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The results and accomplishments of a combined analytical-experimental research program, aimed at understanding and modeling the three-dimensional vortex interactions that take place in turbulent boundary layers, are described. The central theme of the program is that hairpin vortices are the basic building block of boundary-layer turbulence and that many of the observed dynamical features of turbulent shear flows can be explained in terms of how hairpin vortices interact with the background shear, with each other and the viscous flow near solid walls. A basic ~~thrust~~ intent of the program is to cross-compare detailed experimental flow visualization-imaging studies of well-defined three-dimensional hairpin vortices with computational studies of the behavior, evolution and induced effects of comparable vortices. Based on these investigations, a model of the dynamics of turbulent flows near a wall is proposed. Keywords:

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1. Introduction

Most flows occuring in engineering practise involve turbulence. The major portion of boundary layers which form and grow on surfaces such as turbine blades and aircraft wings are turbulent. Turbulence is normally present in most internal flows as well as in most combustion processes. The study and prediction of such flow phenomena is therefore as extremely important area of basic research. In recent times there has been considerable experimental interest in the structure of the time-dependent flow in turbulent boundary layers. It is evident that the flow in the near wall region undergoes a relatively ordered (but complex) cyclic sequence of events. It is in this region where the production occurs, and a good understanding of the dynamics of this region is essential to developing an appreciation of why turbulent flows near walls behave the way they do; this in turn is critical to developing models which reflect the true physics of the near wall region. It is also important to the development of means to intelligently manipulate or control the flow in order to obtain a specific effect, such as enhanced heat transfer, drag reduction, or noise control.

This is the final report of a three year effort aimed at developing an understanding of the dynamics of the turbulence near walls. The research has been a combined experimental/theoretical program which seeks to elucidate the three-dimensional characteristics and behavior of the vortex structures which are believed to be intimately associated with the production processes near a wall in a turbulent boundary layer. A basic thrust of the program is to meld detailed experimental flow visualization-imaging studies of well-defined three-dimensional vortex structures with computational studies of the behaviour, evolution and induced effects of comparable vortices. The research suggests that hairpin vortices are basic building blocks of boundary-layer turbulence and that many of the features of the overall structure and production processes that are observed in turbulent flows near walls can be explained in terms of the motion and effects of hairpin vortices; such vortices give rise to "low-speed" streaks and are regenerative when in proximity to a wall. Key aspects of the program are focussed on developing quantitative velocity and vorticity information in two and three dimensions from flow visualization-imaging data, as well as pattern recognition techniques for turbulent flows based on analytical/computational models. The objective of the program is to identify the basic flow physics of the near-wall flow processes and to develop the simplest possible analytical/computational models which capture the essential features. It has been possible to develop predictive models in this manner for nominally two-dimensional flows and at present, the extensions of these concepts into more complex situations in three dimensions is in progress.

In this introductory section, a brief overview of the program will be given. This will be followed in section 2 with a detailed description of a proposed model of the dynamics of the turbulent boundary layer, which has been developed as a consequence of the research on this contract. Associated references are given in section3 and in section 4, associated publications, presentations and theses are described.

Bounded turbulent flows are comprised of a rich array of scales and flow structures which are generated and interact by means of complex, three-dimensional vortex dynamics. In addition the process of transition to bounded turbulent flow is known to pass through a complex evolution from two-dimensional to three-dimensional wave amplifications, which culminate in the development of organized three-dimensional vorticity and vortex distributions. Unfortunately the complexities of three-dimensional voretx motions in most turbulent and transitional flows are difficult to monitor and measure directly; this is because such structures develop in a Lagrangian sense and their evolution is often masked by interference with neighbouring flow structures.

In lieu of attempts at direct detection and measurement of three-dimensional vortices in bounded shear flows, methods have been developed (Acarlar and Smith, 1987a,1987b) to synthesize and study selected vortices of the hairpin type in a controlled and relatively simple environment. The objective is to gain an appreciation of how hairpin vortices evolve in a shear flow, how they interact with each other and the nature of the flow response they induce as they move close to a wall. In the first series of experiments, hairpin vortices were generated within laminar boundary layers by means of shedding from a protruberance in the wall or by controlled injection through the bounding surface. In recent work single hairpin vortices have been generated in a laminar boundary layer through computer-controlled injection at the surface. The experimental work has been complimented by companion computational and analytical studies of the motion of vortices and the nature of the flow convected vortices induce near a wall (Hon and Walker, 1987; Ersoy and Walker, 1985,1987; Walker et al, 1987; Walker and Herzog, 1987). The results of these collective studies show that three-dimensional hairpin vortices yield most of the flow visualization patterns observed in both turbulent and transitional boundary layers. In addition, recent studies by Lu and Smith (1988) has demonstrated that two-dimensional space-time velocity patterns can be shown to match quite closely with many of the space-time velocity patterns measured in turbulent boundary layers.

As a consequence of the above experimental and analytical studies, it has been possible to identify a number of significant general features of hairpin vortex motion. First hairpin vortices are low-speed streak creators and induce a

streaky structure in the flow near the wall as they are convected above (Acarlar and Smith, 1987; Hon and Walker, 1987). Hairpin vortices are also regenerative in at least two ways. As a single hairpin vortex convects in a shear flow, it develops subsidiary hairpin vortices in the spanwise direction; consequently a hairpin vortex will produce like structures in the spanwise direction as it moves in a shear flow. As this process evolves, the legs of the hairpin, move downward toward the surface where they become increasingly active in inducing wall-layer eruptions. The major process of regeneration which leads to bursting and the production of new turbulence in the near-wall region is associated with a fundamental fluid mechanics phenomena which may be termed a vortex/boundary-layer interaction. The general features of this phenomena have been identified through a series of computational and experimental studies. All vortices in motion above a wall induce a region of adverse pressure gradient on the flow near the wall; with the passage of time, the action of the pressure gradient on the viscous flow near the wall induces an unsteady separation effect. This is turn leads to a very localized boundary-layer growth and eventual eruption of the viscous flow near the wall. A wide variety of complex separation phenomena can occur depending upon the nature of the parent vortex. However the one feature that is common is that if any vortex is in proximity to a wall for a sufficient period of time, an eruption of the flow near the wall is apparently inevitable. The stronger the vortex is and/or the closer the vortex is to the wall, the more rapidly this type of event will develop. Even in situations where the vortex-induced motion is not strong, the study of Walker and Herzog (1987) shows that inflectional points are produced at locations remote from the wall-layer streak; this situation is expected to be unstable and lead to a local roll-over of the flow. These results suggest that regardless of the strength, it is the effect of convected vorticity on the viscous flow near the wall, which leads to the strong viscous-inviscid interactions and eruptive events that are observed in the near wall region of turbulent boundary layers.

The wall layer eruptions in turbulent flows near walls may be classified as a strong unsteady viscous-inviscid interaction. It is very difficult to compute the evolution of this type of unsteady separating flow at high Reynolds numbers; the major difficulty is that as the eruption develops, it focusses into a region of very narrow extent in the streamwise direction at locations that are unknown a priori. For this reason it is essentially impossible to resolve the relevant details of the flow at high Reynolds numbers as the eruption develops using methods based on the Eulerian description of the fluid motion. Methods are under development to track the flow into interaction using Lagrangian coordinates (Peridier, Smith and Walker,1988). Because most of the turbulence production occurs during the periods when the wall-layer flow breaks down and becomes interactive, it is important to develop computational methods which can cope with this type of

phenomenon.

An appreciation of the nature of the wall-layer dynamics has already had a significant impact on the development of prediction methods for turbulent boundary layers; Walker et al (1988) have developed a turbulence model for the wall-layer region which is based on the coherent structure of the near-wall flow. The methodology has recently been implimented by Walker, Werle and Ece (1988) to develop an efficient algorithm for the prediction of nominally two-dimensional turbulent boundary layers. An understanding of the salient features of the flow structure opens the possibility of extension of these concepts to fully three-dimensional mean flows, as well as rational methods of control (either active or passive) for decreasing surface drag, increasing mixing or surface heat transfer and decreasing or controlling flow separation.

In the next section, an overall model of the dynamics of the turbulent boundary layer will be described.

2. A Model of Turbulent Flows Near Walls

2.1 Introduction

In this section a model of the dynamics and production processes for turbulent flows near walls will be described. The model is based on our previous extensive experimental and analytical studies as well as the experimental investigations of others. The principal hypothesis is that the hairpin vortex is the basic building block in turbulence near a wall. Furthermore, many of the observed phenomena in turbulent boundary layers can be explained in terms of the types of flows induced by moving hairpin vortices. The important part of the production process takes place very close to the wall and it will be argued here that the process can be explained in terms of how hairpin vortices interact with each other and how they interact with the viscous flow near a solid surface.

The turbulent boundary layer is an extremely complex unsteady flow; indeed even the motion of an individual hairpin vortex in an otherwise undisturbed environment is very complicated. Consequently it is not realistic to attempt to explain all the nuances of the motion at this stage; rather the focus will be on events which take place within the turbulence which are considered to be of prime importance. Moreover our interest here is in constructing a model and identifying the mechanisms which apply in the limit of large Reynolds numbers in order that the model provide an asymptotic description over a wide range of Reynolds numbers. Unfortunately most of the experimental work, by necessity, has been at low Reynolds numbers and often suggests a myriad of possible cause and effect relationships. In order to construct an asympotitc description, it is necessary to focus on the physical processes that dominate the physics at large Reynolds numbers. From a purely experimental standpoint, this is very difficult since the flow fields at increasing Reynolds numbers tend to evolve into ever narrowing and convecting zones. Therefore, the present model is based upon a combined theoretical and experimental approach. It is worthwhile at this point to summarize some of the generally agreed upon features of the time-dependent flow in the near-wall region.

Since the original observations of the cyclic nature of turbulent flows near walls (Kline et al, 1967), a large number of experimental studies have clearly established the general nature of the processes involved (Willmarth, 1975; Cantwell,1981). Although a variety of questions concerning the cause and effect relationships of the observed phenomena are not resolved, it is clear that two main features dominate the dynamics of the near-wall flow, namely the low-speed streaks and the bursting phenomena. If observations are carried out over a fixed area of the wall, the wall layer will be seen to be in a quiescent state (Kline et al, 1967) for a majority of the total observation time. Here the term "wall layer" is used

to denote the portion of the flow from the wall to where the mean streamwise velocity profile is essentially logarithmic in y (the distance from the wall); in addition, the term "quiescent" implies a perio of relative inactivity when no strong interactions between the wall layer and the outer part of the flow occur. During the quiescent period, the wall-layer streaks are readily observed by introducing flow markers such as dye or hydrogen bubbles in water; the markers are then observed to collect into relatively long streaks which are essentially aligned in the streamwise direction. The streaks are separated by an average spanwise distance of $100\nu/u_\tau$ (Kline et al, 1967; Willmarth,1975; Smith and Metzler,1983); here ν is the kinematic viscosity and u_τ is the local mean friction velocity. The streaks are elongated in the streamwise direction and typically may have a length on the order of $1000\ \nu/u_\tau$ (Blackwelder and Eckelmann,1979; Smith and Metzler, 1983) . The streamwise velocity in the vicinity of the streaks is generally less than that of the mean profile and thus the streaks are often referred to as "low speed". The cause of the low-speed streaks is not generally agreed upon.

While the observed portion of the wall-layer flow is in the quiescent state, the time-dependent flow may be considered to possess a distinct double structure, consisting of a well-defined inner wall layer and an effectively inviscid outer region. For a turbulent boundary layer, the outer region consists of the portion above locations where the mean velocity profile is logarithmic in y; for internal flows, the outer region consists of the core flow outside the fully turbulent zone near the wall. During the quiescent period, the flow in the wall layer is relatively well-ordered, consisting of an organized motion between streaks, while the flow in the outer region is complex and relatively less well defined. Experiments indicate that the flow in the outer region consists of slowly overturning large rollers or clouds of vorticity which extend across most of the boundary layer (or core region in an internal flow) and which contain large numbers of smaller individual vortices (Head and Bandyophadyay,1981; Falco, 1977). In any event, during the quiescent phase the wall layer is very thin with respect to the thickness of the outer region and no strong interactions take place between both zones. The quiescent state is observed to terminate at isolated spanwise and streamwise locations in the bursting process, which is invariably seen to be associated with a low-speed streak. Initially, the streak is observed to lift away from the wall (Kim,Kline and Reynolds, 1967) and oscillations in both the spanwise and normal directions develop. The oscillations appear to increase in amplitude and scale until a local breakdown occurs in the form of a violent eruption of wall-layer fluid into the outer region. The eruption is soon followed by a "sweep" of high-speed, outer-region fluid toward the wall (Corino and Brodkey,1969; Offen and Kline,1974) and in the process, the chaotic motion due to the burst is swept away. At this stage, the wall-layer streaks may be observed again

locally but at somewhat different spanwise locations; with this deep penetration of high-speed fluid toward the wall, a new quiescent period begins. Over a large number of cycles, the spanwise distribution of streaks is random. It should be noted that during the quiescent state, the boundary between the wall layer and outer region is not static or distinct at some fixed value of $y^+ = yu_\tau/\nu$; rather the boundary is continually in motion outward as the wall-layer thickness grows continuously due to viscous diffusion.

The cause of the bursting phenomenon is not agreed upon, although a variety of authors have suggested that it is associated with the vortex motions in the outer region (see for example Nychas,Hershey and Brodkey, 1973; Doligalski and Walker, 1984). However if questions of cause are set aside for the moment, it is clear that the bursting phenomenon represents a local breakdown of a hitherto relatively well-ordered wall-layer flow. The brief periods when the wall layer and the outer regions interact strongly may be classified as unsteady viscous-inviscid interactions. Although the duration of the interaction is short with respect to the average length of the quiescent state, the vast majority of Reynolds stress production occurs during these periods of breakdown and not during the quiescent state (Kim et al, 1971; Willmarth,1975; Cantwell, 1981). The bursting process is the fundamental regenerative mechanism of production in which new vorticity from the near-wall region is abruptly and intermittently introduced into the outer region.

It is evident that a number of important questions need to be addressed in formulating an explanation of the dynamics of turbulent flows near walls. Central among these questions are:

(1) What flow structures cause the low-speed streaks?

(2) What causes the observed local breakdowns of the wall-layer flow which lead to the observed eruptions?

(3) How are the processes of turbulence production related to observed flow structure and how does the turbulence sustain itself?

These points as well as related issues will be considered in the following sections.

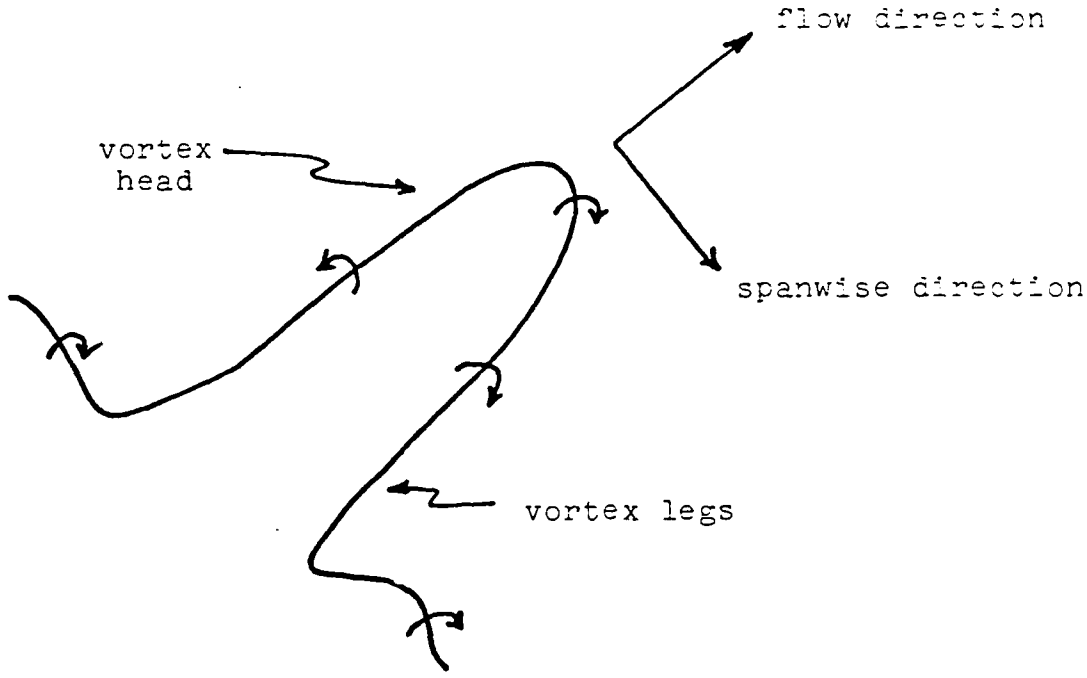
2.2 Background

It is commonly believed that the vortex motions which are readily observable in boundary-layer turbulence play an important role in the dynamics of the turbulence. A variety of vortex motions have been proposed as a basic model. In an early study by Nychas, Hershey and Brodkey (1973), it was suggested that (what appeared to be) large tranverse convecting vortices were somehow associated with the bursting events near the wall.

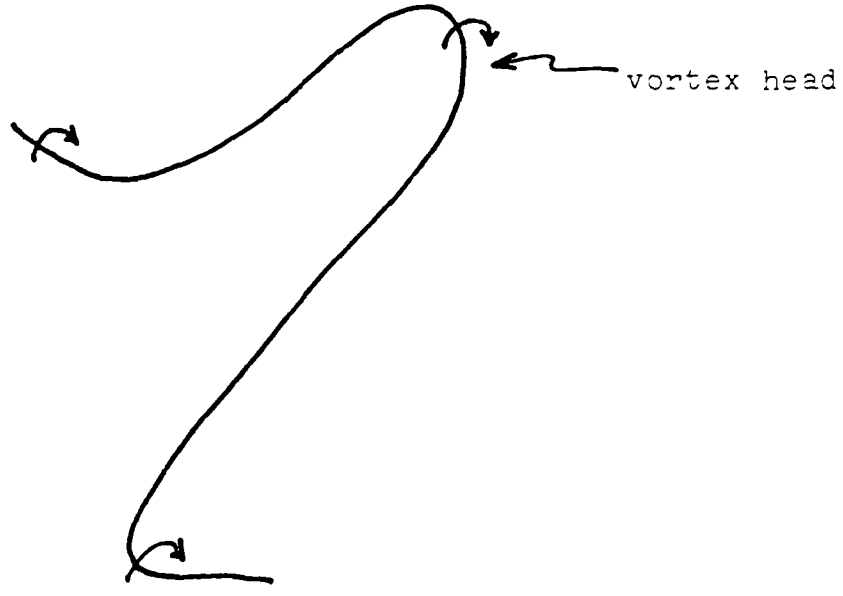
Bakewell and Lumley (1967) and later Blackwelder (1978) and Blackwelder and Eckelmann (1979) suggested that long counter-rotating streamwise vortex pairs are an important feature of the time-dependent flow near the wall. Falco (1977,1981,1982) has proposed that convected ring-like vortices are an important dynamical feature of turbulent boundary layers. Perhaps the most popular vortex model is the hairpin vortex which has been proposed as the basic building block of boundary-layer turbulence by Theodorsen (1952), Willmarth and Tu (1967), Kline et al (1967), Offen and Kline (1973,1975), Smith (1978), Wallace (1982), Head and Bandyophadyay (1981), Perry,Lim and Teh (1981), Utami and Ueno, 1983, Perry and Chong (1982), Smith and Metzler (1983), Smith (1984) and Acarlar and Smith (1984,1987a,1987b) among others.

