $\omega = \alpha\,\omega$, the magnitude of the stretching is

$$\alpha \bullet (\omega \bullet \mathbf{S})$$

The x-component of the stretching is actually the complicated expression

$$\begin{aligned} \text{Stretching} = \alpha_x\{ & \omega_x [\alpha_x S_{xx} + \alpha_y S_{xy} + \alpha_z S_{xz}] \\ & + \omega_y [\alpha_x S_{yx} + \alpha_y S_{yy} + \alpha_z S_{yz}] \\ & + \omega_z [\alpha_x S_{zx} + \alpha_y S_{zy} + \alpha_z S_{zz}]\} \end{aligned}$$

The x- turning component perpendicular to α is

$$\begin{aligned} \text{turning} = & [\omega_x S_{xx} + \omega_y S_{yx} + \omega_z S_{zx} \;(1 - \alpha_x \alpha_x) \\ & - \alpha_x\{\omega_x [\alpha_y S_{xy} + \alpha_z S_{xz}] \\ & + \omega_y [\alpha_x S_{yx} + \alpha_y S_{yy} + \alpha_z S_{yz}] \\ & + \omega_z [\alpha_x S_{zx} + \alpha_y S_{zy} + \alpha_z S_{zz}]\} \end{aligned}$$

Hence, there is more to stretching than $\omega_x S_{xx}$ and turning also has a contribution from $\omega_x S_{xx}$. (a more compact notation is to introduce the "strain vector "(Panton(1995)) $\mathbf{d} \equiv \alpha \bullet \mathbf{S}$. This vector gives the straining motion between two particles on a vortex line. Then the stretching component is $\alpha\ (\omega \bullet \mathbf{d})$ and the turning component $\omega\,[\alpha \bullet \mathbf{d} - \alpha\,(\alpha \bullet \mathbf{d})\,]$) Figure 12 depicts the vectors.

Self-Sustaining Mechanisms

Researchers agree that important events occur in the inner region, $0<y^+<50$, where the Reynolds stress is first produced and the kinetic energy production term reaches a maximum. turbulence. The evidence also points to the bursting process as a major element. Hence most proposed mechanisms involve the low speed streaks as a point of departure.

In this presentation the major characteristics of the various concepts will be outlined. The reader should consult the original papers for more elaboration .

Self-Sustaining mechanisms can be classified by several characteristics. Is the mechanism cyclic or intermittent.? This is not easy to decide in certain cases. A cyclic mechanism has a definite loop with a specific feedback process. The cycle is not necessarily periodic as the duration of component events may vary. On the other hand an intermittent self-sustaining mechanism is one that at some point requires a non-specific disturbance. The turbulence is in an unstable configuration waiting for a disturbance to set the subsequent events in progress.

Another characteristic of importance is location of the mechanism. Is the mechanism confined to the inner region (say y^+ <100-150)? Alternately, some schemes envision an event from the outer layer interaction with the inner layer.

Another characteristic concerns the nature of the process. Does the mechanism include an instability? The flow evolves to a configuration that only a small local perturbation will set off a sequence of events. The alternate view uses the fact that in certain conditions a vortex can generate another vortex. This parent-offspring event is integral to many proposed mechanisms.

The detailed discussion of various concepts will be given by classifying them as instability driven or parent-offspring driven. The first group will be self-sustaining mechanisms that contain the vortex regeneration by parent-offspring events.

Parent-Offspring Vortex Mechanisms

Figure 13 (courtesy of M. Stanislas and P. DuPont, Ecole Centrale de Lille) shows the elemental process of an ring vortex interacting with a wall. A boundary layer exists near the wall because it is moving. The action of the ring rolls up boundary layer vorticity and ejects an offspring vortex as shown. The same process would occur if a line vortex were used. Also the existing vorticity near the wall is not absolutely necessary. A strong vortex approaching a no-slip wall will produce its own layer of vorticity.

Bernard and Wallace (1997) envision, Fig. 14, that strong vortices near a wall produce (usually) opposite signed vortices as show. This occurs opportunistically as necessary local conditions prevail. The process is varied, complex and can take a number of forms. They have interpreted the process in terms of vorticity and made model calculations. Reynolds stress production associated with a convection vortex is shown in Fig. 15. Hanratty and Papavassiliou(1997) produced this figure from DNS calculations of a channel flow. Brook and Hanratty(1993) suggest that the vortex regeneration process is not related to the outer flow. In the category of parent-offspring mechanisms Smith and Walker (1997) provide a detailed picture. In Fig. 16 they show a symmetric horseshoe vortex and note places where secondary vortices are born. Local adverse pressure gradients cause vortical fluid to erupt and roll up into secondary hairpin. A schematic of their cyclic self-sustaining process is depicted in Fig. 17. A low-speed streak is generated by the passing of an hairpin vortex. A strong enough vortex, perhaps the legs of the original vortex or perhaps another, interacts (viscous-inviscid interaction shown on the figure) to an cause ejection from the streak. The subsequent vortex-wall interaction regenerate the hairpin vortices. Sweeps are the inrush of high speed fluid following formation of a new hairpin at the surface. Zhou, Meinhart, Blanchara, and Adrain(1997) and Tomkins, Adrain, and Balachandar(1998) subscribe to the parent-offspring vortex regeneration theme. However, they add hairpins grouping into packets as an important element. This is depicted in Fig. 18. From an initial vortex regeneration occurs grouping the vortices into packets. The number of packets increases with Reynolds number. Their packets cover the entire layer as shown in Fig. 19. Note that they claim a similarity with the vortex array observed in the outer layer by Head and Bandyopadhyay(1981).

A distinct type of inner-outer interaction is proposed by Klewicki(1997)Fig. 20. A ring vortex in the outer region over a pair of streaks reorganizes spanwise vorticity into two vortices creating a sweep in between. One side is the primary vortex and the upstream the pocket vortex. additional interactions of the pocket vortex with the streaks form more hairpin vortices.