A variety of terms have been used to describe hairpin vortices and here the term will be used to denote any vortex having the characteristic shape indicated in figure 2.1. A vortex Reynolds number may be defined by $R_v = \Gamma/\nu$, where Γ is the circulation about the vortex core and ν is the kinematic viscosity. At increasing vortex Reynolds numbers, the vorticity tends to become more tightly concentrated in smaller and smaller core regions. Head and Bandyophadyay (1981) have pointed out that many of the terms employed refer to the same type of structure, but at different Reynolds numbers. For example: (1) at low Reynolds numbers, the vortex core is relatively thick and the term "vortex loop" has been used; (2) at low to moderate values of R_v, the core thickness diminishes and the term "horsehoe vortex" is common, and (3) at moderate to high values of R_v the vorticity is concentrated in a thin core and the term "hairpin vortex" is used. In this section, "hairpin" vortex denotes any vortex having the shape indicated in figure 2.1; moreover most of the discussion will be focussed on the type of hairpin vortex depicted in figure 2.1(a) which is symmetric in the spanwise directions. It is worthwhile to note due to mutual interactions between the myriad flow structures comprising a turbulent boundary layer that a high percentage of hairpin vortices in boundary-layer turbulence are undoubtedly asymmetric in the spanwise direction similar to the type indicated in figure 2.1(b). However a good mathematical model is the simplest one which captures the essential features of the observed physical phenomena and it is believed that the symmetric hairpin serves this purpose.

Some terminology that will be used throughout this section is also shown in figure 2.1. The tip of the characteristic vortex shape will be referred to as the vortex head while the portions of the vortex that are mainly aligned in the streamwise direction and are close to the wall will be termed the vortex legs. In figure 2.1, the vortices are shown only over a range in the spanwise direction. It is worthwhile to note that in three-dimensions all vortex tubes must eventually form closed loops; they cannot terminate in the fluid or on solid walls (since the no-slip condition prohibits termination



(a) Symmetric hairpin vortex



(b) Asymmetric hairpin vortex

Figure 2.1. Schematic diagram of hairpin vortices

on a solid surface (Lighthill,1963)). A single vortex may be envisaged as being made up of several elementary vortex tubes which agglomerate and recirculate about one another in the vortex core (Utami and Ueno, 1983). Thus the vortices depicted in figure 2.1 may continue outwards in the spanwise direction (perhaps to other hairpin vortices) or may evolve in such a manner so that the individual tubes comprising the vortex core unwrap to form a vortex sheet at some spanwise location.

Head and Bandyophadyay (1981) carried out a series of wind tunnel flow visualization experiments using smoke; their results suggest that the turbulent boundary layer consists of a "forest" of hairpin vortices which continually stretch in the shear near the wall and appear to be inclined at a characteristic angle of 45^{o} to the wall. A similar picture has also been put forth by Perry and Chong (1982) who have conjectured that the turbulent boundary layer is dominated by a systematic hierarchy of hairpin vortices. There are some appealing features about these types of overall boundary-layer structure but the physical picture seems incomplete. For example, there is no clear explanation concerning the origin of the vortices or the processes leading to the production of new vorticity near the wall. In addition, the concept of a series of hairpin vortices which continually stretch and intertwine in a shear flow does not yield a regenerative pattern of evolution.

Recently Smith (1984) has proposed a model of the physical processes that occur near the wall in a turbulent flow; the model was based on extensive flow visualization experiments in water as well as a previous model due to Offen and Kline (1975). In the latter study, it was suggested that the lift-up of the low-speed streaks (which appears to be a precursor of the bursting process) is associated with the temporary imposition of an adverse presure gradient on the wall layer by some type of convected disturbance. Smith (1984) also adopts this point of view and suggests that one effect of the local adverse pressure gradient is to induce an inflectional behavior in the streamwise veolcity profile near the interface of the streak and the high-speed outer region fluid. The instantaneous inflectional profile is assumed to be unstable and to give rise to a series of roll-ups into secondary hairpin vortices. As the hairpin vortices are convected away from the surface, a strong vortex stretching process in the streamwise direction causes an intensification of the local vorticity levels in the legs of the hairpin vortices; the counter-rotating legs of the hairpin vortices act to scavage low-momentum fluid and to pump it away from the wall, thereby reinforcing the low-speed streak, and thus giving the appearance of streak persistence. The bursting process was suggested to be due to the breakup of the low-speed streak, which is lifted by the counter-rotating legs of the hairpin vortex; the rapid ejection was conjectured to be due to the local streamwise adverse pressure gradient imposed on the flow near the wall by the moving head of the hairpin vortex

(see also Doligalski and Walker, 1984).

In order to observe the motion of hairpin vortices in a controlled environment, Acarlar and Smith (1984,1987a,1987b) carried out a series of experiments where hairpin vortices were artificially generated in a sub-critical laminar boundary layer on a flat surface. In one study (Acarlar and Smith, 1987a), the hairpin vortices were generated by shedding that occurs naturally from a small hemispherical protruberance on the wall; the flow structure is indicated schematically in figure 2.2 where it may be inferred that the flow downstream of the obstacle consists of a convected train of hairpin vortices in an otherwise laminar boundary layer. In another study (Acarlar and Smith 1987b) hairpin vortices were observed to form above a stream of low-speed dye which was introduced from a streamwise-oriented slot in the wall. Flow visualization, carried out using hydrogen bubble wires and dye, determined that the convecting hairpin vortices produce flow patterns which are very similar to those observed in the near-wall region of a turbulent boundary layer. A specific example is depicted in figure 2.3 from Acarlar and Smith (1984); here the bubble line patterns generated by a hydrogen bubble wire oriented normal to the wall may be observed for (a) a convected hairpin vortex in a laminar boundary-layer flow and (b) a sequence from a fully turbulent boundary layer. In figure 2.3(a), the quantity $x/R = 20$ indicates that the flow pattern is at a streamwise distance equal to 20 hemisphere radii from the protruberance; Re_θ is the Reynolds number based on momentum thickness. In figure 2.4 (again from Acarlar and Smith, 1984), the bubble wire was oriented across the span of the flow and close to the wall. It may be observed that the convecting hairpin vortices produce a "streaky" structure near the wall (figure 2.4(a)) which is very similar to the typical patterns observed in turbulent boundary layers (figure 2.4(b)). In addition to the flow visualization studies, Acarlar and Smith (1984,1987a) also carried out a series of quantitative measurements in the region downstream of the hemisphere. It was found that measured velocities and statistics were very similar to those obtained in a turbulent boundary layer. In particular, the mean streamwise velocity profile exhibited a logarithmic portion near the wall similar to the "law of the wall". Consequently it appears that a regular train of convected hairpin vortices produces many of the essential features of a turbulent boundary-layer flow. Furthermore it is reasonable to conclude from the available experimental evidence that the hairpin vortex is an important part of the flow structure in turbulent flows near walls.

2.3 The Dynamics of Hairpin Vortices

The motion of hairpin vortices involves the convection of concentrated vorticity with the vortex core in an unsteady three-dimensional sheared flow. In three dimensional

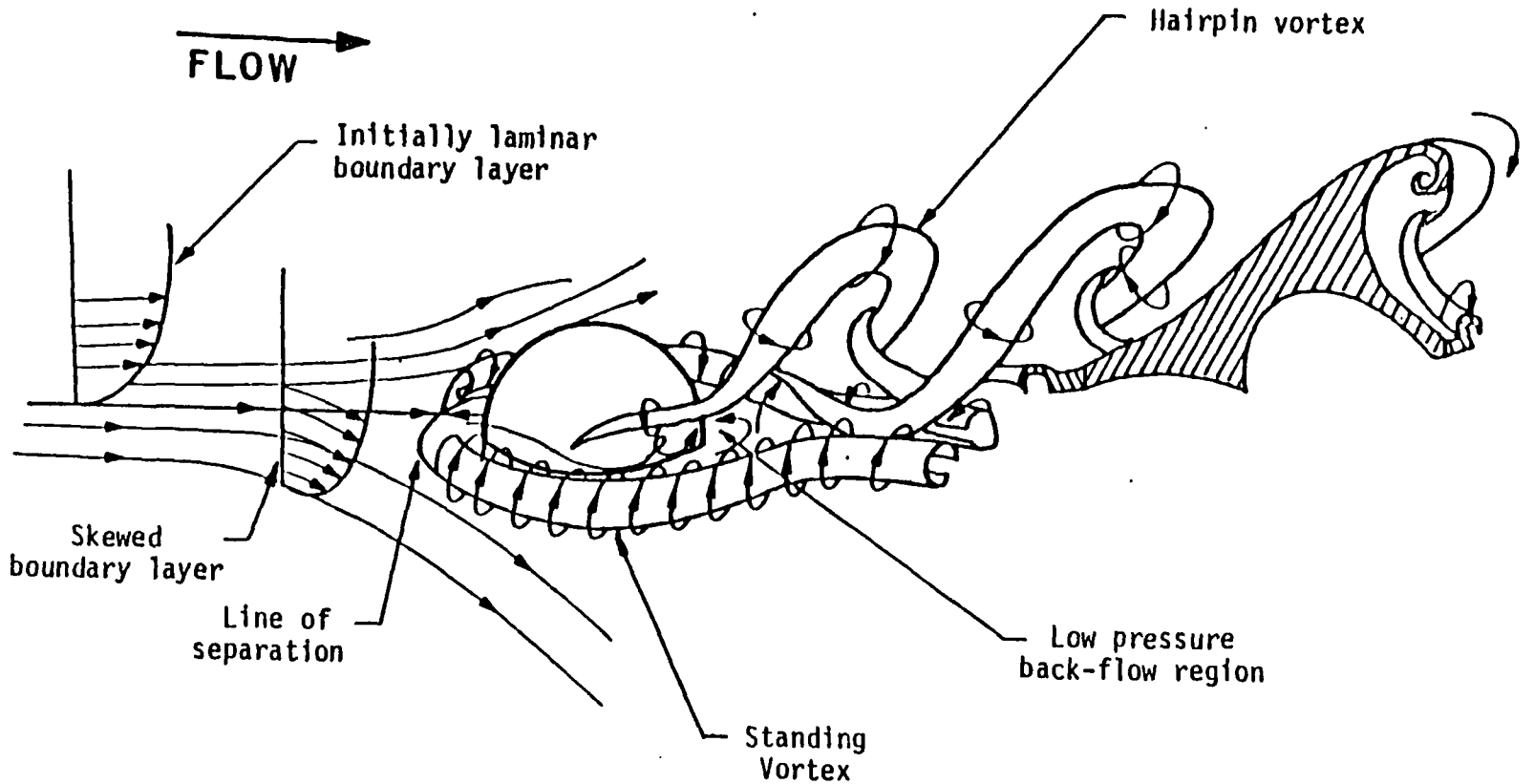
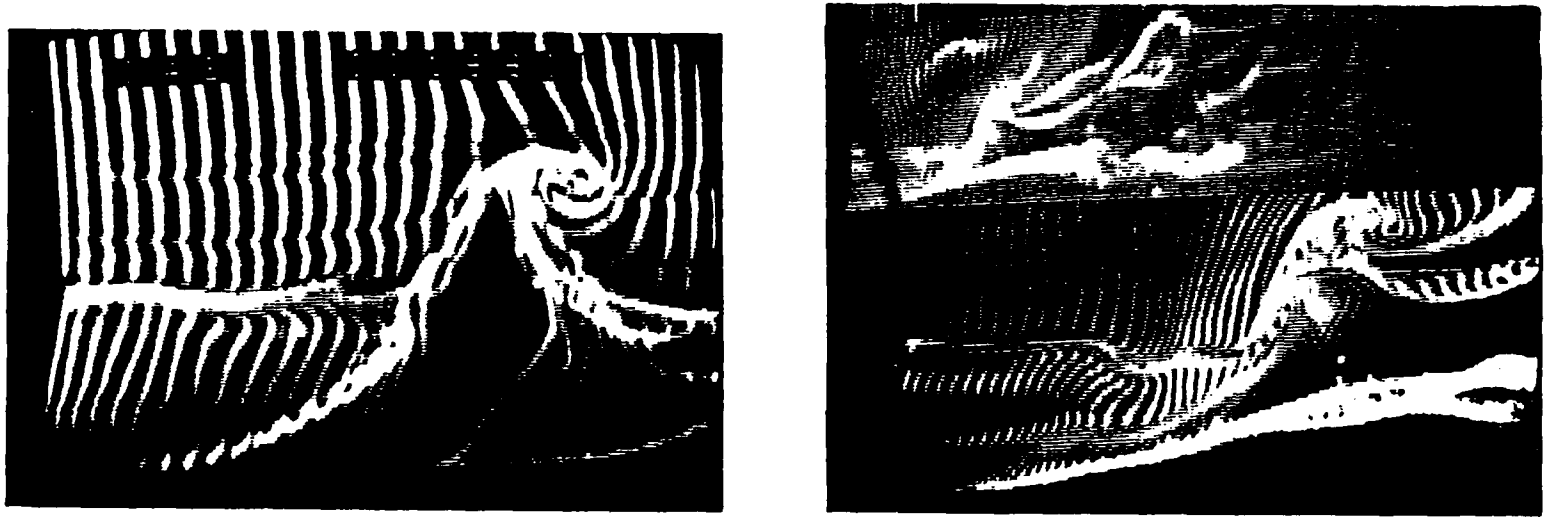


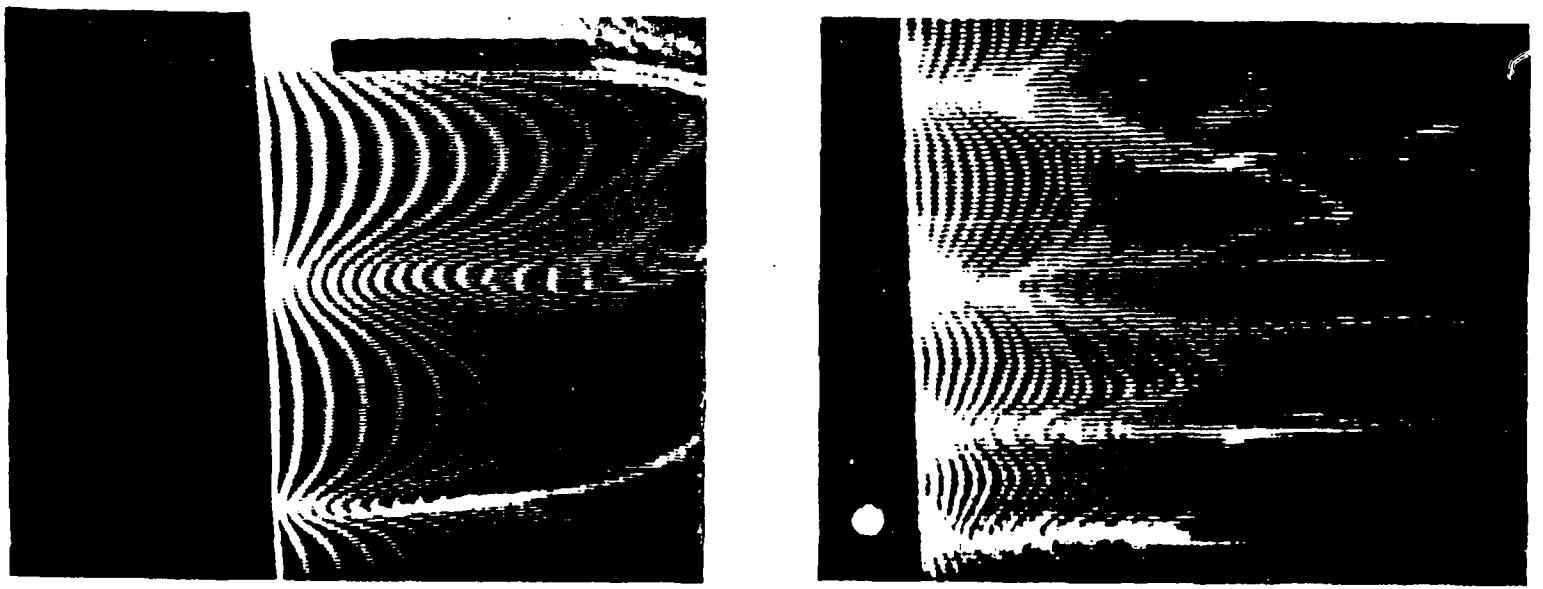
Figure 2.2. Schematic of near-wake structures in the hemisphere wake



a) Hair-pin vortex, X/R = 20

b) Turbulent boundary layer, Re_θ = 2200

Fig. 2.3. Side-view comparison between hair-pin vortex and turbulent boundary layer patterns.



a) Hair-pin vortex, X/R = 20, $y_{wire}/R = 0.08$ b) Turbulent boundary layer, $Re_\theta = 2200, y^+_{wire} = 5$

Fig. 2.4. Top-view comparison between hair-pin vortex and turbulent boundary layer pattern.

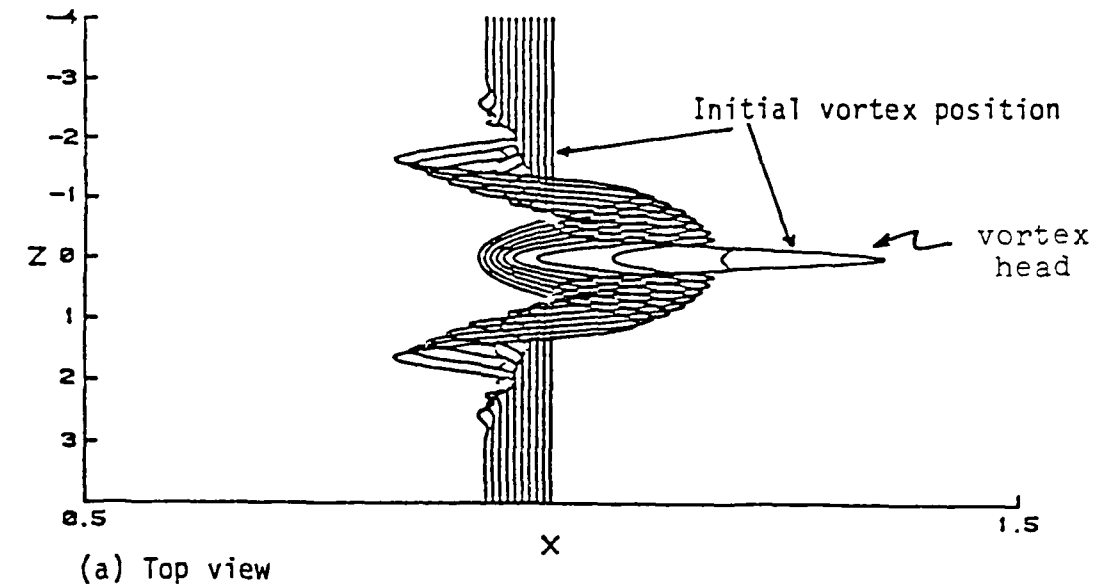
situations, vorticity evolves in ways which are not easily understood and which cannot readily be adduced through intuitive arguments. Therefore, in order to gain an appreciation of the motion of hairpin vortices in a flow near a wall, numerical simulations of the evolution of a hairpin vortex were carried out by Hon and Walker (1988) using the Biot-Savart law. Complete results and the numerical algorithm are described by Hon and Walker (1987) and here only two representative sequences will be described.

Calculated results for a hairpin vortex (having the sense of vorticity indicated in figure 2.1) in an otherwise stagnant flow above a wall are shown in figure 2.5; essentially the same development occurs when the vortex is in a uniform flow, with the exception that the vortex is convected uniformly. The initial vortex configuration consists of a three-dimensional distortion in an otherwise two-dimensional vortex. The computations are performed using dimensional variables defined in terms of the vortex strength and the distance of the two-dimensional part of the vortex from the wall. The shape of the vortex changes rapidly and a small time step ($\Delta t = 0.0002$) was necessary in order to achieve smooth results; the vortex position is plotted at intervals corresponding to every 40 time steps in figure 2.5. Each point on the vortex moves in the velocity field induced by the vortex as well as the image vortex below the wall at $y = 0$. For the calculations depicted in figure 2.5 there were 800 nodal points on the vortex out to spanwise locations of $z = \pm 4$, beyond which the vortex was assumed to remain a straight line. The straight portions of the vortex move continuously to the left under the action of the image vortex. It may be observed that the head of the vortex moves rapidly backward and after a brief interval moves downward toward the wall. It is evident that the vortex evolves in such a manner so that high local curvature is rapidly diminished. As the vortex head bends backward, the legs of the vortex curl backward in a counter-clockwise direction and the disturbance begins to work its way outward in the spanwise direction as the vortex evolves into a "cork-screw" shape; however the vortex does not spread to any great extent in the streamwise direction. The numerical integrations are time consuming and were terminated at $t = 0.072$ when the general trends in the trajectory were evident.

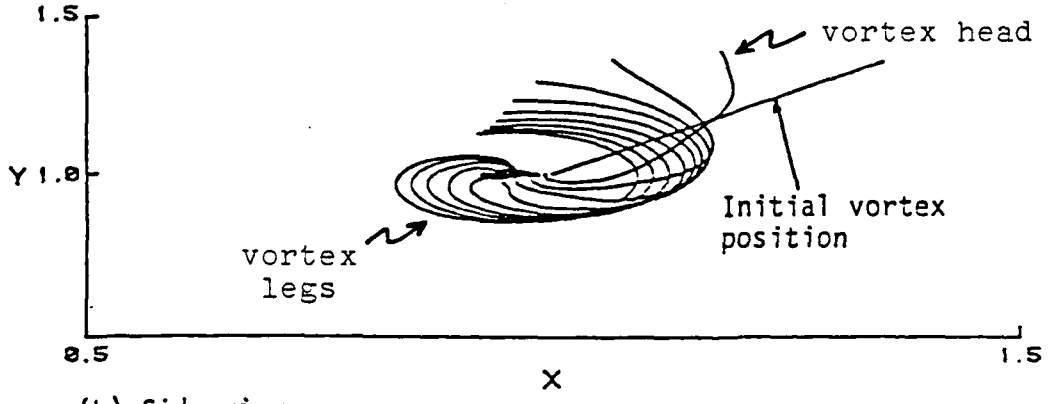
Once the hairpin vortex is embedded in a shear flow near the wall, the development changes quite dramatically. In Hon and Walker (1987), a region of uniform shear was assumed near the wall according to

$$\begin{aligned} U_b(y) &= yV/y_s \ , \quad y < y_s , \\ U_b(y) &= V \ , \quad y > y_s . \end{aligned} \tag{2.1}$$

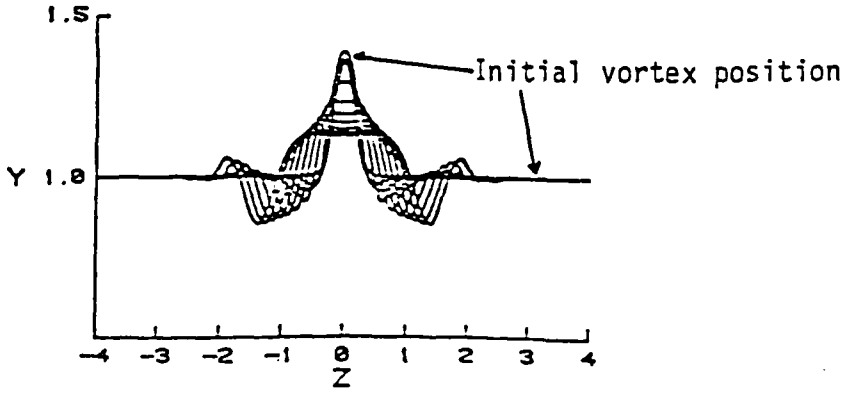
Here U_b denotes a background flow in the x-direction. In figure 2.6 the evolution of a two-dimensional vortex with a



(a) Top view



(b) Side view



(c) End view

Figure 2.5 - Temporal development for a hairpin vortex in a stagnant flow.

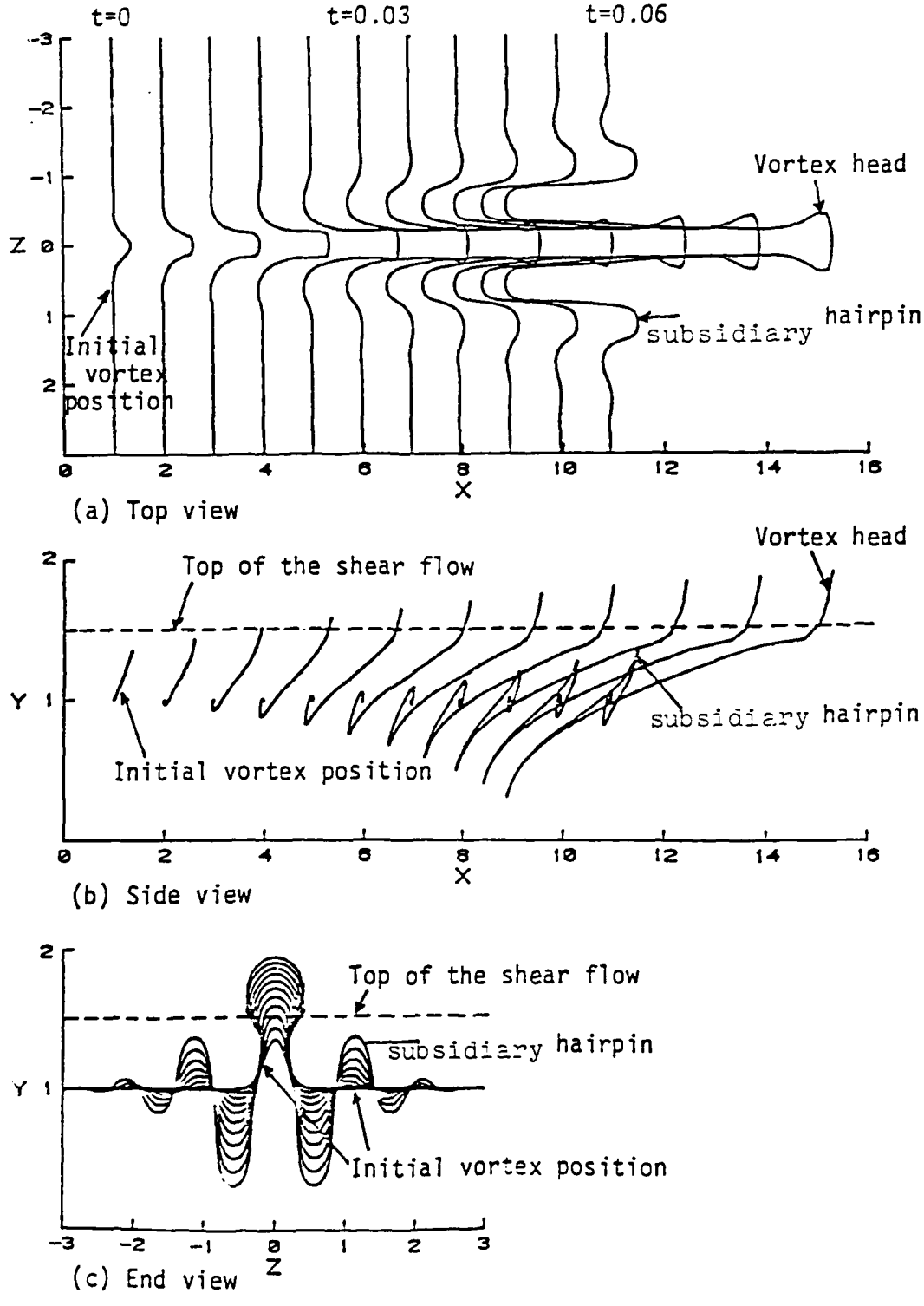


Figure 2.6- Temporal development for a hairpin vortex in a shear flow (V=250); the vortex position is plotted every 30 time steps (Δt=0.0002).

three-dimensional distortion is shown for a case corresponding to V = 250, y_s = 1.5 and the two-dimensional part of the vortex is at y = 1. The typical self-induced velocities near the hairpin vortex head are on the order of 25 units for the initial configuration shown in figure 2.6; consequently, the case considered in figure 2.6 corresponds to a hairpin vortex developing in a relatively strong shear flow. It is evident that a profound effect of the shear flow is to spread the original disturbance substantially in both the streamwise and spanwise directions. The vortex head lifts away from the wall, bends backward and eventually rises into the region of uniform flow. This type of behavior was noted by Acarlar and Smith (1984) and more recently by Haidari, Taylor and Smith(1988) for single hairpin vortices. An interpretation of the observations is shown in figure 2.7. It is also clear in figure 2.6 that vortex legs develop to the side of the vortex head and move progressively downward toward the wall; as this process evolves new subsidiary hairpin vortices begin to develop outboard of the original hairpin vortex on the initially undisturbed part of the vortex. A continuation of the computed results for this case is depicted in figure 2.8 where it may be observed that the trends of figure 2.6 continue. In this calculation, the dimensionless radius of the vortex core was taken to be small (a = 0.02) in order that the computation could be carried on as far as possible in time; shortly after t = 0.078 the vortex core touched the wall, thus terminating the calculation. At this stage the original disturbance has spread over a distance in excess of 20 times its original extent in the streamwise direction. In addition two well-developed subsidiary hairpin vortices have formed outboard of the original disturbance with additional hairpins forming outside of these.

The dynamical features computed in this simulation are in broad agreement with the experimental observations of Acarlar and Smith (1987a,1987b) and Haidari, Taylor and Smith (1989). The heads of the hairpins were invariably seen to lift upward from the wall and to bend backwards. In figure 2.9, from Acarlar and Smith (1984), a hairpin vortex is moving toward the observer and as it approaches a hydrogen bubble wire is pulsed, thus marking the flow with a line of bubbles. In this sequence, the movement of the hairpin legs toward the surface may be readily inferred, in qualitative agreement with the sequence depicted in figure 2.6 and 2.8. The spreading of the hairpin vortex in the spanwise direction and the evolution of subsidiary hairpin vortices may be regarded as regenerative in a sense; that is the original hairpin vortex interacts with the shear flow to produce multiple hairpins to the side. This process was observed in the experiments of Acarlar and Smith (1987a) and has recently been documented by Taylor and Smith (1988). In the recent study of Taylor and Smith (1988), single hairpin vortices were generated in a marginally critical boundary layer by controlled fluid injection through a streamwise slot. As these hairpins moved downstream, they were observed to develop lateral hairpins in a manner consistent

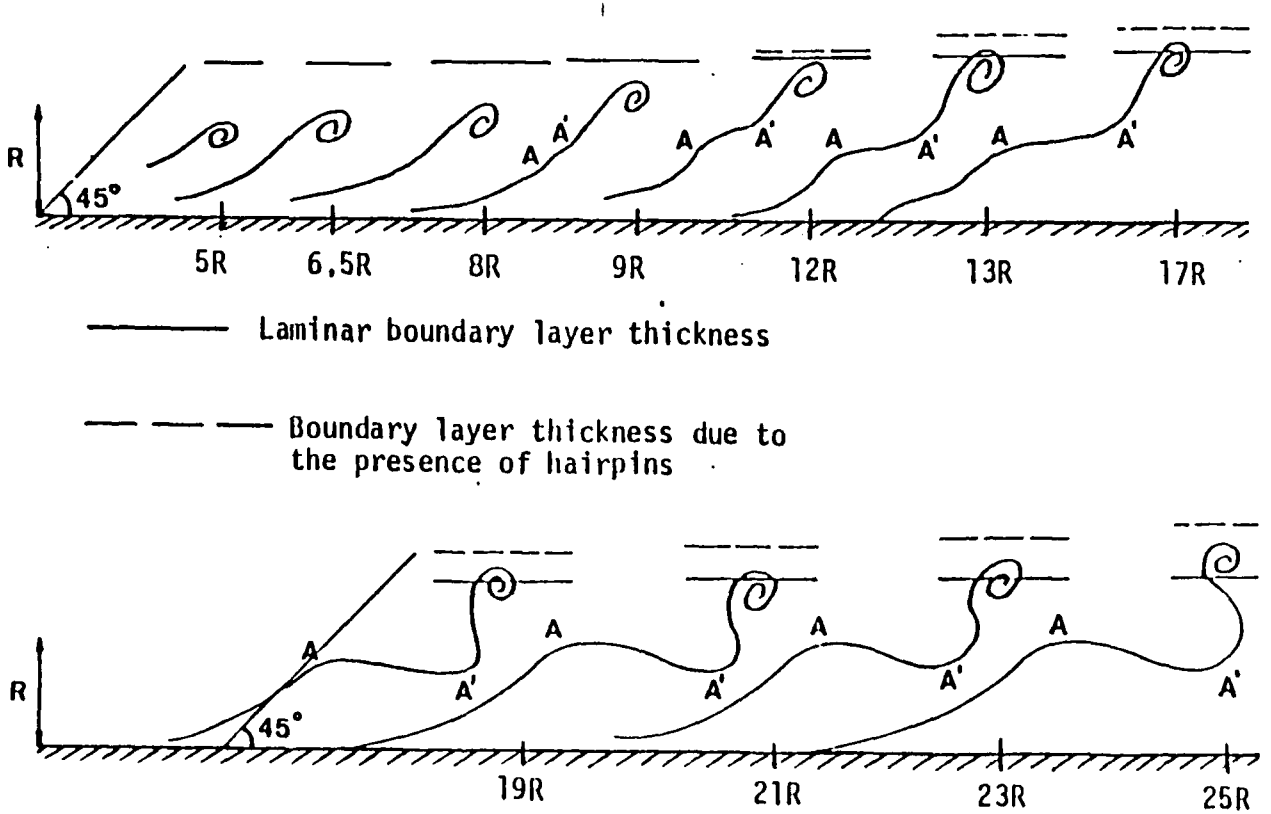


Figure 2.7 Change of the size of a hairpin vortex at various downstream locations. Re_R=800.

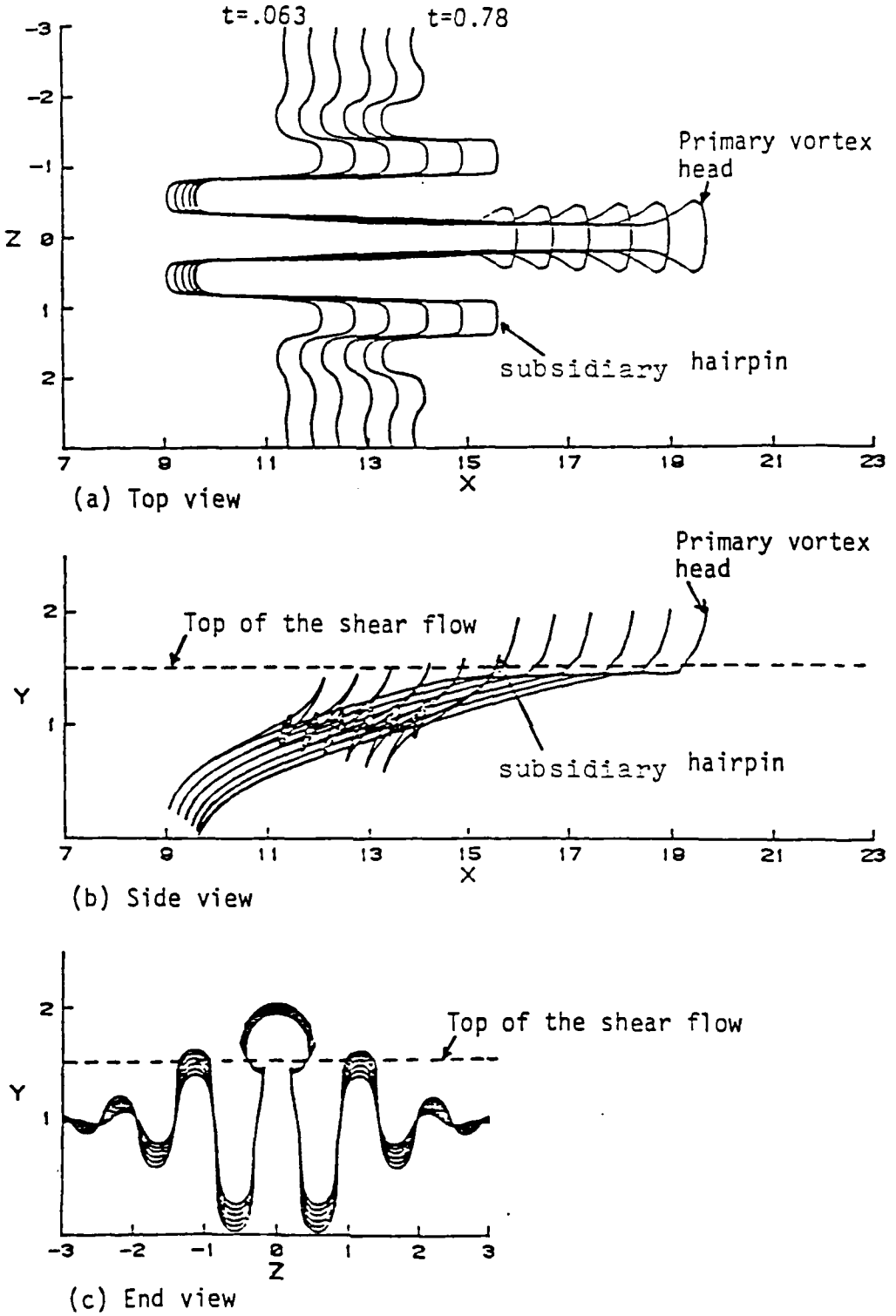


Figure 2.8 - Continuation of integration ; the vortex position is plotted every 15 time steps ($\Delta t=0.0002$).