Streak Instability Mechanisms

Next, the category of self-sustaining mechanisms based on instability mechanisms will be discussed. Figure 21 is taken from Blackwelder (1997). As covered in the section on Simple Structures and Events, streamwise vortices collect low speed fluid from the wall into low speed streaks (LLS in the figure) as they are convected along. This causes the velocity profile U(y,z) to have inflectional profiles. Since plane inflectional profiles are known to be inviscidly unstable, Blackwelder proposes that the oscillation, ejection, and breakup are the result of this instability. The figure shows uncertain interactions with the outer region. In turn the outer region motions toward the wall sweep in high speed fluid and form the pockets. A further connections to and the origin of the streamwise vortices are uncertain in Blackwelder's.

In an AIAA paper Jimenez and Pinelli(1997) tested the viability of the streak instability mechanism and the parent-offspring mechanism. They made DNS computations in a "minimal channel" flow. A minimal channel is a flow with where the x and z dimensions of the computational domain are shrunk so small that the large eddies of the outer flow cannot form, but turbulence is maintained. Thus, the test is rather sever. By artificially modifying the boundary conditions and equations they could promote or inhibit either mechanism. They concluded that the streak instability cycle is possible and needs no outer region. On the other hand the parent-offspring cycle did not appear viable. This later conclusion may be modified by higher Re_* and/or larger domains.

Waleffe and Kim(1997) in a series of computations have investigated the streak instability cycle for plane Couette flow. They reduced the Reynolds number until only the essential features of the turbulent flow remained. From this and other stability calculations they propose a cycle where the streaks (recall that "streak" implies a U velocity profile with low and high speed oscillations in z, but no variation in x and no vortex like swirl) are linearly unstable. This instability is a long wavelength, sinuous, inviscid instability. See Fig. 22. The instability grows and non linearly interacts with the streak to produce a new streamwise vortex. The vortex in turn would be convected over the wall to produce a new streak by the standard process. This cycle is completely within the inner region.

Turbulent Poiseuille flow in a channel was examined in great detail by Shoppa and Hussain (1997) . They identified a sinuous, linear, inviscid instability that occurs if the streak strength is sufficiently strong. Upon nonlinear saturation, "stretching" of the streak waviness by $\omega_x \, \partial u/\partial x$ causes formation of a streamwise vortex. The cycle is then completed by formation of a new streak by the vortex. Cross-sections in the yz plane are shown in Fig. 23 at various times in the process. Contours of constant ω_x vorticity are depicted. A further result of import is that Shoppa and Hussain can observe the three-dimensional structure of the vortex and neighbors as they develop and form arch vortices and internal shear layers. This correlates with the coherent structures they previously educed from channel flow DNS data (see figure 10). Their work makes a prediction about almost all Reynolds stress producing events previously observed. As noted by Moser(1998) it provides many specific details that can be tested against data.

Spectral analysis of turbulence using bases functions determined from DNS of channel flows has given some insights into the dynamics of turbulence. The functions are known as POD, proper orthogonal decomposition, or KL eigenfunctions, Karhunen-Loeve. Aubry(1998) discusses the model she previously presented. Truncating a system of equations at six modes Aubry modeled the region $y^+ < 40$. Among the many assumptions necessary is a fluctuation pressure boundary condition at $y^+ = 40$. Thus, an inherent assumption is that the outer region actively initiates events in the inner layer. In solutions of the truncated system Aubry observes that stable streamwise vortices exist for a period followed by a rush of activity similar to a burst. A new quiescent period ensues.

Sirovich(1998) and Omurtag and Sirovich(1988) project DNS data onto a eigenfunction basis and observe the evolution of coefficients. They note that streak and streamwise modes interact with a propagating mode. The propagating mode has a velocity characteristic of the free stream and hence implies an outer-inner interaction. They also conclude that a low dimensional model will require 100 modes that are carefully selected to represent the correct physical elements. Identification of dominant self-sustaining mechanisms awaits further progress.

Summary

It is possible that several self-sustaining mechanisms exist in wall turbulence. Two general classes of mechanisms are the parent-offspring vortex class and the streak instability class. Within each class there is general agreement on the major points. Research groups do, however, differ in the details and elaboration. It is an open question whether the outer layer is actively involved in the mechanism. The majority favor a mechanism confined to the inner layer. The streak instability mechanism can exist at low Re in a situation without an outer layer whereas the vortex parent-offspring mechanism cannot. It is not clear whether the cause is the low Reynolds number or the lack of an outer layer.

The summary and evaluation papers of Bogard(1998), Smits(1998), and Moser(1998). are useful references for an overview of this subject.

Acknowledgment

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Figure 1. Mean velocity profiles in a pipe for Re* from 200 to 100,000.

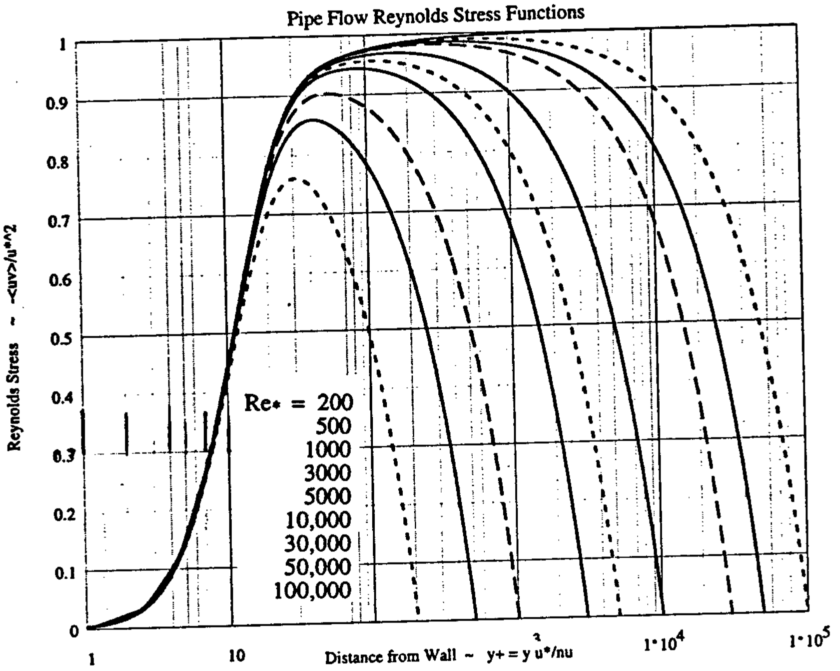


Figure 2. Reynolds stress with Re* values from 200 to 100,000.

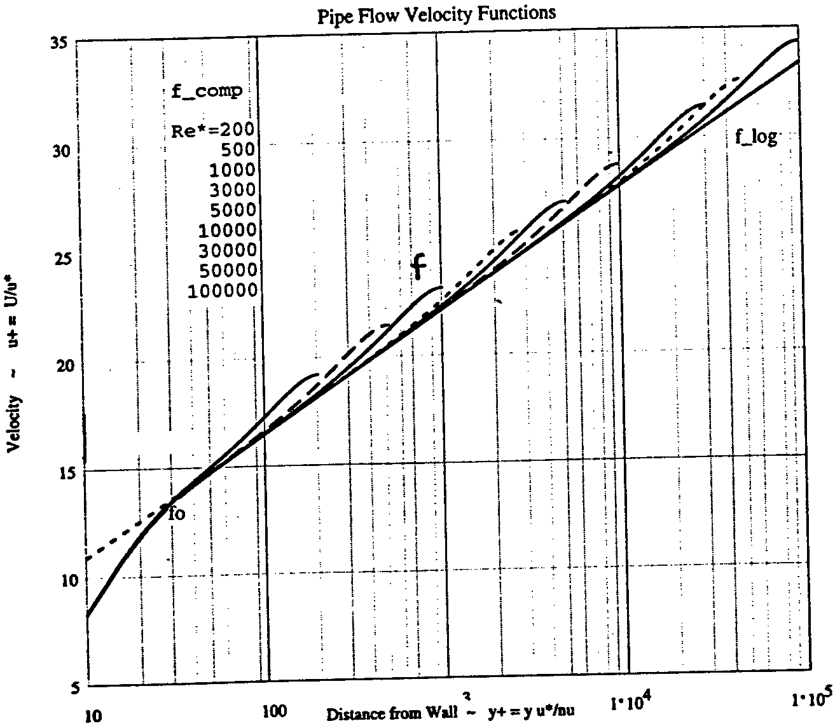


Figure 3. Turbulent energe production for Re* values from 200 to 100,000.

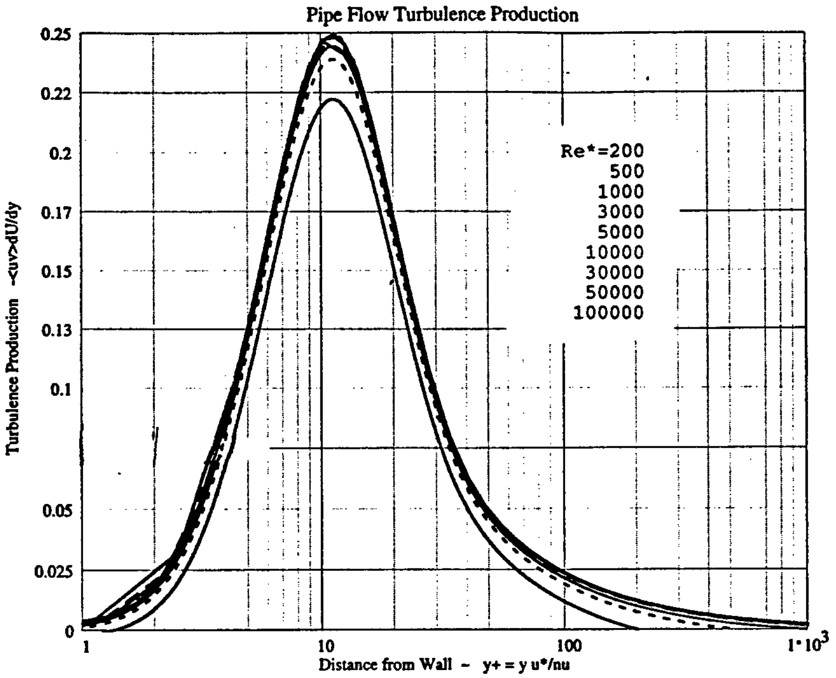
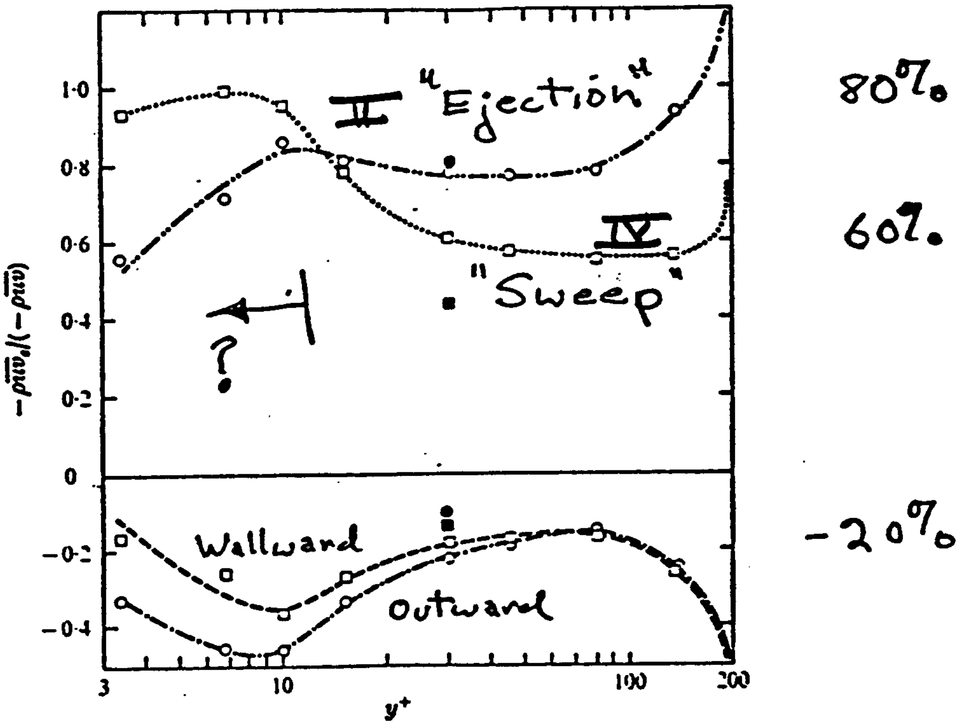


Figure 4. Quadrant contribution to Reynolds stress from Wallace et al. (1972).