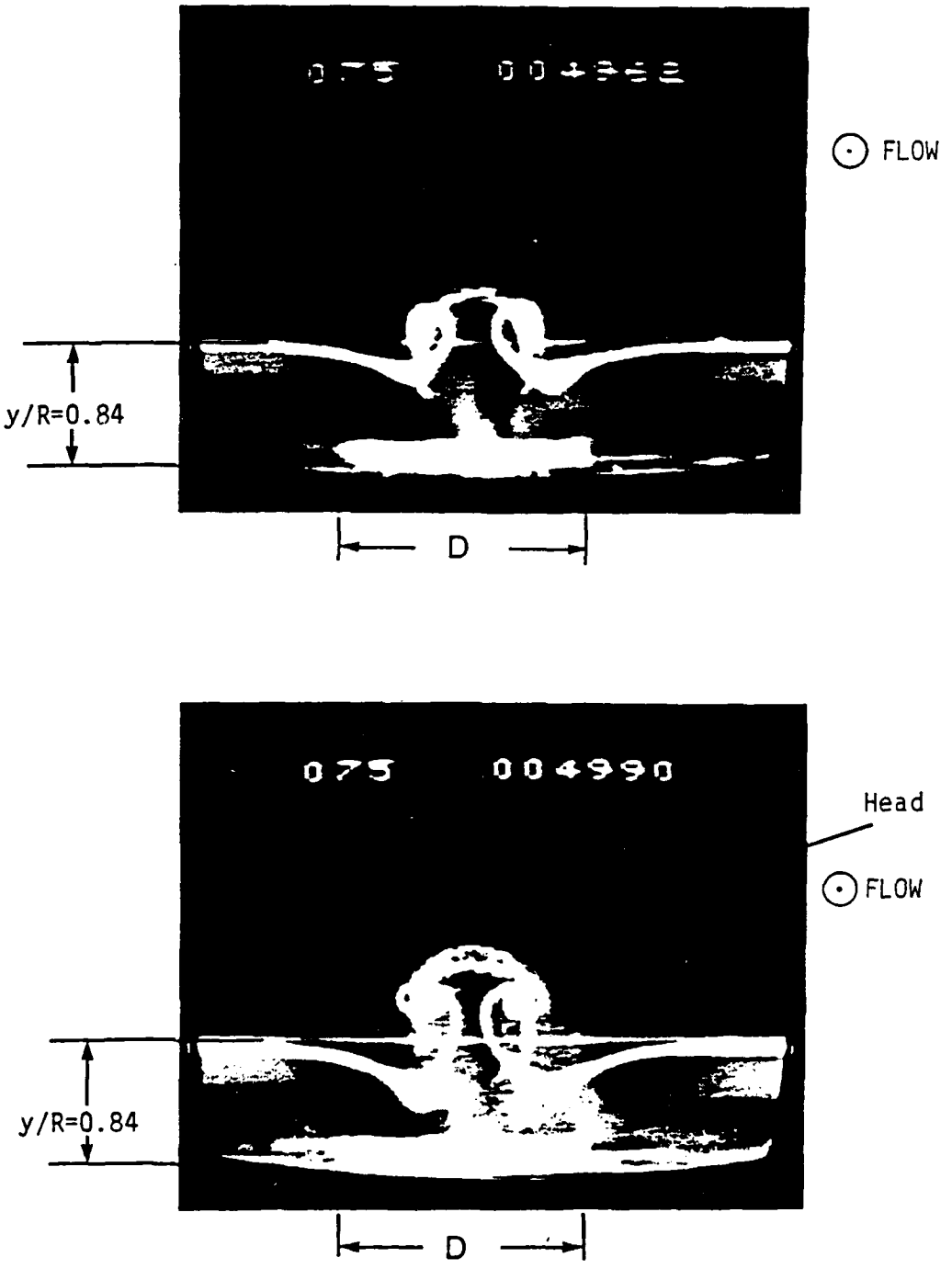


Figure 2.9 - Flow visualization sequence reproduced from Acarlar and Smith (1984) showing a hairpin vortex moving toward the observer; the visualization is accomplished with a hydrogen bubble wire.

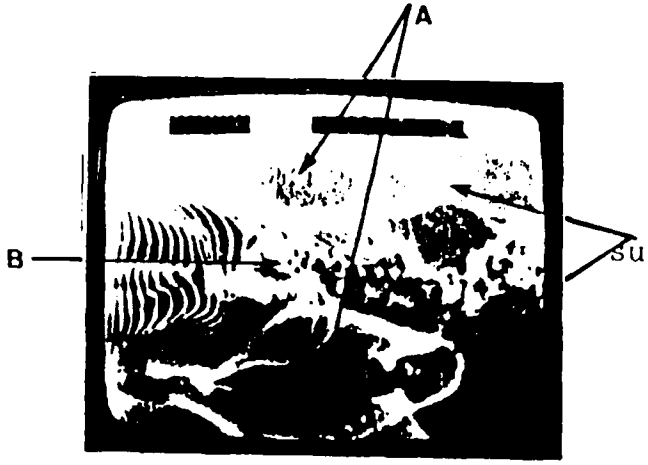
with the simulations of Hon and Walker (1987, 1988). Eventually a flow structure, not unilke a turbulent spot, but more controlled in it spreading and evolutionary behavior, developed from the single hairpin. A schematic of this process with accompanying photograph of the flow visualization results is shown in figure 2.10.

A final point, relating to the dynamics of hairpin vortices discussed in this section, is associated with the phenomenon of so-called "inverted hairpin vortices" which are sometimes observed in turbulent boundary layers. It may be seen in figures 2.6 and 2.8 that in the region between the primary and subsidiary hairpin vortices, the legs of both vortices form a portion of the vortex which in isolation would appear as an inverted hairpin vortex with its "head" pointed downward toward the wall. It is clear however, from the sequence depicted in figures 2.6 and 2.8 that the "inverted hairpin vortex" is not a separate dynamical feature but a natural consequence of the evolution of the original hairpin vortex in the shear flow.

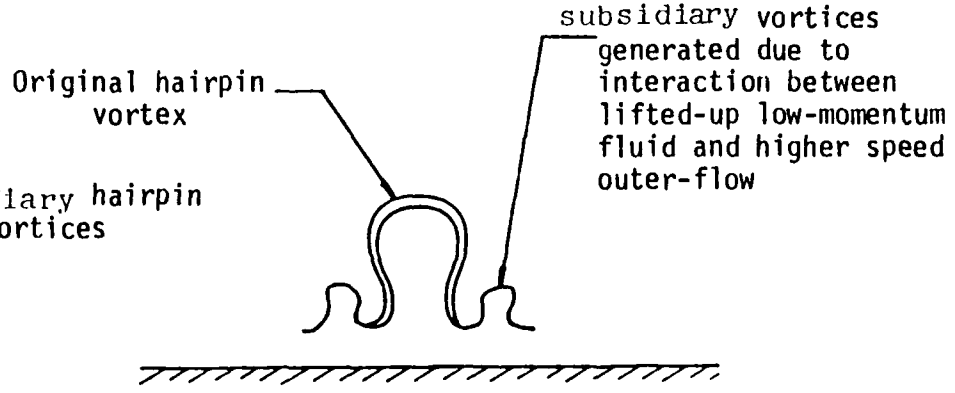
Finally it is must be emphasized that although the present results and dynamics have been presented in the context of a symmetric hairpin vortex in an undisturbed shear flow, the general dynamical features discussed here appear to be supported by extensive flow-visualization studies in fully turbulent boundary layers (Smith and Metzler, 1983; Smith, 1989; Aacarlar and Smith, 1987a). The symmetric hairpin vortex is regarded here as the simplest conceptual model which captures the main features of turbulent dynamics near the wall. In a turbulent boundary layer, there are considerable three-dimensional background disturbances and it is acknowledged that most hairpin vortices in this environment will not be symmetric. However trends similar to those depicted in figures 2.6 and 2.8 are expected to persist since the main influence on individual the vortex motion is associated with the local velocities near that part of the vortex.

2.4 Kinematic Effects of Hairpin Vortices

As a hairpin vortex is convected in a shear flow above a wall, the vorticular motion near the core induces various kinematical effects on the surrounding flow; these effects may be readily predicted by the Biot-Savart law as well as physical intuition (once the vortex trajectory is known). The most important of these effects is the nature of the flow induced near the wall by the moving vortex. In this section it is argued that the wall-layer streaks are the signature or "footprints" of convected hairpin vortices in the near-wall region. It should be emphasized that the major focus in this section will be on features of the wall-layer flow which can be explained purely on the basis of kinematical effects of the vortex motion; this is as opposed to dynamical effects associated with the the viscous response of the near-wall flow



(b) Top-view, y/R=0.465, x/R=7.5



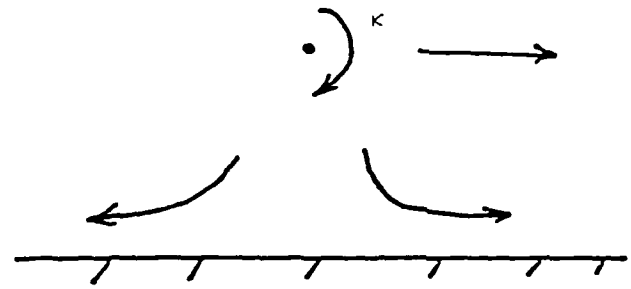
(c) Schematic of generation of lateral secondary vortices

Figure 2.10. Generation of lateral subsidiary vortices

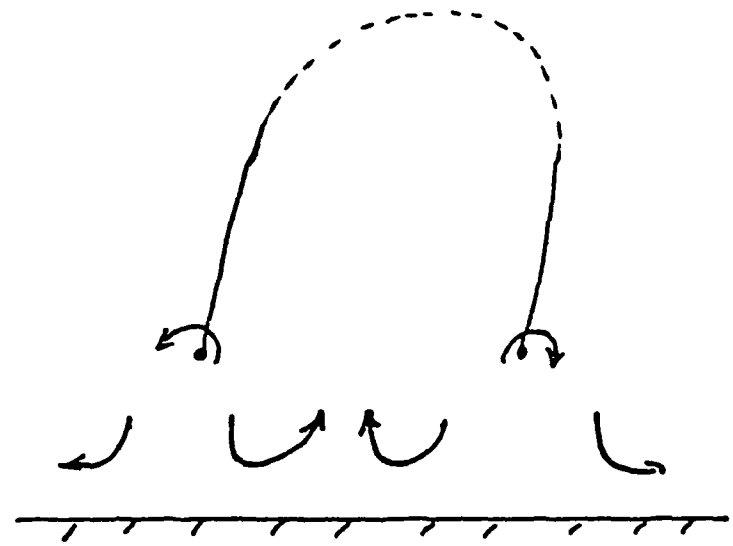
to the moving hairpin. It is these dynamical effects which lead to the observed eruption of the wall-layer flow and the production of new vorticity from the wall region; these effects will be dealt with in detail in subsequent sections. At this stage it is important to appreciate the detailed nature of the motion produced by a moving hairpin vortex.

Consider first the motion produced by the hairpin in a plane parallel to the streamwise direction; as indicated in figure 2.11(a), the moving hairpin will appear in this plane as a convected transverse vortex when the plane of flow visualization happens to be between the two legs of the hairpin vortex. In fact flow visualization studies have commonly been carried out by introducing the flow markers along a line normal to the wall and a variety of authors have reported "transverse" vortices (eg. Corino and Brodkey, 1969). As the core of the vortex passes, sharp streamwise acceleration above the head and sharp deceleration below the head will be observed; this is the typical signature of the vortex head (Hon and Walker, 1987 ,1988; Lu and Smith,1988). At locations closer to the wall, the vortex head induces motion upstream ahead of the vortex and downstream motion behind the vortex head. However, since the vortex is being convected downstream, an observer in the laboratory frame of reference sees a deceleration in flow speed near the wall with the approach of the vortex and a subsequent acceleration as the vortex head passes; again this behavior has been noted by several authors (eg. Corino and Brodkey, 1969) and some of the main features of may easily be seen in the simple model of the flow induced by a convected two-dimensional vortex (Doligalski and Walker, 1984). In a recent study comparing experimentally generated hairpin vortices to ensemble-averaged turbulent boundary-layer behavior, Lu and Smith (1988) indicate that the velocity-pressure characteristics, including the aceeleration-deceleration behavior, induced by the passage of the hairpin head is strongly similar to the turbulence characteristics in proximity to a detected "burst" event. A clear connection between the passage of a hairpin vortex structure and commonly established ensemble-averaged properties during bursting is clearly established.

Now consider the kinematical effects induced in the crossflow plane (normal to the wall and the flow direction) as viewed by an upstream observer. At a given instant, a plane normal to the streamwise direction cuts the vortex legs in two locations and to an observer in this plane, the flow appears to be due to a pair of counter-rotating streamwise vortices. In reality, the legs of the vortex curve upward toward the vortex head, as indicated schematically in figure 2.11(b) and make their closest approach to the wall near the trailing vortex legs (c.f. figures 2.6 and 2.8). Indeed as subsidiary hairpin vortices develop, an observer in the crossflow plane will see multiple counter-rotating pairs. For a single pair, as sketched



(a) Side view



(b) End view (crossflow plane)

Figure 2.11. Kinematic effects of a moving hairpin vortex.

in figure 2.11(b), it is evident that the nature of the flow produced in the crossflow plane is a downwash toward the wall outboard of the legs and an induced upflow between the legs. Thus the kinematic action of the legs provides a convergence of the flow between the legs and will act to sweep any flow markers (such as dye,hydrogen bubbles or smoke) toward the symmetry plane of the hairpin; for an asymmetric hairpin the sweeping action will be toward a central region between the hairpin legs. Consequently, a wall-layer streak may be regarded as the signature or trail of a convecting hairpin vortex in the wall layer. This has been confirmed in the experimental studies of Acarlar and Smith (1984,1987a) (c.f. figure 2.4) as well as in numerical simulations of Hon and Walker (1987); in these simulations, the evolution of several "simulated hydrogen bubble lines", consisting of initially straight lines close to the wall and oriented normal to the flow direction, was computed as a hairpin vortex (of the type depicted in figures 2.6 and 2.8) passed overhead. The effect of the moving hairpin vortex was to draw the marker lines into the region between the hairpin legs thus giving the appearance of a streaky structure near the wall.

It should be acknowledged that the hairpin vortex is not the only type of vortex structure which can produce streaks near the wall. Hon and Walker (1987) have also carried out simulations to determine the effect on marker lines for a closed loop vortex convected in a uniform flow above a wall. When the sense of rotation of the vortex is such that the vortex loop draws progressively away from the wall, the induced vortex flow near the wall is toward a region corresponding to the current streamwise location of the midregions of the vortex. Thus the moving vortex loop also will act to provide a convergence of flow markers and the subsequent trail will appear similar to a wall-layer streak. This is confirmed in the numerical simulations of Hon and Walker (1987) and experiments with convected rings by Falco (unpublished). Indeed Falco (1981,1982) has proposed that ring-like vortex loops are a principal dynamical feature of turbulent flows; it is possible that such vortices are present in the turbulence although interpretation of results based on flow visualization using smoke in air is always difficult. One problem is associated with the origin of such vortex loops. It is true that in numerical calculations on the evolution of hairpin vortices Moin,Leonard and Kim (1986) and Hon and Walker (1987), there is an indication that under certain circumstances, the hairpin vortex legs approach each other so closely that the vortex cores touch; once this occurs a complex process is expected wherein the cores break and the recombine. In such a process, a loop vortex consisting of the original hairpin vortex head would be released and convect downstream, leaving a smaller hairpin vortex behind. This process has been observed experimentally (Haji-Haidari and Smith, 1988). However, this "breaking" process is not particularly common, occurring under the most controlled conditions and clearly the rings, when they

form, have their origin from a hairpin vortex and leave in their wake a smaller hairpin vortex. Thus although it is possible for rings to form, the evidence at present seems to overwhelmingly favor the hairpin vortex as the dominant structure in the turbulence.