R. S. Brodkey, J. M. Wallace and H. Eckelmann



GURE 1. The classified Reynolds stresses normalized with the local average Reynolds ess. ●, ■, results of Willmarth & Lu (1972). ·····, sweep; —··—, ejection; —·—, outward interaction; – – –, i_w, wallward interaction.

Figure 5. Horseshoe concept from Theodorsen (1955)

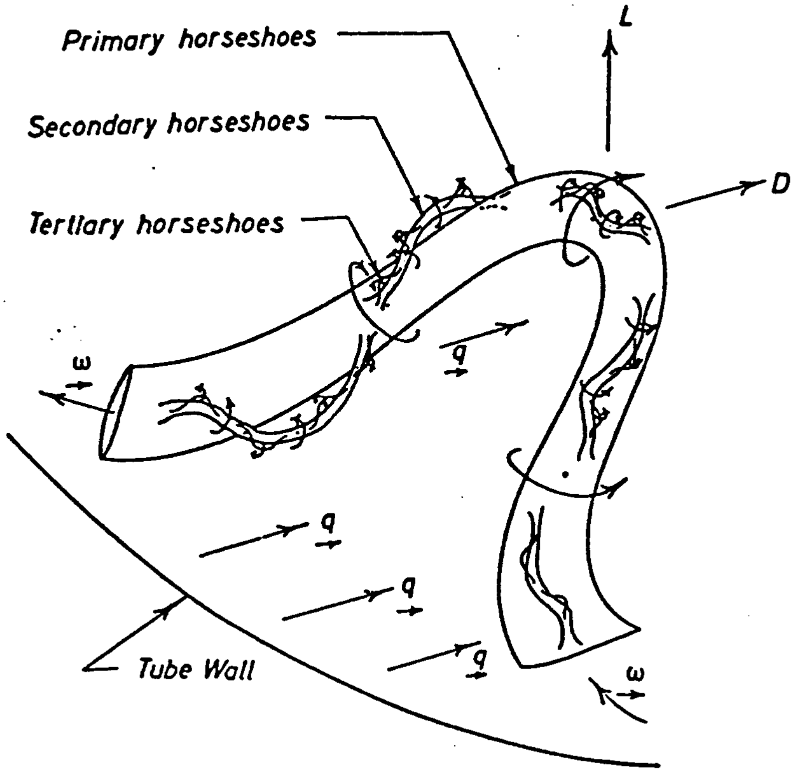


Figure 6. Attached vortices from the 1976 version of Townsend's book.

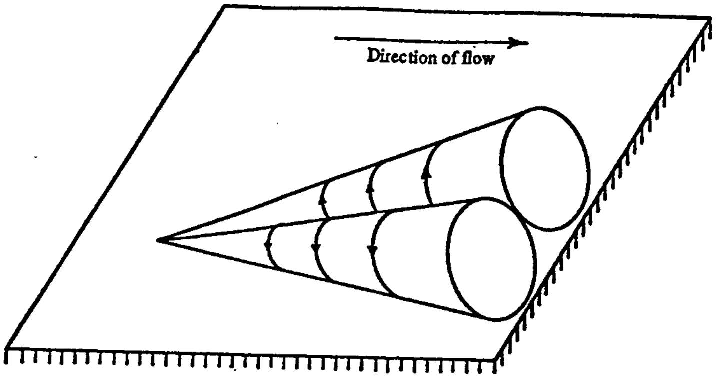
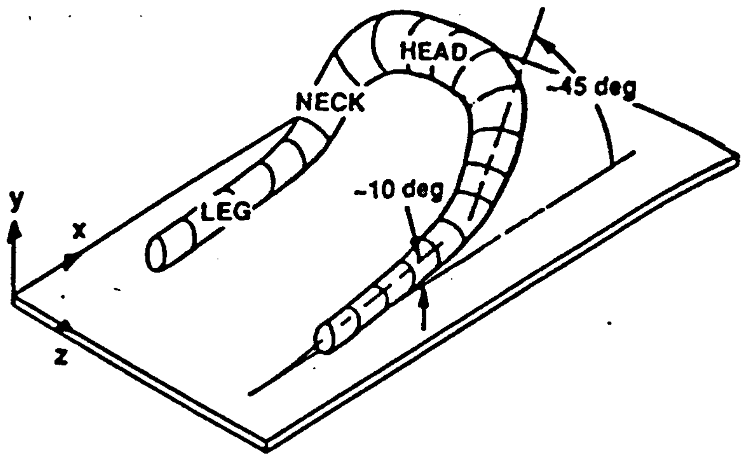


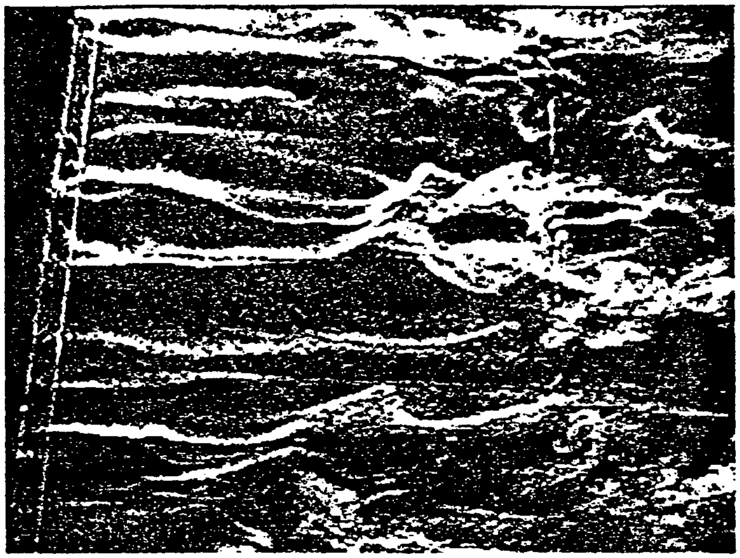
Fig. 5.8. Sketch of a double-cone eddy.

Figure 7. Parts of a Horseshoe vortex from Robinson(1991).



Nomenclature for schematic hairpin vortex.

Figure 8 Low-speed streaks courtesy of David Bogard and Steven Truejillo; University of Texas.



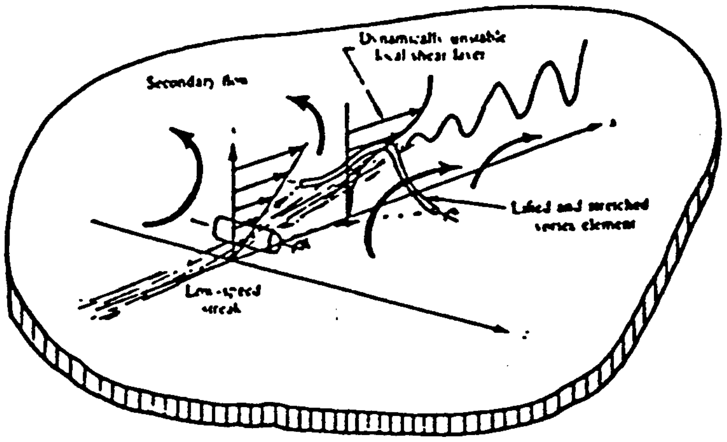


Figure 9 **Kline et al (1967). "The mechanics of streak breakup."**

Figure 10. Vortices in different regions (from Robinson (1991)).

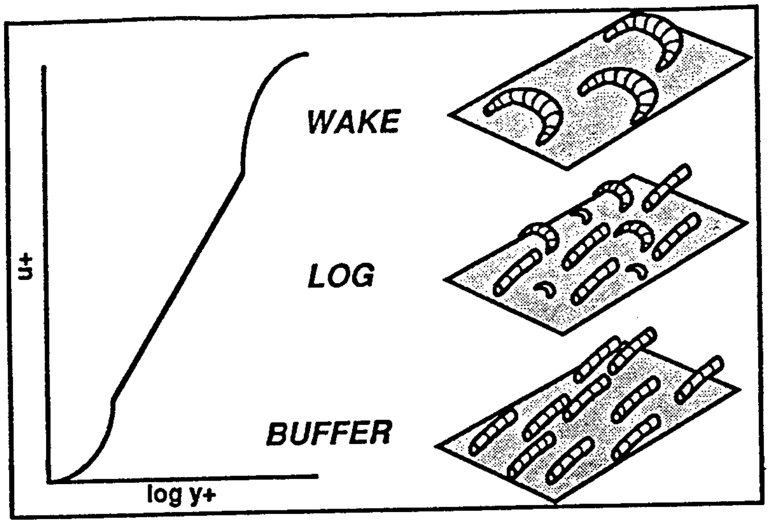


Fig. 11. Near wall vortex structures according to Shoppa and Hussain(1997).

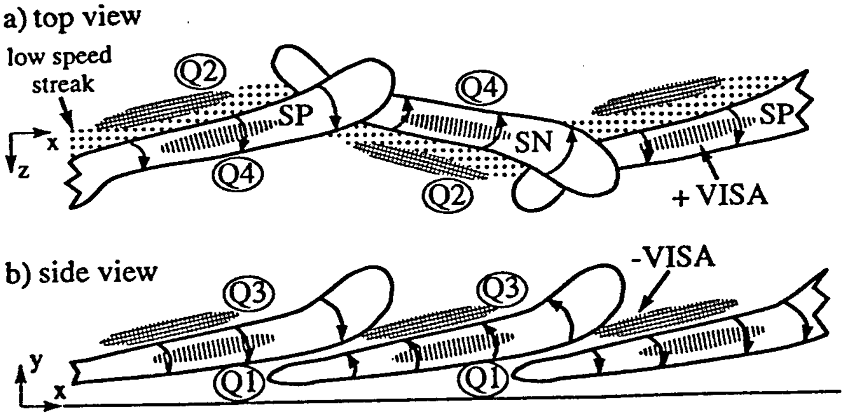


Figure 12 Strain vector showing *dv/ds* for particle P' wrt P on a vortex line.

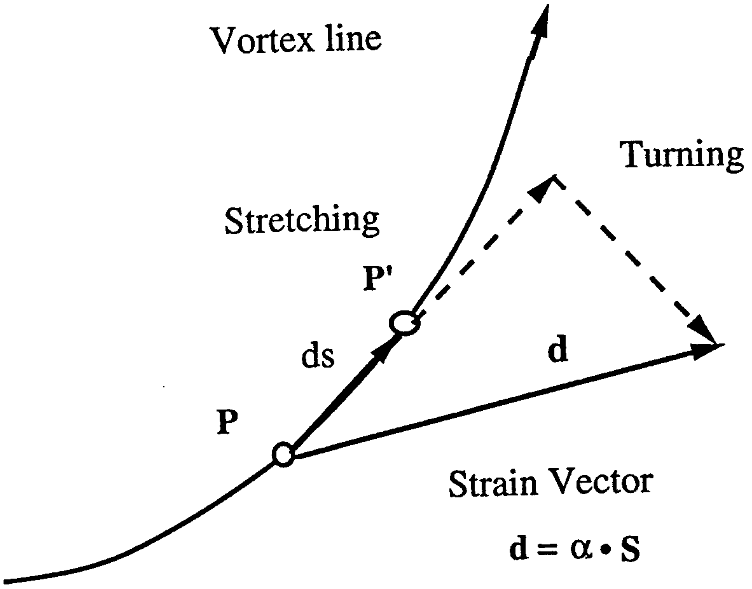


Figure 13 Elemental process of an ring vortex interacting with a wall. Picture courtesy of M. Stanislas and P. DuPont, Ecole Centrale de Lille.