2.5 Interaction with the Surface Flow

2.5.1 Introduction

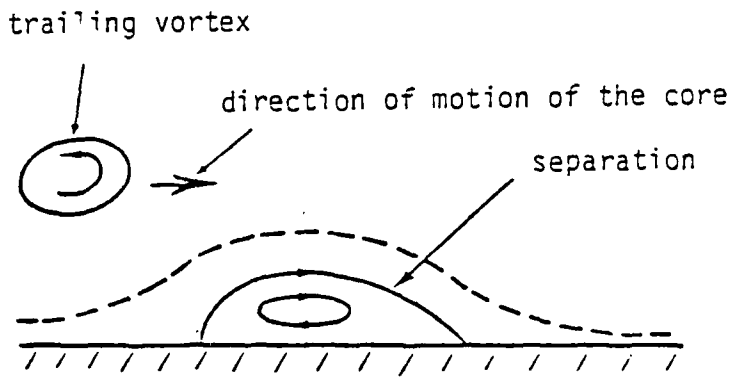
In the previous section it was argued that the wall-layer streaks are the trail of convected hairpin vortices in motion above the wall. In this section, the fundamental question of regeneration and turbulence production near the wall will be addressed. The central question surrounds the physical mechanisms whereby new vorticity from the region near the wall is continually introduced into the outer regions of the boundary layer. In the outer region remote from the wall, the vorticity in the hairpin vortices is in a continual state of redistribution, due to the axial decay of the viscous cores which takes place through viscous diffusion. For the most part, the process of redistribution takes place in an unhindered fashion as the vortices move outward, away from the wall; here cancellation of vorticity can occur as regions of opposite-signed vorticity interact with one another. On occasion, convective processes in the outer part of the boundary layer may act to concentrate or re-focus the vorticity back into narrow regions, but in general the outer part of the boundary layer is a region where the local levels of vorticity are decaying . One process, wherein a local intensification of outer region vorticity may occur, is associated with convection down toward the surface; in this case, vortex stretching can give rise to local intensification of a vortex as it approaches the wall. As the overall levels of vorticity diminish in the outer regions of the boundary layer, a process of replenishment must occur in order for the turbulent boundary layer to sustain itself; within the turbulent boundary layer, the only source of vorticity is the wall. It has been argued here that vortices which are remote from the wall are basically inactive and consequently the discussion must focus on the effects of convected vortices near the wall. Here the typical structure near the wall is considered to be the convected hairpin vortex, having relatively strong levels of vorticity in the sense that the vortex Reynolds number $R_\nu = \Gamma/\nu$ is large; in this definition, Γ is the circulation about the vortex core and ν is the kinematic viscosity. The hairpin vortices may be relatively long in the streamwise direction (c.f. section 4.3) but are considered to have dimensions in the spanwise direction on the order of $100\nu/u_\tau$, where u_τ is the local friction velocity. Thus the spanwise dimensions are small with respect to the boundary-layer thickness. Such vortices are "active" in the sense that they are close to the wall and directly influence the viscous flow there, as opposed to vortices which are remote from the wall and are relatively "inactive". Finally

it is envisaged that at any instant there are a large number of hairpin vortices near the wall (at least one for every streak); furthermore there will be a wide variation in vortex strengths (and consequently R_y), with some hairpins being relatively strong and some weak. This viewpoint is similar to the model proposed by Perry and Chong (1982), where it was conjectured that the turbulent boundary layer is comprised of a heirarchy of hairpin vortices. A key point is that in order for a concentration of hairpins to be present near the surface, there must exist a continual process of renewal near the wall in which new hairpin vortices are created through an interaction with the wall-layer flow; this last point was not addressed by Perry and Chong (1982). In this section, the focus is on this hairpin vortex creation process.

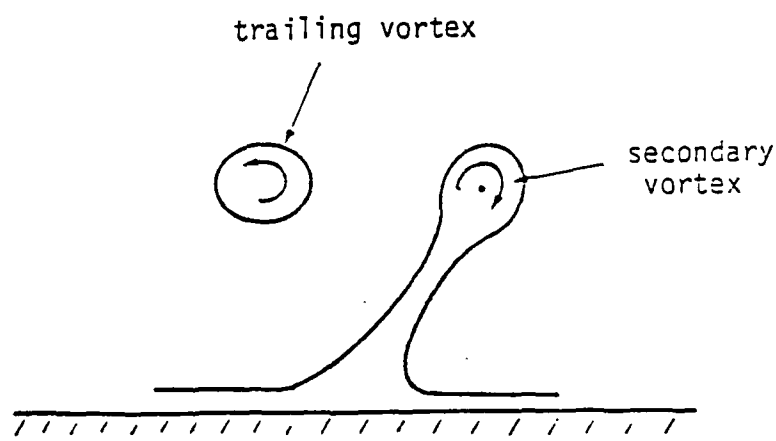
2.5.2 Production of Secondary Vortices

The regeneration of hairpin vortices is a complex process and before attempting to detailed discussion, it is worthwhile to develop an appreciation of the general effects of convected vortex motion near a wall. To this end, some simple vortex-wall configurations will be considered first. One of the first experimental studies to show the phenomenon of vortex regeneration was carried out by Harvey and Perry (1971), who simulated conditions involving the interaction of aircraft trailing vortices with a ground plane. The experiment was carried out in a wind tunnel with a moving belt on the floor of the tunnel; a single stationary wing was mounted in the tunnel wall and the trailing vortex created at the wing tip convected outboard and downward toward the moving belt. The vortex was observed to induce flow separation on the moving belt in the form of a secondary vortex, which was initially attached to the belt. These experimental observations were confirmed by a later theoretical study by Walker (1978), who computed the unsteady boundary-layer development due to the motion of a single two-dimensional vortex above a wall in an otherwise stagnant fluid. It was determined that boundary-layer separation (in the form of a closed recirculating eddy) occurred; this event was soon followed by explosive boundary-layer growth near the region of separation. The numerical solutions were suggestive that a strong viscous-inviscid interaction would develop; this was supported by the interpretations of Harvey and Perry (1971) who reported that an eruption occured in the form of the ejection of the secondary vortex, as indicated in figure 2.12. The ejected secondary vortex is of the opposite rotation to the primary vortex which created it and as a result, an essentially inviscid interaction occurs with the primary vortex ,causing it to rebound away from the wall due to the velocity field of the secondary vortex.

Well-defined two-dimensional vortices are difficult to produce in the laboratory. However in recent years, the same basic effect has been observed experimentaly by a number of authors, for vortex rings which approach a plane wall (Cerra



(a) Before interaction



(b) During interaction

Figure 2.12 Schematic sketch of the interpretation (from Harvey and Perry, 1971) of the events before and during the interaction of a trailing aircraft vortex with the ground plane.

and Smith, 1983; Falco, 1982,1983; Didden and Ho, 1986; Walker,Smith,Cerra and Doligalski, 1987). In the majority of these studies, a well-defined vortex ring was produced using a piston-cylinder arrangement, while in the study by Didden and Ho (1986), vortex rings were convected toward the surface on the perimeter of a pulsed jet. According to inviscid theory, the vortex rings should continually expand in diameter as they approach the wall. However in all cases, the moving vortex ring was observed to induce the creation of a secondary vortex ring in the boundary layer near the wall, which was subsequently ejected into the outer flow. In some cases, the primary vortex ring was then seen to induce the creation and eruption of a tertiary ring. The secondary (and tertiary) vortices were observed to contain vorticity of comparable magnitude to the primary vortex but of the opposite sign; the eruption of the secondary ring caused a rebounding of the primary vortex ring, as well as arresting its outward motion.

The important aspect of these fundamental studies, in relation to the present development, is that they show (in a well-controlled environment and in a non-controversial way) how one vortex can induce the creation of a secondary vortex in a viscous flow near a wall. The secondary vortex then is observed to be ejected from the boundary layer and in this manner a region of concentrated vorticity is abruptly introduced into the outer flow. This phenomenon is therefore very suggestive of the fluid mechanical processes occuring in the bursting sequence in turbulent boundary layers.

In a studies which are more directly related to the sense of convected vorticity typically observed in turbulent boundary layers, Doligalski and Walker (1978,1984) and Doligalski,Smith and Walker (1981) have investigated the configurations depicted schematically in figure 2.13, corresponding to two-dimensional vortices of negative rotation convected in a uniform flow and a shear flow respectively. Flow visualization in a turbulent boundary layer is often carried out in a plane normal to the wall (and parallel to the streamwise direction) and often reveals vortex motions having the sense of rotation indicated in figures 2.13 (c.f. figure 2.3). In fact the visualization plane generally reveals a slice of a three-dimensional vortex and will most often consist of a slice through the head of a hairpin vortex. In any event, the type of velocity distibution imposed on the flow near the wall by a convecting two-dimensional vortex simulates the local effect due to the moving hairpin head. Computations were carried out to determine the viscous response of the boundary-layer flow for a variety of convection speeds. The numerical results show a variety of complicated unsteady separation effects that occur within the boundary-layer flow; however, for all convection speeds, events take place in the boundary layer that are eventually expected to lead to an eruption and creation of a secondary vortex, as indicated in figure 2.13. In this physical process, the convecting vortex induces an eruption of boundary-layer fluid

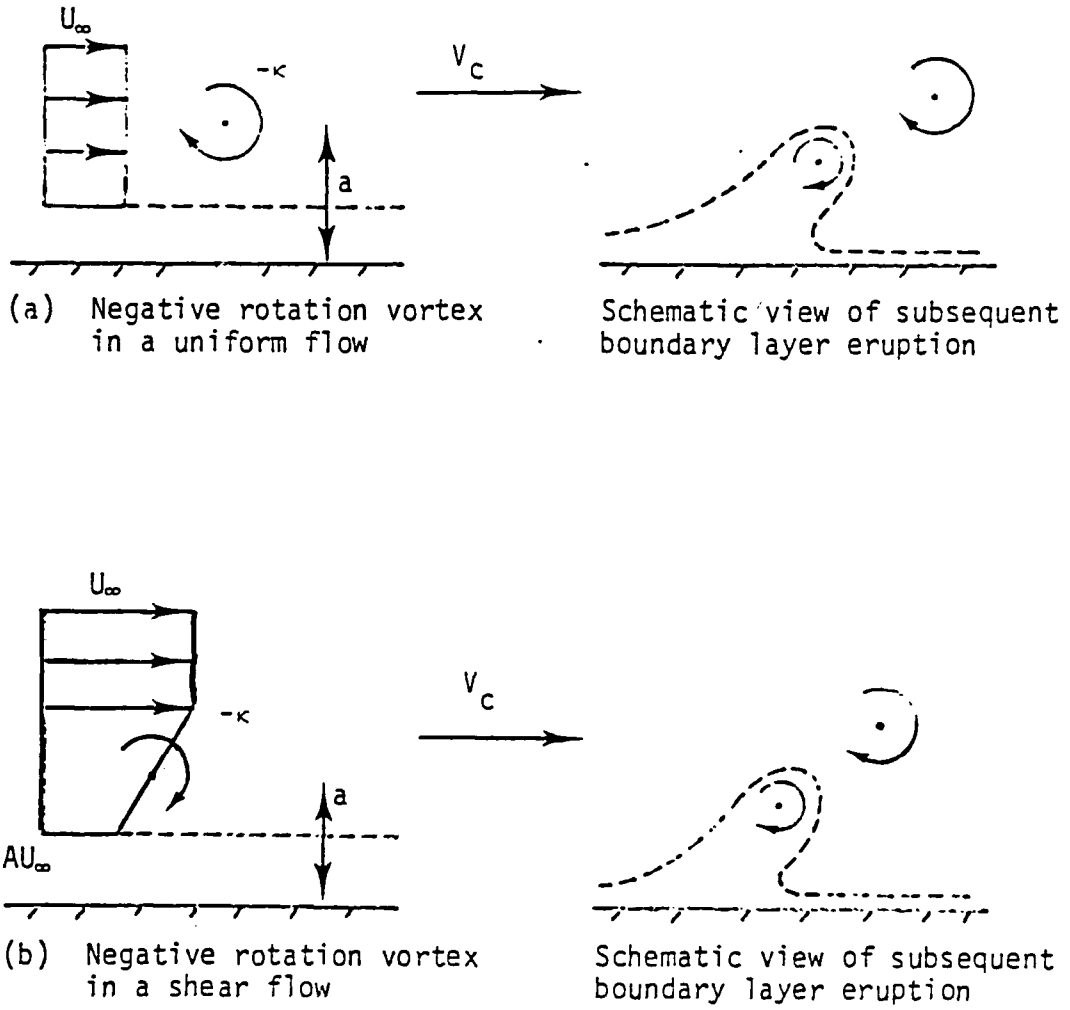
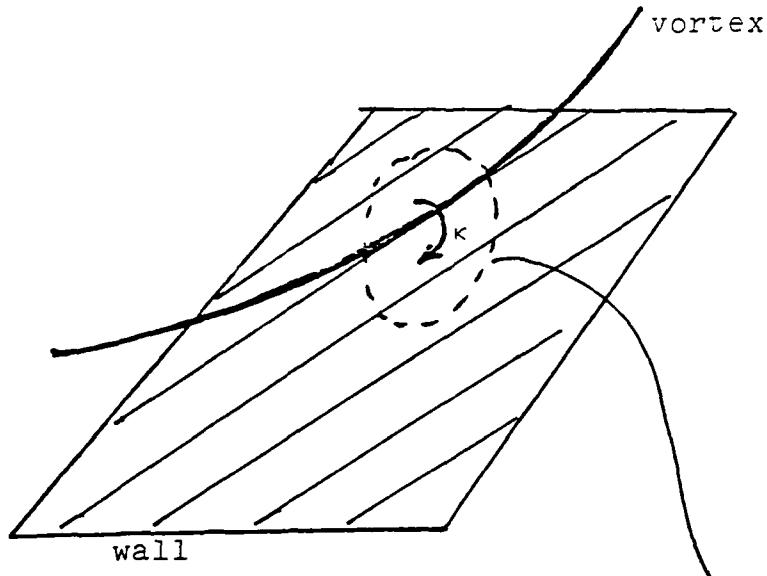
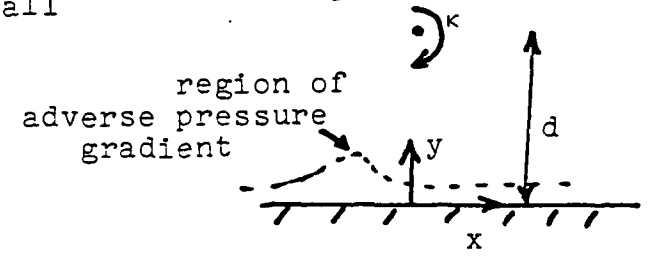


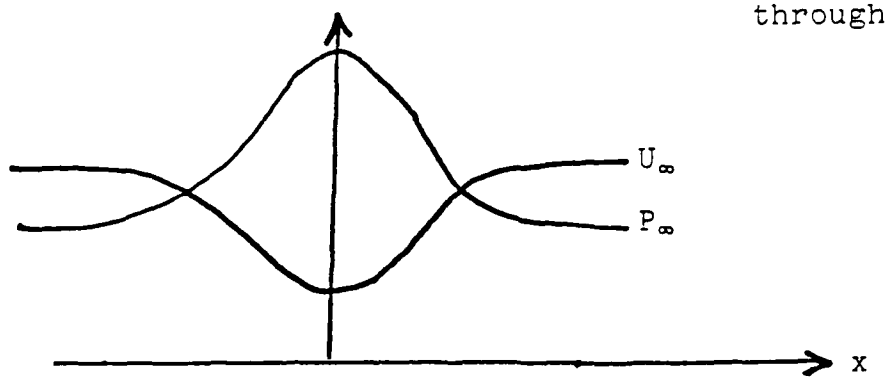
Figure 2.13 The vortex-boundary layer configurations considered by (a) Doligalski and Walker (1985) and (b) Doligalski et al (1980).



(a) three-dimensional vortex in motion above a wall



(b) detail of a slice through the vortex



(c) Typical instantaneous velocity and pressure distributions near the wall induced by a moving vortex

Figure 2.14. Nature of the flow near a wall induced by a moving vortex.

and, in a strong viscous-inviscid interaction, new vorticity from the wall region is abruptly introduced into the outer flow. Although two-dimensional vortices are difficult to produce in the laboratory, the phenomenon was observed by Doligalski et (1981) for a relatively weak primary vortex.

At this stage it is worthwhile to remark that, although the aforementioned vortex-induced viscous flows (as well as the situations that will be subsequently discussed) exhibit a wide variety of complex unsteady flow patterns, the one feature that they all have in common is that the moving vortex always induces a region of adverse pressure gradient on the flow near the wall. In figure 2.14(a), a portion of a three-dimensional vortex moves above a plane wall. In figure 2.14(b), the local detail in a plane normal to the vortex is depicted schematically. With the indicated sense of rotation, a region of deceleration occurs upstream of the vortex; this is followed by a region of acceleration and adverse pressure gradient behind the vortex. The three aspects that are critical in this situation are: (1) the distance of the vortex from the wall ; (2) the vortex strength κ and (3) the vortex Reynolds number $R_v = 2\pi\kappa/\nu$. For large vortex Reynolds numbers, the viscous flow near the wall is only able to withstand the action of the adverse pressure gradient induced by the moving vortex for a finite period of time. Eventually an unsteady separation effect occurs within the viscous flow near the wall and an eruption occurs in the zone of imposed adverse pressure gradient. The time scale associated with the period to eruption is $O(\kappa/d)$; thus an eruptive response is expected sooner, the stronger the vortex and/or the closer the vortex is to the wall. In any case, once a vortex is close enough to a wall for a sufficient period of time, an eruption of the viscous flow near the wall is apparently inevitable.

One question that arises it how large must the Reynolds number R_v be in order for the eruptive phenomenon to take place. The experiments of Harvey and Perry (1971) were carried out for vortex Reynolds number $O(10^5)$ and in those cases, violent eruptions of secondary vortices were observed which had strengths comparable to the primary vortex. In the experiments of Walker, Smith, Cerra and Doligalski (1987), the creation of secondary vortex rings and subsequent eruptions were observed at moderate Reynolds number $O(10^4)$; however a generic trend in these experiments was observed at an early stage and the time to eruption soon becomes independent of Reynolds number. The bulk of the theoretical studies (e.g. Walker (1978), Walker et al (1987)) are based on the boundary-layer equations which are valid in the limit of infinite Reynolds numbers; the experiments suggest that the theory provides a asymptotic description of the nature of the viscous response to vortex motion over a wide range of Reynolds numbers. It should be noted however that the eruptive effect apparently disappears for sufficiently low R_v. In calculations at low vortex Reynolds numbers (up tp 150), Peace and Riley (1983) found that a vortex

pair moving toward a wall rebounded but that no separation occured near the wall. In the experiments of Walker et al (1987), a limiting situation occured when no secondary vortex rings were observed once the primary ring was sufficiently weak. Thus the nature of the viscous response to the vortex motion is apparently Reynolds number dependent and separation (and the creation of secondary vortices) does not occur below some critical Reynolds number. It should be noted however that, since values of the kinematic viscosity are typically quite small for fluids such as air or water, it does not require a large vortex strength in order to obtain an appreciable vortex Reynolds number.