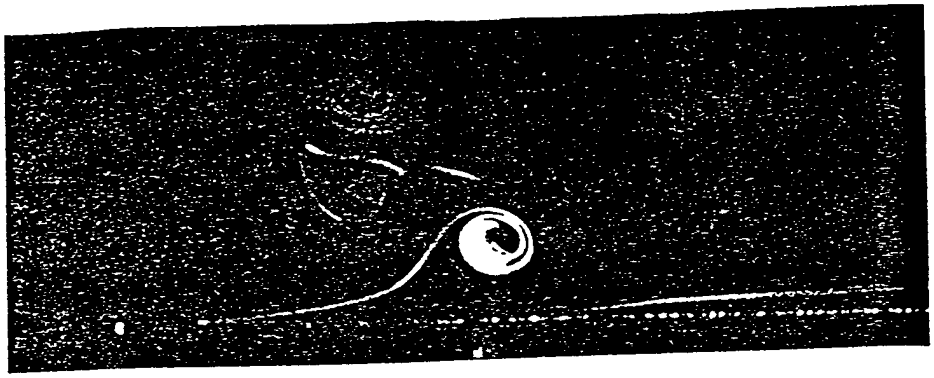
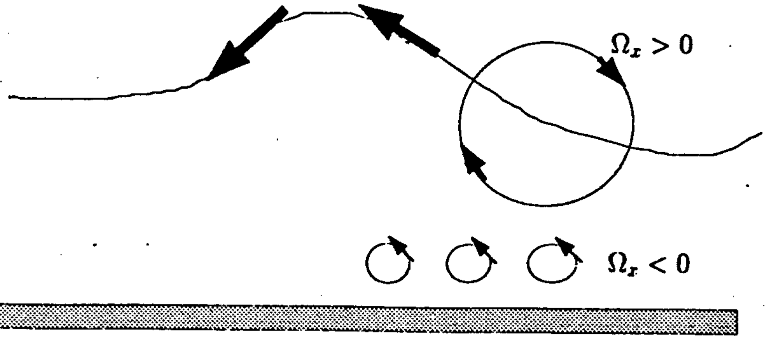


Figure 14. Strong vortices parent offspring vortices (from Bernard and Wallace (1997)).



Conceptualization of the self-replication process. Flow is into the page.

Figure 15. Reynolds stress production associated vortex (from Hanratty and Papavassiliou(1997)).

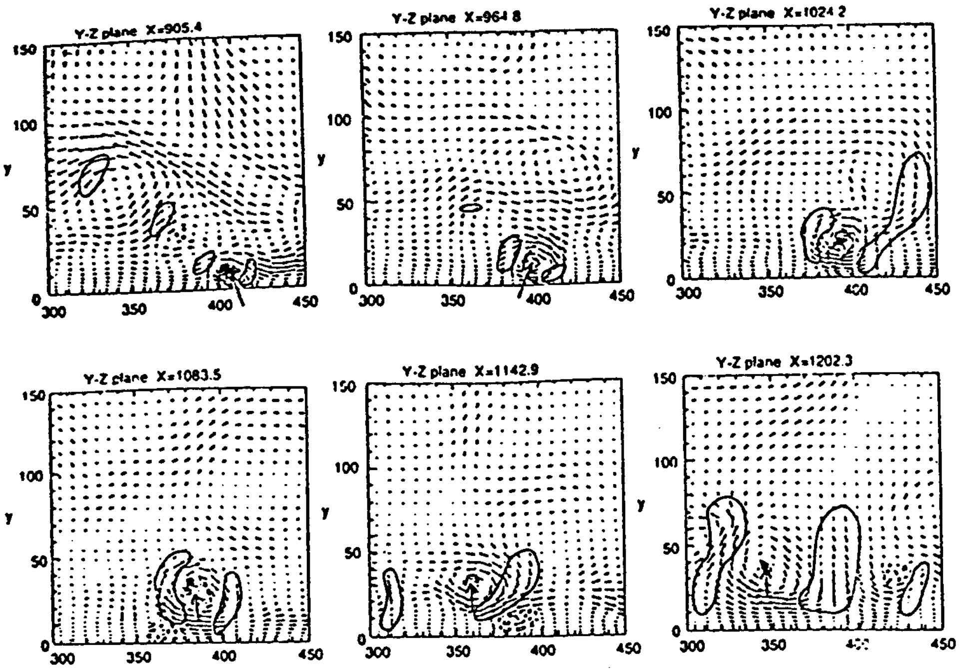
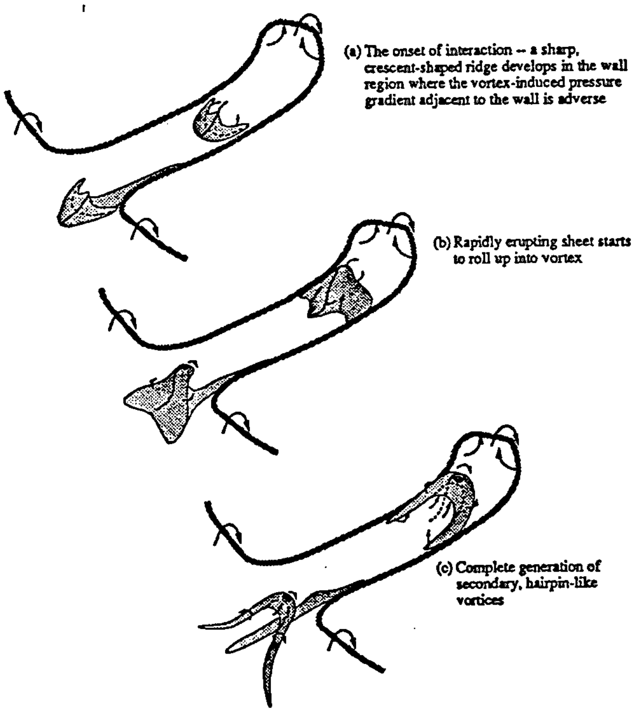


Figure 16. Smith and Walker (1997); Secondary vortices are born from primary.

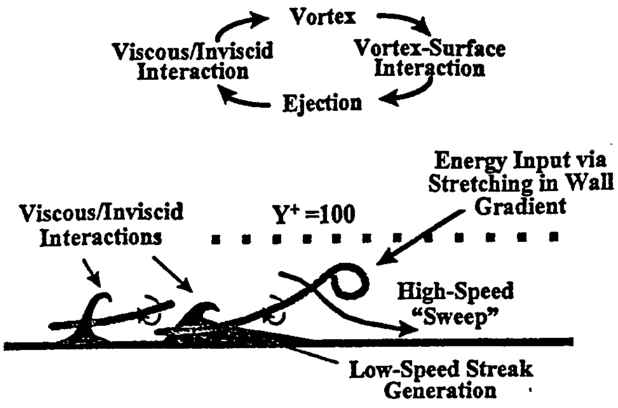


(a) The onset of interaction -- a sharp, crescent-shaped ridge develops in the wall region where the vortex-induced pressure gradient adjacent to the wall is adverse

(b) Rapidly erupting sheet starts to roll up into vortex

(c) Complete generation of secondary, hairpin-like vortices

Figure 17. Self-sustaining process according to Smith and Walker (1997).



Generalized process of near-wall turbulence regeneration

Figure 18 Hairpins packets from Zhou, Meinhart, Blanchara, and Adrain(1997).

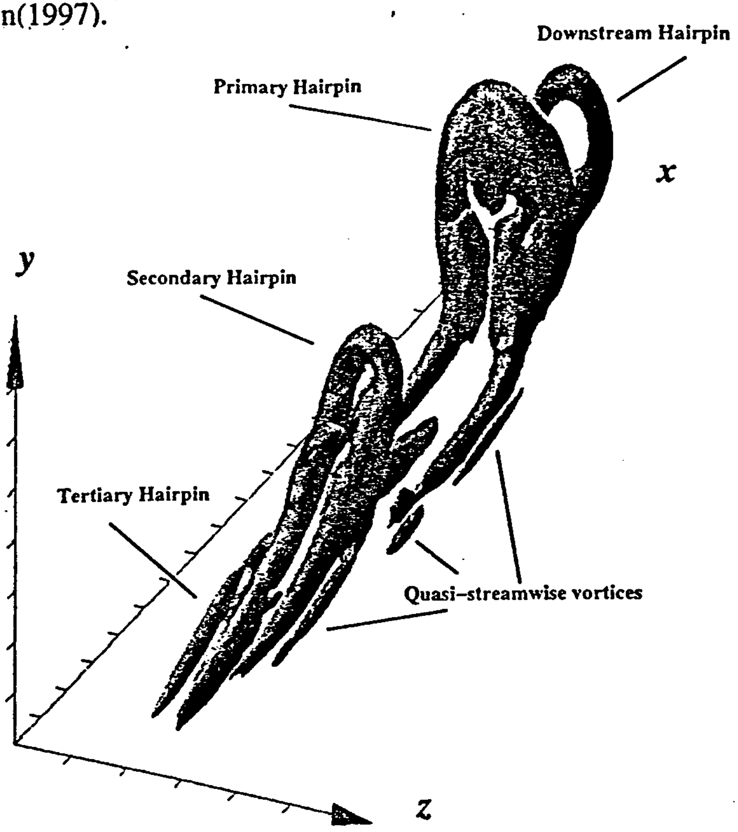
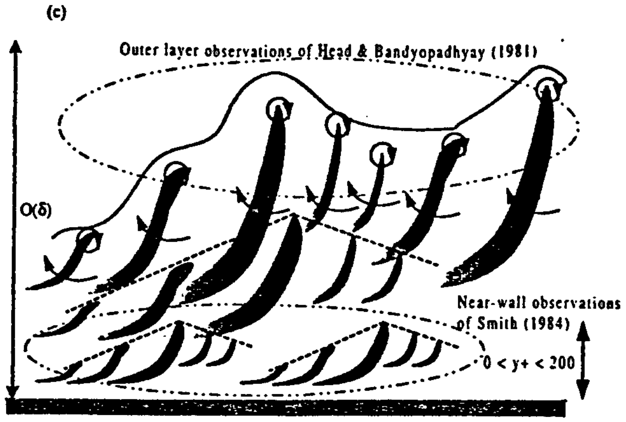


Figure 19 Packets cover the entire layer. From Tomkins, Adrain, and Balachandar(1998).



. Hairpin packet models. (a) Head and Bandyopadhyay [9]; (b) Smith [11]; (c) Hierarchy of packets as observed in [7].