The development of a region of local deceleration-acceleration due to the passage of a hairpin vortex has also been recently demonstrated by Lu and Smith (1988). Using image processing of hydrogen bubble visualization of a convecting hairpin vortex in a laminar boundary layer, they showed that the fluid adjacent to the surface will first decelerate and then accelerate during the passage of a hairpin vortex head. This was observed to be accompanied by a convecting region of significant local pressure gradient, due to the translating vortex, which changed from negative to positive in a manner remarkably consistent with the behavior suggested by the two-dimensional convected vortex model. Another important aspect of the Lu and Smith (1988) study was that they were able to illustrate the consistency of the above velocity and pressure gradient behavior to regions of turbulent "bursting" within a fully turbulent boundary layer, as detected by the VITA threshold technique of Blackwelder and Kaplan (1976). Comparison of the velocity and pressure variations for the hairpin vortex and turbulent bursting in many cases indicated the processes were virtually indentical.

2.5.3 Counter-rotating Vortex Pairs and Gortler Vortices

The study of Doligalski and Walker (1984) suggests that a moving hairpin vortex head will induce a pressure distribution on the flow near the wall that will actuate an eruptive response near the wall. However it has been demonstrated (Hon and Walker,1987, Acarlar and Smith, 1987a,1987b) that the hairpin head draws progressively away from the wall (c.f. figure 2.6); as this occurs the influence of the hairpin head on the flow near the wall gradually diminishes and it is to be expected that other portions of the vortex will have a more profound effect on the near-wall region. It is evident (c.f. figure 2.6) that the vortex legs are the portion of the hairpin structure that make the closest approach to the wall. Generally the vortex legs are inclined to the wall but to a good approximation the local nature of the flow induced by the hairpin may be understood by consideration of the flow induced by counter-rotating vortex pairs which are parallel to the bounding surface. In fact, a number of authors (Blackwelder,

1978, Blackwelder and Eckelmann, 1979; Blackwelder, 1983; Nikolaides, Lau and Hanratty, 1983; Cantwell, 1981; Blackwelder and Swearingen, 1987) have suggested that counter-rotating vortex pairs are an important feature of the near-wall region. Here it is argued that what may appear to be counter-rotating streamwise vortices are in reality the stretched legs of hairpin vortices. At the same time, much concerning the dynamics near the wall can be learned by studying the motion of counter-rotating vortex pairs. Ersoy and Walker (1985,1986) have considered such motions and the results of their studies are shown schematically in figure 2.15. In the configuration of figure 2.15(a), the vortex pair advances toward the wall and a region of adverse pressure gradient is imposed on the viscous flow near the wall outboard of the vortices; the region where an unsteady separation occurs near the wall and where an ejection of secondary vortices is expected is also shown schematically in figure 2.15(a). The situation which is relevant to the effects of hairpin vortices in the crossflow plane is depicted in figure 2.15(b); now, the sense of vorticity is such that the flow is away from the wall between the vortex pair. In this case, the region of adverse pressure gradient near the wall is between the symmetry plane and the streamwise location of each vortex; in this region, separation in the boundary layer leads to the evolution of a secondary vortex pair. Strong boundary-layer growth then ensues in the region indicated in figure 2.15(b) and the ejection of a pair of counter-rotating vortices is expected between the original vortex pair. When the orientation of the vortex pair is not symmetric with respect to the wall as in figures 2.15(c) and 2.15(d), similar eruptive effects occur, with the exceptions that (1) the induced separations in the boundary layer are more complex than in the symmetric case (Ersoy and Walker,1986) and (2) the vortex closest to the wall always has the dominant effect. Thus to some extent, the asymmetric vortex pair influences the flow at the wall more like a single vortex, particularly when one vortex is much closer to the wall. A strongly eruptive response was observed in all cases considered by Ersoy and Walker (1985,1986) with one noteable exception. In the configuration depicted in figure 2.15(b), the vortex pair recedes from the wall; in situations where the vortex pair is initially far from the wall, secondary vortices still develop in the boundary layer. However as the pair recedes from the wall, their influence on the boundary-layer flow gradually diminishes and, if the pair is initially far enough from the wall, the vortices can "escape" the wall region without evoking an eruptive response from the boundary layer. This behavior has recently been observed and confirmed experimentally by Haidari and Smith (1988) using cross-stream hydrogen bubble visualization near the bounding surface during the passage of a single hairpin vortex. Using a laser light sheet, they observed that the legs of the hairpin vortex would induce the same type of two-lobed boundary layer growth as shown in figure 2.15(b). If the hairpin vortex was sufficiently strong, the lobes would merge and eject; if the hairpin vortex was weaker, the lobes

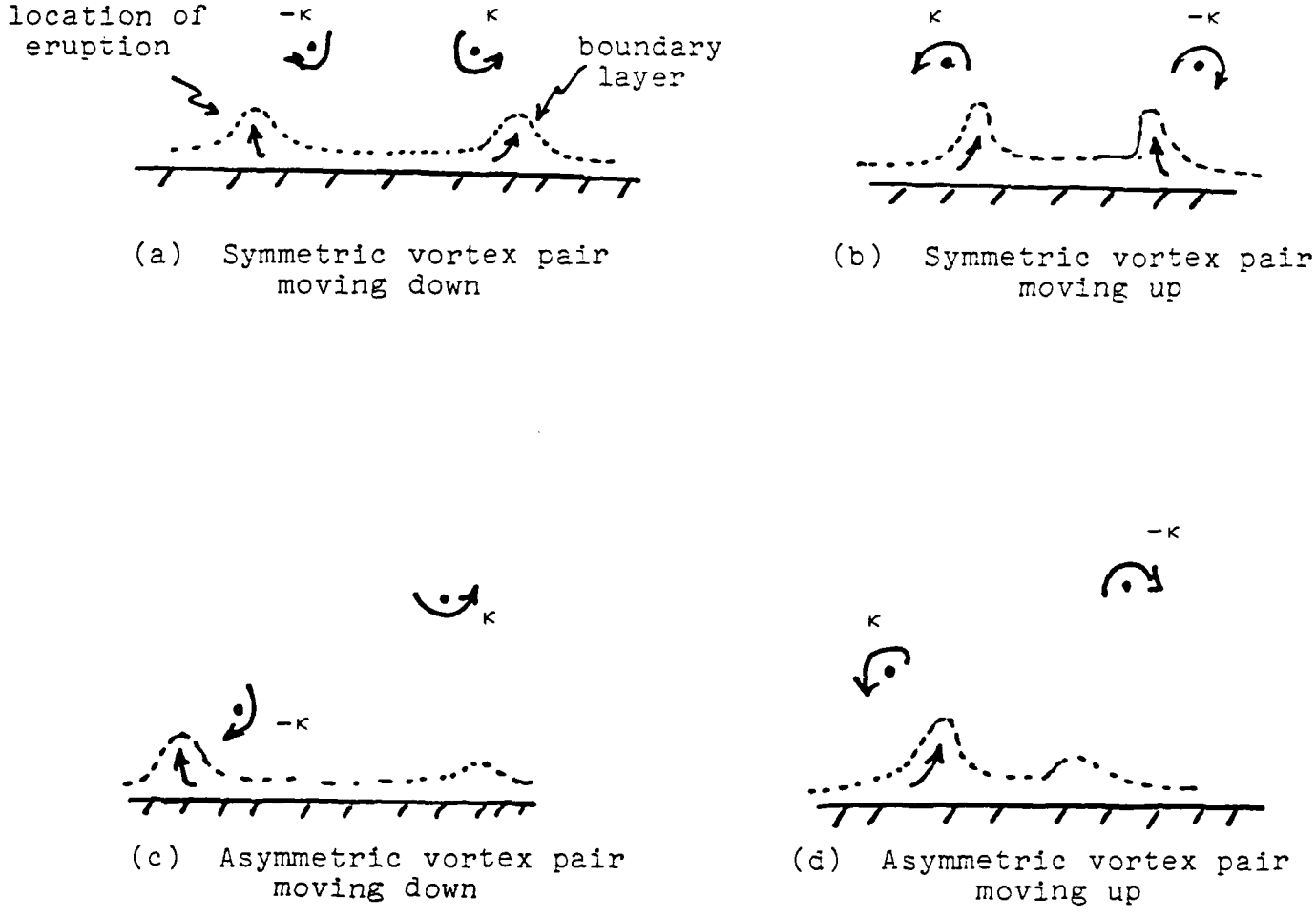


Figure 2.15. Schematic diagram showing the general location of vortex induced eruptions for counter-rotating vortex pairs.

would develop but then slowly collapse as the hairpin passed downstream.

Counter-rotating vortex pairs occur in a number of important fluid flows, one of which is the Taylor-Gortler instability observed in laminar boundary layers along concave walls (Gortler,1940; Bippes,1972; Drazin and Reid,1982). This type of flow has been studied recently by Blackwelder (1983) and Blackwelder and Swearingen (1987); these authors believe that such flows are similar to those found in the near-wall region of turbulent boundary layers. Centrifugal instabilities develop in the laminar boundary-layer flow on a concave wall giving rise to a regular pattern of counter-rotating vortices as indicated schematically in figure 2.16. Here the mean flow is from left to right and streamwise vortices of alternating rotation occur in the spanwise direction in the outer portion of the boundary layer. Note that alternate planes between the vortices have been designated as either upflow or downflow planes corresponding to the direction of the velocity normal to the wall on each plane. This type of flow pattern is similar to one which would produce wall-layer streaks and hence is worthy of study (Blackwelder, 1983).

The interesting feature of this flow is that the Gortler vortices are then subject to another instability at streamwise locations further downstream, which Bippes (1972) has referred to as a "secondary instability" and which apparently leads directly to a turbulent flow. Indeed in the experiments of Bippes(1972), the curvature of the test section was deliberately selected to be large in order to concentrate on the Gortler vortex phenomena and to minimize, in a relative sense, the effect of other flow disturbances such as Tollmein-Schlichting waves. In the experiments (Bippes,1972), turbulence occurs a apparent result of an apparent secondary instability before the boundary layer can become unstable with respect to Tollmein-Schlichting waves. The secondary instability initiates as a marked retardation of the flow near the wall in the region of upflow between the vortex pairs (the upflow plane). This local retardation was so pronounced that Bippes (1972) referred to such local regions as "zones of stagnation". These local retarded zones were observed to give rise to a local thickening of the viscous flow near the wall, which had the dual effect of both forcing the vortices away from the wall and also increasing the spanwise distance between vortex axes. A local increase in the spanwise vorticity apparently occured as fluid from upstream attempted to flow over and around the zones of retarded flow near the wall. This increase in spanwise vorticity was conjectured (Bippes, 1972) to lead to the formation of what appeared to be a transverse vortex. Once this roll-over occured, the flow rapidly became complex and transition to turbulence occurred directly. Bippes (1972) remarked that he believed that the important features triggering the secondary instability were the zones of retarded flow and the boundary-layer growth in the upflow plane between

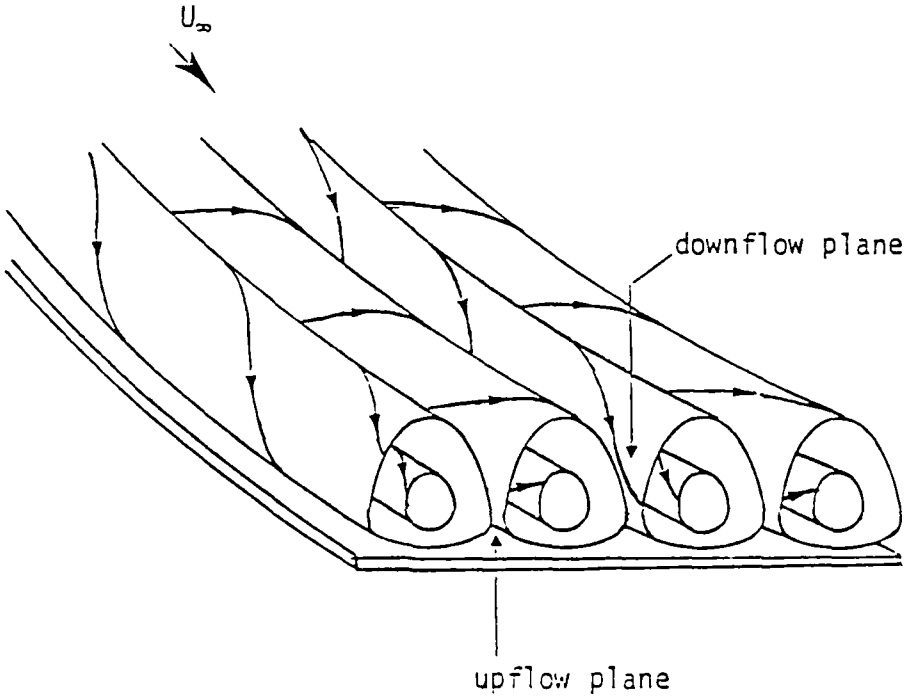


Figure 2.16 Sketch of Görtler vortices in the outer region of a laminar boundary layer on a concave wall prior to the onset of secondary instability.

the Gortler vortex pairs; he also commented that he strongly suspected that a local flow separation was involved in the process.

The "secondary instability" can be explained in terms of the configurations depicted in figure 2.15(b). As fluid particles near the wall and below the Gortler vortices are convected downstream, they experience pressure gradient effects due to the vortices above them. In the region near the upflow plane, the pressure gradient in the lateral direction is adverse and at successive stations downstream the flow near the wall has been exposed to the adverse pressure gradient for progressively longer times. Consequently it may be expected that separation and zones of recirculation will occur in the flow in the crossflow plane as indicated schematically in figure 2.17(b). With the continued influence of the vortices above, the zones of recirculation will expand at successive stations downstream as indicated in figure 2.17(a); in addition strong local growth of the viscous flow near the wall will give rise to a lifting of the Gortler vortices away from the wall as well as increasing the distance between the vortex axes, in agreement with Bippes (1972) observations. In addition, Blackwelder and Swearingen (1987) have reported the evolution of secondary vortices near the wall. The issue of what physical process happens next is also related to the mechanism indicated in figure 2.17. Bippes (1972) reported that once the streamwise velocity profile developed what appeared to be a point of inflection, the roll-up of a "transverse" vortex occured. It should be pointed out that although velocity profiles containing inflection points are known to be unstable in a steady flow (Drazin and Reid,1982), there is no corresponding theoretical framework relating to an inflectional point that evolves in an unsteady three-dimensional flow. Nevertheless experimental observations suggest that once an inflectional point develops, it seems to be the precursor of a strongly interactive event and the roll-over into a vortex structure. However rather than a "transverse" vortex, the thickening region of viscous flow is expected to give rise to the evolution of a hairpin vortex (in much the same manner as reported by Acarlar and Smith (1987b)). Indeed, Haidari and Smith (1988) have demonstrated that the introduction of a streamwise region of retarded flow (by the injection of a finite amount of fluid through a streamwise-oriented slot in the wall) can result in the generation of a single hairpin vortex.

One point of interest concerns how the inflectional point develops and how this inflection is related to the earlier separation in the crossflow plane. As fluid particles near the upflow plane arrive from upstream, they are forced to flow over and around the rapidly thickening zone of retarded and recirculating flow near the wall. In such a situation the velocity profile near the upflow plane may be expected to develop into the shape indicated in figure 2.17(c), approaching

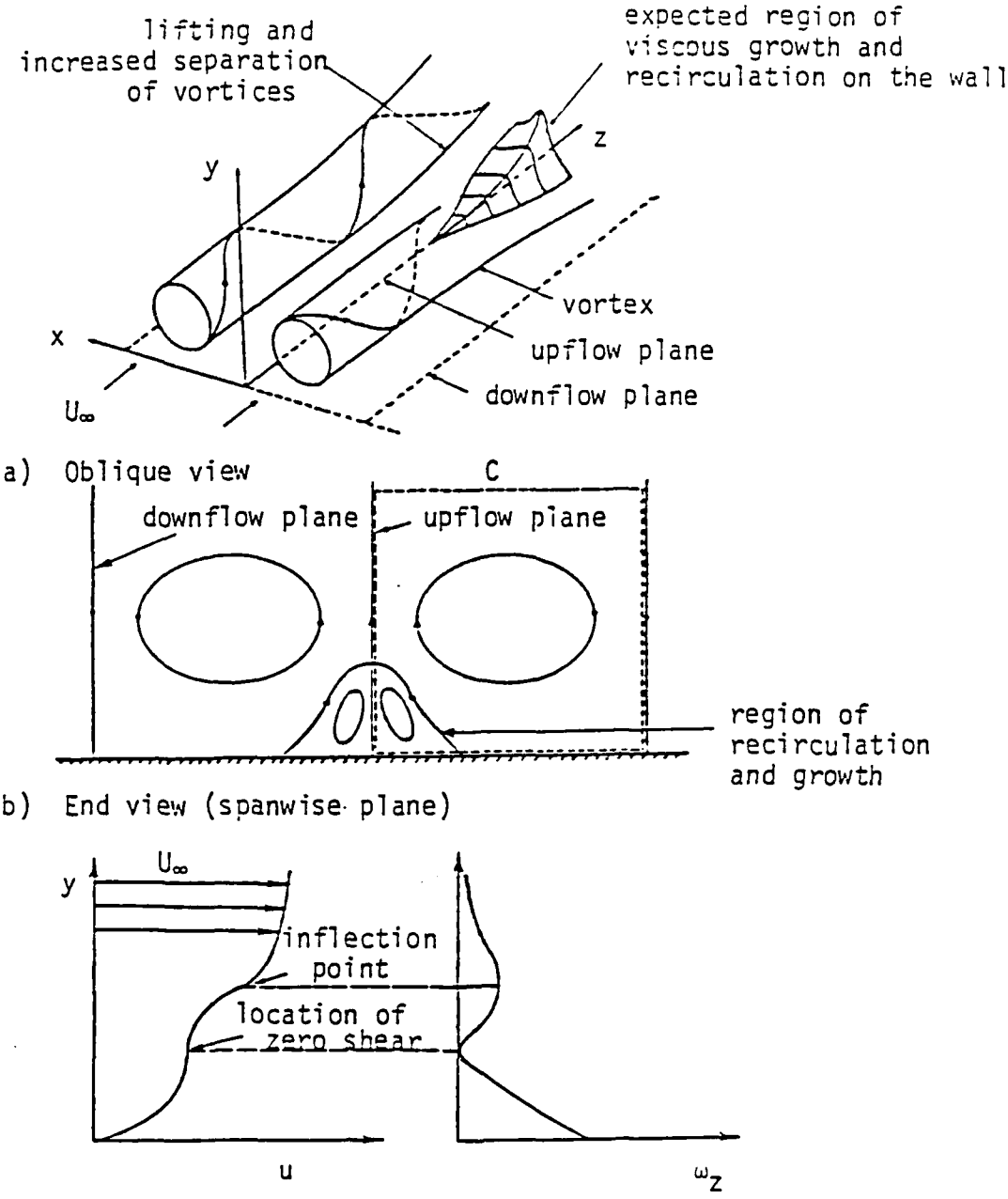


Figure 2.17. Schematic diagrams of the proposed mechanism for the breakdown of Görtler vortex flow.

a condition of vanishing shear at some location above the wall. Note that a condition of vanishing $\partial u/\partial y$ is a necessary condition that must be achieved just before a thickening viscous flow near a wall is about to become strongly interactive with the outer inviscid flow (Sears and Telionis, 1975;Van Dommelen and Shen, 1980). This condition often develops in situations where a boundary-layer flow must negotiate and rise over a thickening region of recirculation (Doligalski and Walker, 1984; Peridier,Smith and Walker,1988). In figure 2.17(c), the instantaneous spanwise vorticity profile is sketched, and it may be inferred that, as a point of zero shear develops in the streamwise profile, it must be accompanied by a point of inflection further away from the wall. Streamwise velocity profiles of the the type sketched in figure 2.17(c) are frequently observed (Bippes,1972; Blackwelder,1983) immediately before an interactive event occurs both in Gortler vortex flows and in turbulent wall flows as well as in the creation of secondary hairpin vortices (Acarlar and Smith, 1987a). Comparable profiles have also been found to be associated with single and ensemble-averaged turbulent bustring sequences by Lu and Smith (1988). These burst-detected events have also been found to "match" , using pattern matching approaches, the charactertistics of a hairpin vortex structure.

2.5.4 Simplified Wall Layer Dynamics

In the previous sections, it has been demonstrated how vortices in well-controlled situations will induce an eruption of flow from the wall. These results are suggestive of the physical mechanism that leads to bursting in the wall-layer region of a turbulent boundary layer. Here a simplified version of the wall-layer dynamics will be considered. Let (x,y,z) denote Cartesian coordinates with corresponding velocity components (u,v,w); here (x,y,z) measure distances in the streamwise, normal and spanwise directions respectively. During a typical quiescent period in the wall layer of a turbulent boundary layer, the appropriate velocity and length scales are u_τ and ν/u_τ respectively; moreover, since the length of the streaks is typically almost an order of magnitude larger than the spanwise spacing or the normal extent of the wall layer, it is reasonable to neglect gradients in the streamwise direction with respect to those in the spanwise and normal directions. Using these scalings and assumptions, a simpler subset of the Navier-Stokes equations is obtained, which governs the velocity distribution (u^+,v^+,w^+) in the wall layer (Walker and Herzog, 1987; Chapman and Kuhn, 1986). Two features of these equations are important. First the solutions for v^+ and w^+, describing the evolution of the motion in the crossflow plane, develop independently of the streamwise velocity u^+; the developing solutions for v^+ and w^+ then feed into the equation for u^+ and hence influence the development of the streamwise velocity profile. Walker and Herzog (1987) have considered solutions of these equations during a typical quiescent period. The presence

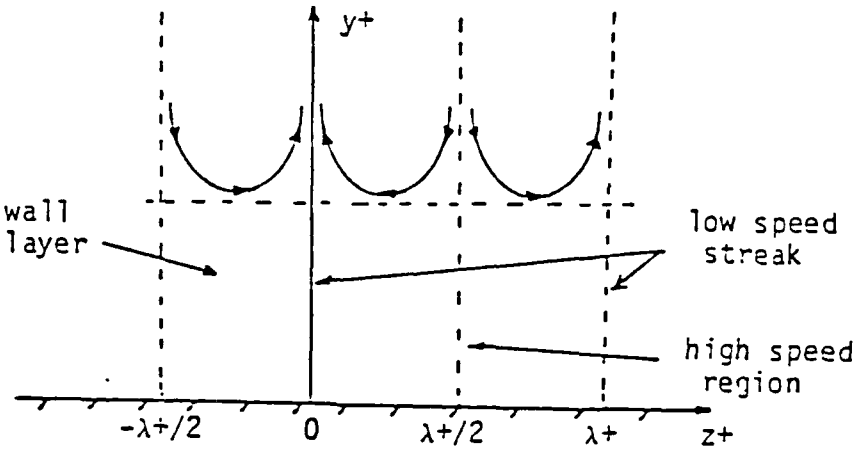


Figure 2.18 Schematic diagram of the assumed wall-layer structure during a typical quiescent period.

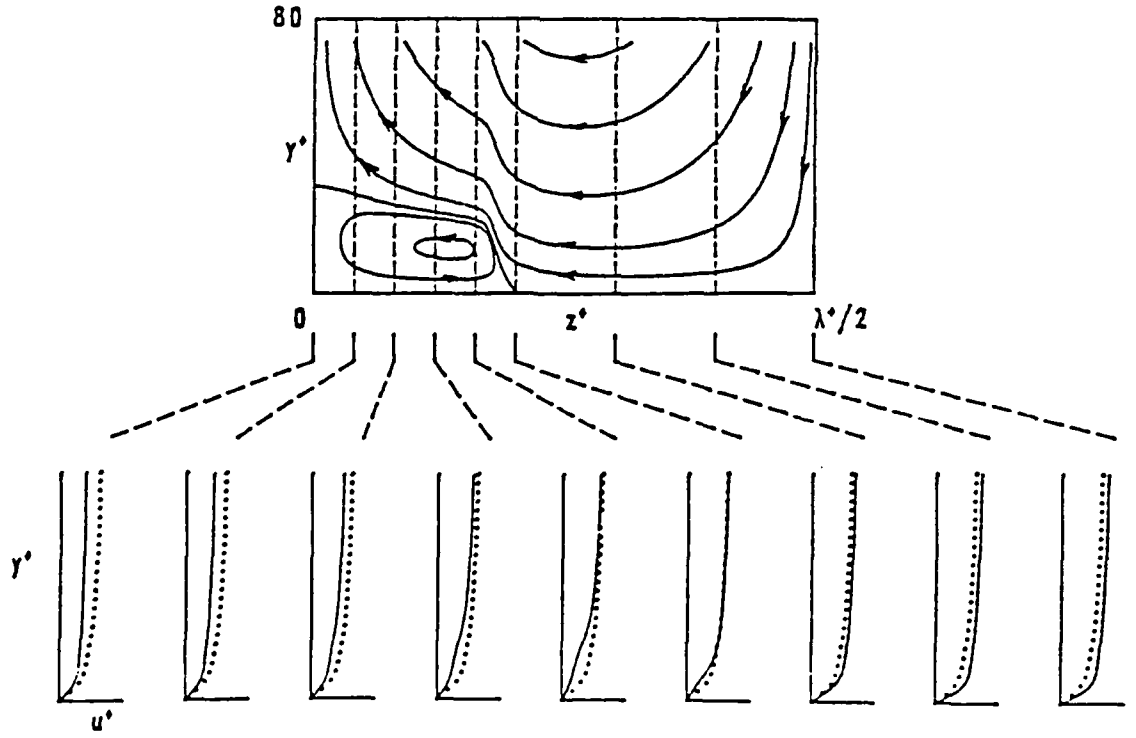


Figure 2.19 Streamwise velocity profiles at various spanwise locations at $t^+=21$ for the limit problem $Re_\lambda \to \infty$.

of the low-speed streaks during the quiescent period indicates that there are planes (perpendicular to the wall) at specific spanwise locations, which on average are aligned in the streamwise direction and across which there is no flow. Consider therefore the flow between a typical pair of low-speed streaks at $z^+ = 0$ and $z^+ = \lambda^+$ as indicated in figure 2.18. It is assumed during the quiescent period that the wall-layer flow is exposed continually to the type of inflow-outflow depicted in figure 2.18 for which

$$w^+ \sim -W_1 \sin\left(\frac{2\pi z^+}{\lambda^+}\right) \text{ as } y^+ \to \infty \quad . \tag{2.3}$$

Other more complicated conditions could be assumed at the outer edge of the wall layer but equation (2.3) is the simplest condition leading to the structure in figure 2.18. The outflow is assumed to be imposed on the wall layer by convected vortices in the outer region; at this stage it is not necessary to be more specific, although this is the type of flow that would be induced in the crossflow plane by a moving hairpin vortex. The main question to be addressed here is the following: If the wall-layer flow is exposed to the type of outflow conditions indicated in figure 2.18, what process or mechanism can possibly lead to destruction and breakup of the assumed structure?

It may be shown (Walker and Herzog, 1987) that the developing flow between streaks depends on a Reynolds number defined by

$$Re_\lambda = W_1 \lambda^+ / 2\pi \quad , \tag{2.4}$$

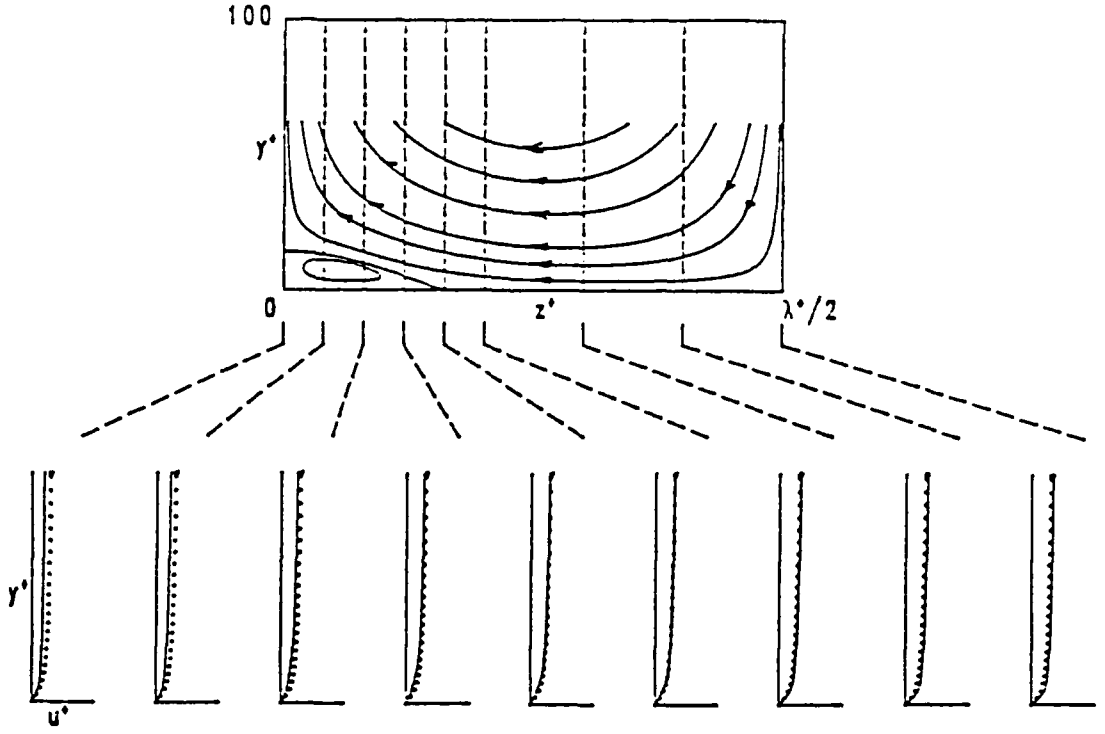
where λ^+ is the mean streak spacing in wall-layer units. Turbulence intensity measurements suggest that an average value of W_1 is around 2 and since $\lambda^+ \approx 100$ (Smith and Metzler,1983), it follows that an average value of Re is about 32. Numerical solutions for the developing flow in the crossflow plane for v^+ and w^+ and then for the evolving streamwise velocity u^+ have been obtained by Walker and Herzog (1987) over a range of Reynolds numbers; for large y^+, the u^+ profile was matched to a logarithmic profile. The first case considered here is the limit problem $Re_\lambda \to \infty$ for which computed results are shown in figure 2.19; here the instantaneous streamlines are shown in the crossflow plane at $t^+ = 21$ with the corresponding streamwise velocity profiles shown at selected locations across the span. The dotted profile represents an average across the span at that instant. Consequently, near the downflow plane (to the right) there is a high-speed region where the streamwise velocity is in excess of the average; by contrast near the streak at $z^+ = 0$, the flow is retarded relative to the average. For $Re_\lambda \to \infty$, separation (in the form of a pair of secondary eddies) occurs near the streak at an early stage. At the point indicated in figure 2.19, an intense variation is developing on the right side of the secondary eddy and here severe

boundary-layer growth is occuring. Shortly after $t^+ = 22$, the calculations could not be continued on in time as the viscous flow procedes toward an eruption and interaction with the outer flow. This the same type of phenomenon that has been described in the previous sections on vortex-induced separations. Thus, one mechanism for the breakdown of the structure depicted in figure 2.18 has been identified. The wall-layer flow , after exposure to the adverse pressure gradient associated with the pumping action, erupts through a strong outward motion in the crossflow in a narrow band near the outside of the secondary eddies. It is expected that this type of eruption will be very violent and reminiscent of the "superbursts" observed in turbulent boundary layers; in such events the erupting fluid from the wall layer is ejected most of the way across the outer region. Large Reynolds numbers in this context may be thought of as situations where the pumping action of the outflow is particularly strong.

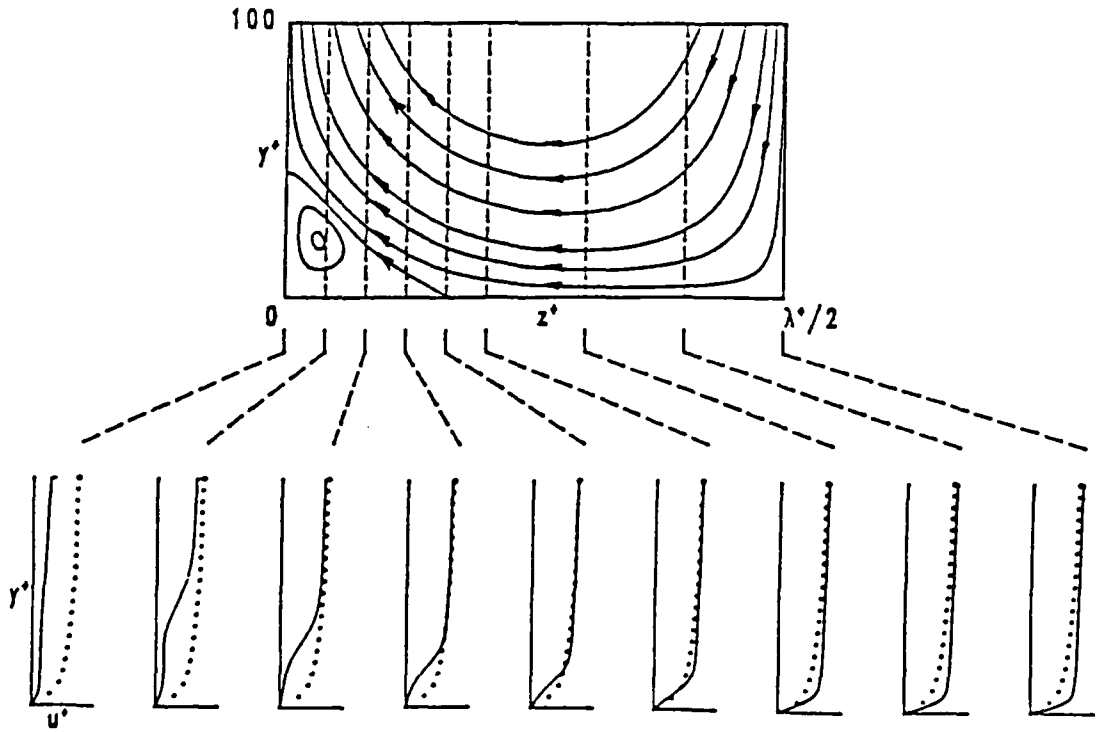
Solutions for finite Reynolds numbers have also been obtained by Walker and Herzog (1987). Over a range of large but finite Reynolds numbers, the tendancy for the crossflow plane motion to become eruptive persists. Finally as the Reynolds number is decreased, this eruptive nature diminishes and a new apparent second mechanism of breakdown develops. Calculated results for $Re_\lambda = 509$ are shown in figure 2.20 at $t^+ = 15$ and at $t^+ = 100$. It may be observed that secondary eddies appear once again in the crossflow plane. However the new feature is that the streamwise velocity profile develops an inflectional behavior in the region near the recirculation. This local inflectional profile is expected to be unstable to small disturbances and a local roll-over is anticipated, resulting in the creation of a new vortex (possibly of the hairpin type); the cycle thus terminates in a strongly interactive event.

As the Reynolds number is lowered still further, there comes a stage when no secondary eddies appear in the crossflow plane during a cycle (up to $t^+ = 100$) and no inflectional behavior in the streamwise velocity profiles is observed. The implication of these results is that not every streak will burst. This is confirmed by a recent experimental study by Haidari and Smith (1988). The outflow imposed on the wall-layer flow must be of a sufficient strength to evoke a significant response. For very strong outflows, a violent eruption of the crossflow plane motion occurs; for outflows of lower strength, an inflectional behavior develops in the streamwise velocity profile which is expected to lead to a local overturning of the flow.

Note that Haidari and Smith (1988) investigated the near-wall repsonse to the passage of a single hairpin vortex, generated by controlled fluid injection through a streamwise surface slot. They observed that the passage of a hairpin vortex of sufficient strength will elicit the development and eruption of secondary eddies in the cross-flow plane. As the



t^+=15.



t^+=100.

Figure 2.20 Cross-flow plane streamlines and streamwise velocity profiles at various times for Re_λ=509.

relative strength of the hairpin vortex was decreased, either by modifying the injection characteristics or by downstream decay of the hairpin vortex, development of streaks, but not eruption, was noted. Still further reductions in strength resulted in parallel reduction in surface interaction in agreement with the theoretical results.