Figure 20. Vortex regeneration according to Klewicki(1998)

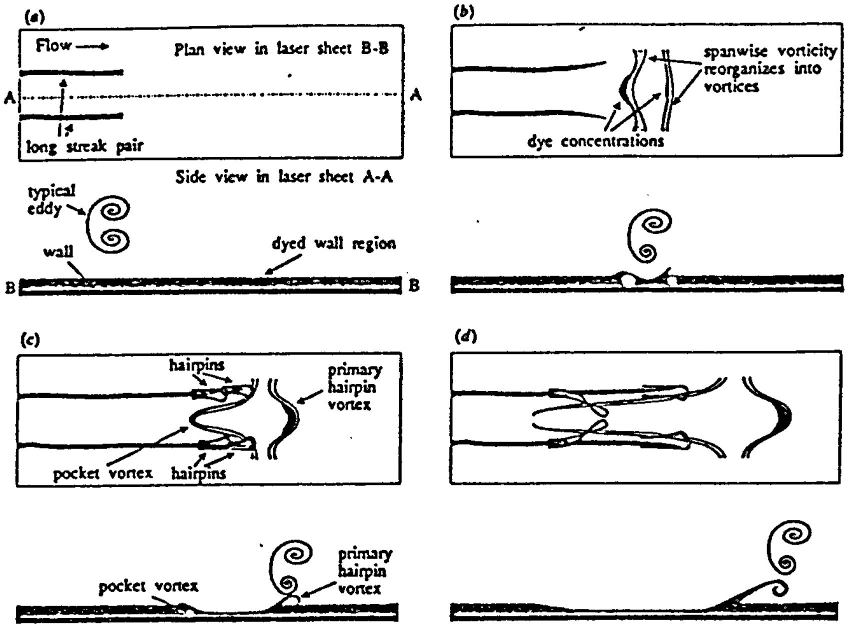
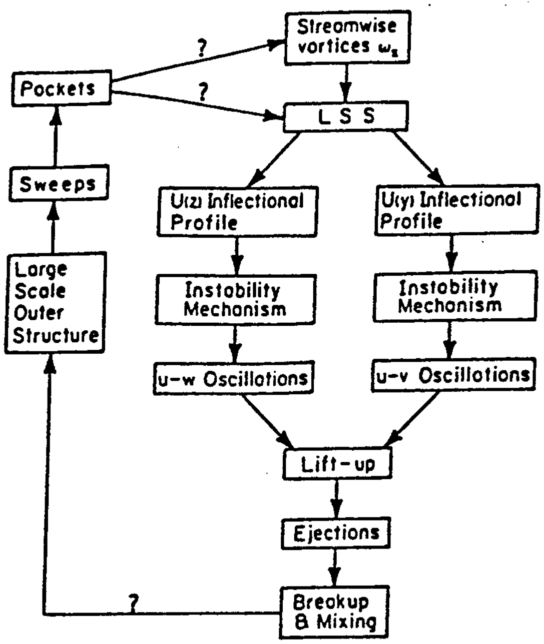
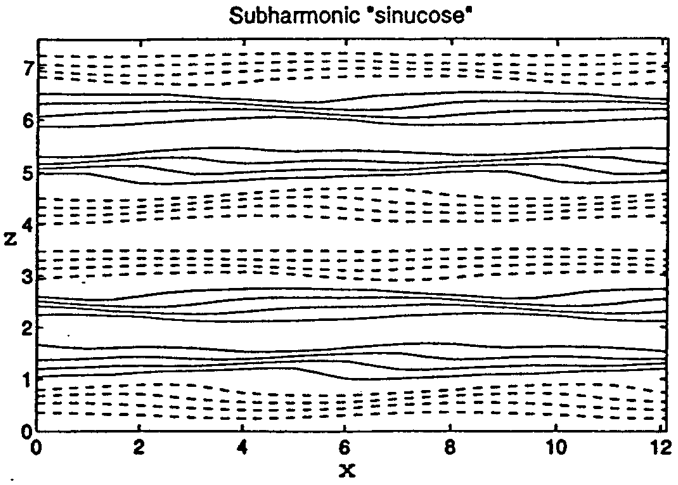


Figure 21 Self-sustaining process from Blackwelder (1997).



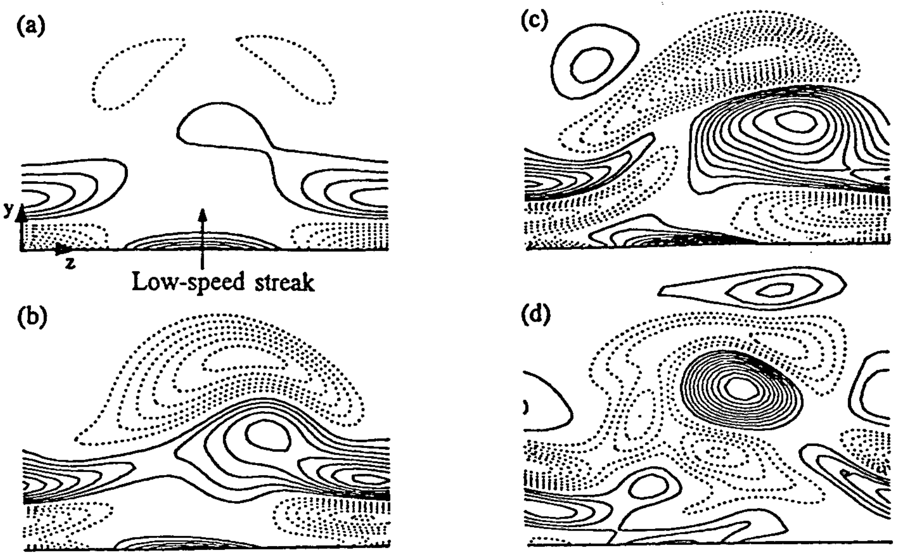
Sequence of events in the bursting process. The questionable linkages are denoted by '?'.

Figure 22. Streak instability mode in x-z plane. FromWaleffe and Kim(1997).



Subharmonic "sinucose" mode of instability of streaks at $R = 3000$. Contours of u at 0.1417 increments at the centerline $y = 0$. Positive contours solid, negative contours dashed, 3/2 periods in x.

Figure 23.Vorticity cross-sections in the *yz* plane computed by Schoppa and Hussain (1997)



. Streamwise vortex formation due to finite-amplitude streak instability, illustrated by cross-stream distributions of ω_x at (a) t^+=17, (b) t^+=51, (c) t^+=103, (d) t^+=928. Planes in (b) and (c) are tracked with the instability phase speed of approximately $0.6U_c$.