2.5.5 Regeneration of Hairpin Vortices

In the previous sections, a sequence of progressively more involved vortex-induced eruptions has been considered; with this background, it is now possible to address the question of the production of secondary hairpin vortices. As a hairpin vortex moves over a wall, it induces an unsteady three-dimensional pressure distribution on the flow near the wall and it is of interest to understand the nature of the viscous response at the wall to this pressure distribution. The results of the previous sections suggest that the response must be eruptive in character, but the precise nature and location of the eruption needs to be addressed. Consider the schematic diagram of a moving hairpin vortex depicted in figure 2.21; as the vortex moves over the wall, it evolves into a twisting and distorting shape, but a symmetrical hairpin vortex in a uniform shear maintains a plane of symmetry (at $z = 0$) as indicated in figure 2.21. The nature of the streamwise velocity distribution imposed by the moving hairpin near the wall and on the symmetry plane (for the evolving hairpin vortex depicted in figures 2.6 and 2.8) is shown in figure 2.22. Initially, the streamwise velocity distribution near the wall shows a region of strong deceleration and the subsequent acceleration. This is clearly shown by the recent experimental work on hairpin vortices by Lu and Smith (1988). With the passage of time, the vortex head moves away from the wall and the maximum inviscid speed induced by the vortex diminishes slightly, which is again confirmed experimentally by Lu and Smith (1988). At a later stage ($t = 0.04$), the hairpin head has both moved further away from the wall and downstream. With the downstream movement of the head and the evolution of subsidiary vortex heads, additional local minima develop in the induced flow near the wall; as a result, the viscous flow near the wall is exposed to multiple zones of adverse pressure gradient as indicated in figure 2.22. Note that with increasing time, the streamwise velocity near the wall is influenced over an increasing distance in the streamwise direction; in addition the zone containing the largest adverse pressure gradient is associated with the legs of the primary hairpin vortex (near $x = 10$ at $t = 0.07$ in figure 2.22).

The spanwise velocity distribution near the wall vanishes as $z \to 0$ but w is of the form,

$$w \sim z\, \theta_\infty(x,t) \qquad (2.5)$$

and it follows that θ_∞ is proportional to the spanwise velocity

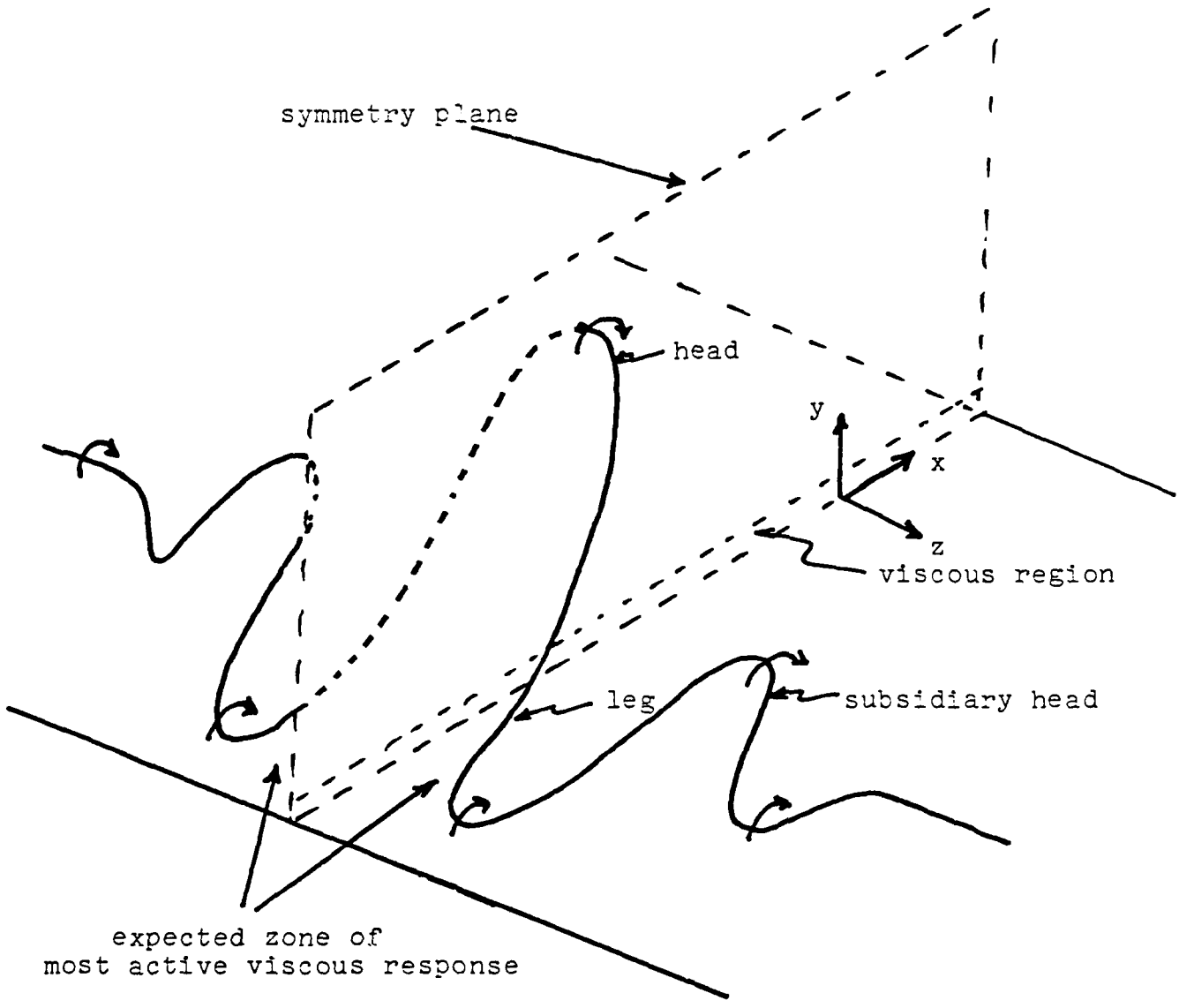


Figure 2.21. Schematic diagram of a hairpin vortex convected above a wall.

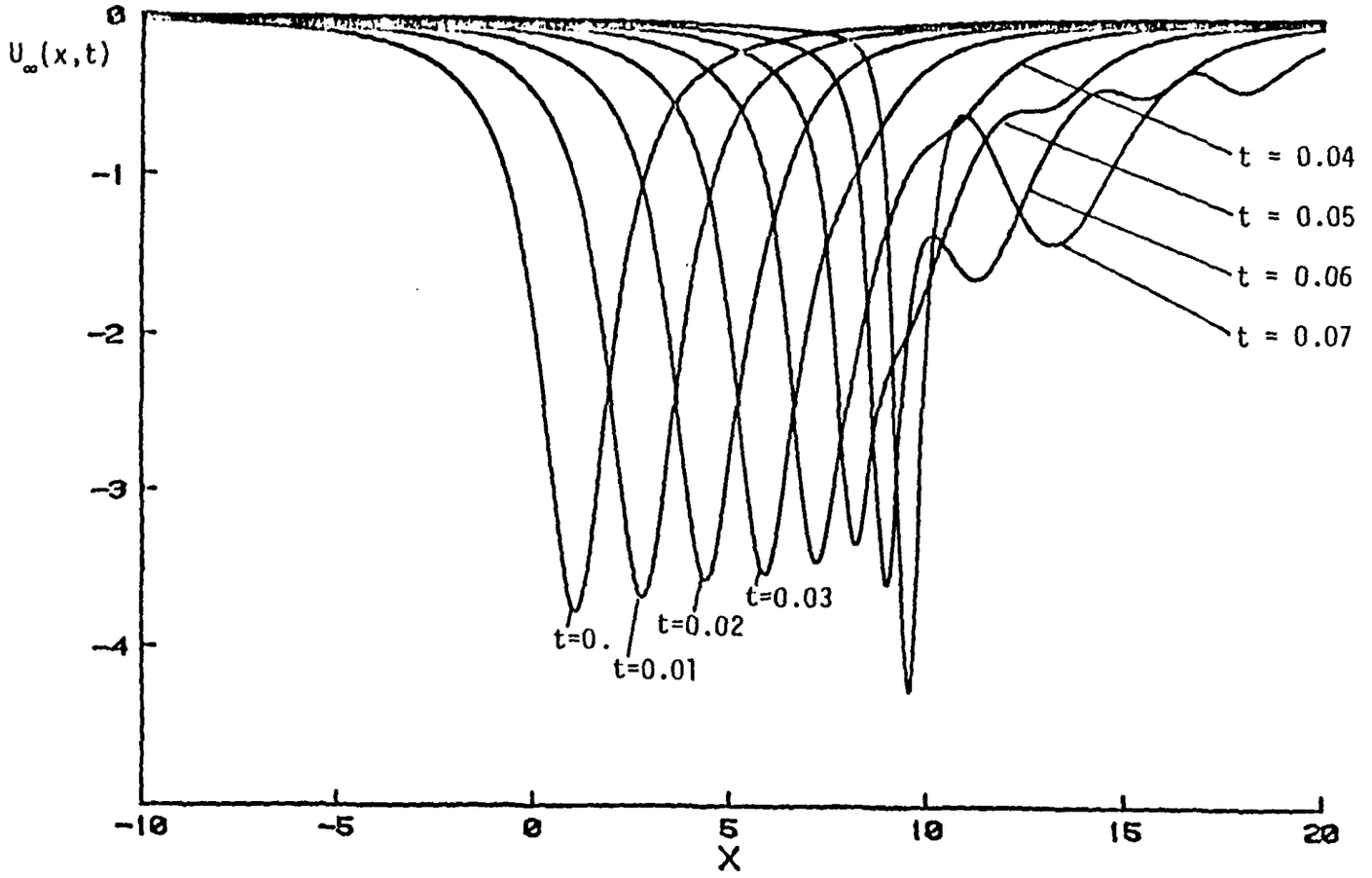


Figure 2.22- Inviscid streamwise velocity on the symmetry plane near the wall induced by a moving hairpin vortex in shear.

near the symmetry plane. The temporal development of θ_∞ for the sequence depicted in figures 2.6 and 2.8 is shown in figure 2.23. Two features are of interest here. First the moving hairpin vortex induces an inflow toward the symmetry plane which progressively strengthens with time as the hairpin legs move toward the surface. Secondly as time increases and the vortex stretches in shear, the streamwise extent , over which significant inflow toward the symmetry plane occurs, lengthens. To a certain extent, the flow near the symmetry plane is similar to that induced by a pair of counter-rotating vortices, except near the current streamwise location of the trailing parts of vortex legs that are nearest the wall (near x = 10 at t = 0.07) and where very strong local inflows develop.

The viscous flow on the symmetry plane develops independently of the rest of the boundary layer on the wall; numerical solutions have been obtained on the symmetry plane by Hon and Walker (1987). These calculations show that a complex unsteady separation phenomenon quickly evolves in the viscous flow near the wall and that this leads to a rapidly developing boundary-layer growth behind the vortex head and near the trailing legs of the primary vortex. Thus it is reasonable to conclude that a strong interaction with the outer flow will occur; however the strongest part of this interaction may not occur on the symmetry plane. It is likely that the strongest response will occur off the symmetry plane where the trailing ends of the hairpin vortex legs make the closest approach to the surface. This zone is indicated schematically in figure 2.21 and it is here where the boundary-layer response is expected to be most strongly eruptive. This has been observed to be the case in cross-flow plane visualization of the surface response to the passage of single hairpin vortices by Haidari and Smith (1988). In these studies, two local separations of the wall layer, each corresponding to the position of closest approach of the hairpin legs, were observed to grow. Under sufficiently hairpins eruptions were observed from the wall layer.

In any event, the moving vortex is thus seen to induce strong vicous-layer growth in the region behind the head and near the trailing portion of the hairpin vortex legs. As the erupting boundary-layer fluid penetrates further off the wall, into regions of higher relative streamwise velocity, the evolution of an inflectional streamwise profile (c.f. figure 2.17) is expected and then a roll-over into another secondary vortex. This process was observed repeatedly by Acarlar and Smith (1987a,1987b) as indicated in figure 2.24. In figure 2.25, the motion of a train of hairpin vortices above a synthetic dye streak (Acarlar and Smith, 1987b) is also shown. Here the hairpin heads have been labelled 1,2,3; as the vortices are convected downstream, the evolution of secondary hairpins in the locations labelled 1',2' and 3' may be clearly observed. It should be noted that the creation of these secondary hairpins involves a roll-over and that it occurs in

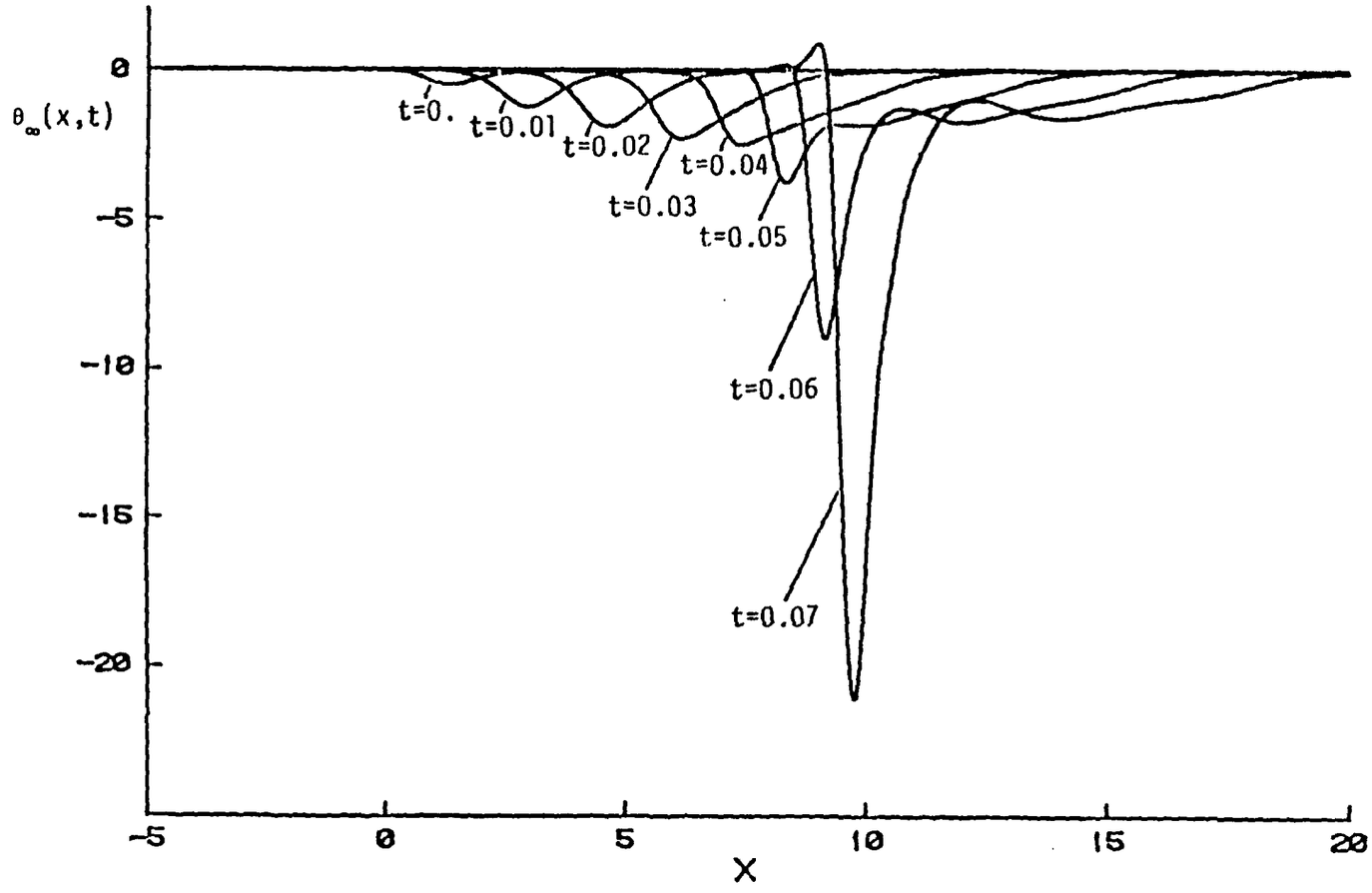


Figure 2.23- Temporal development of the spanwise velocity distribution near the symmetry plane induced by the moving hairpin vortex in shear.

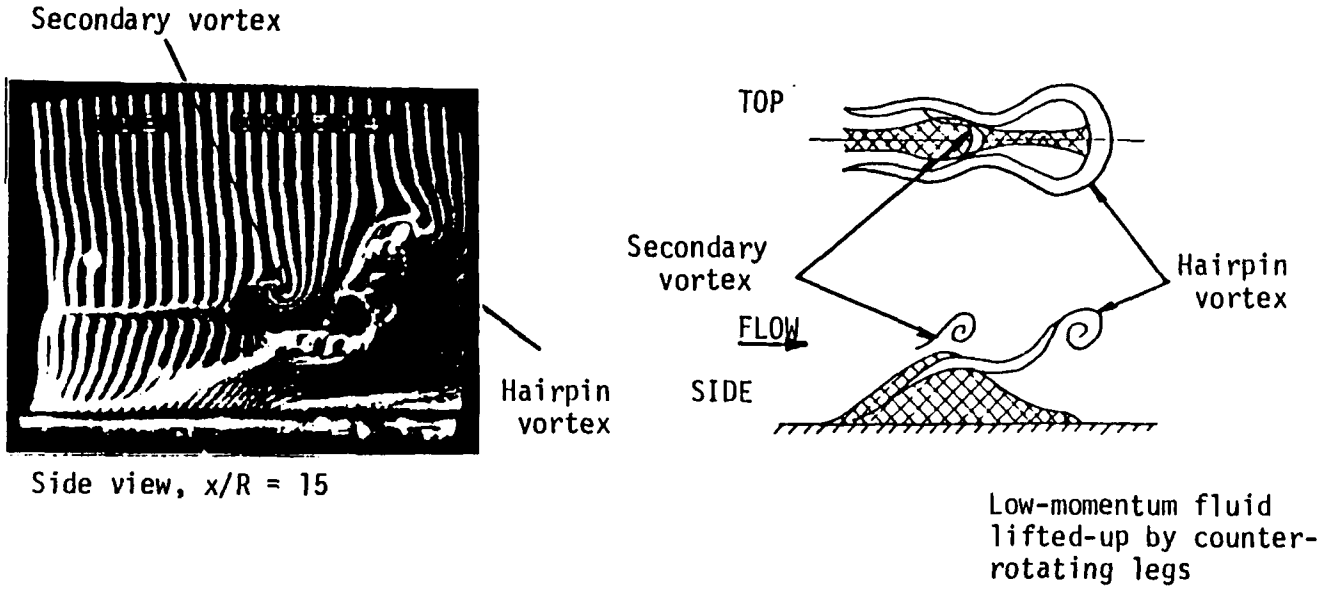


Figure 2.24. Secondary vortex generated on the plane of symmetry due to shear layer roll-up.

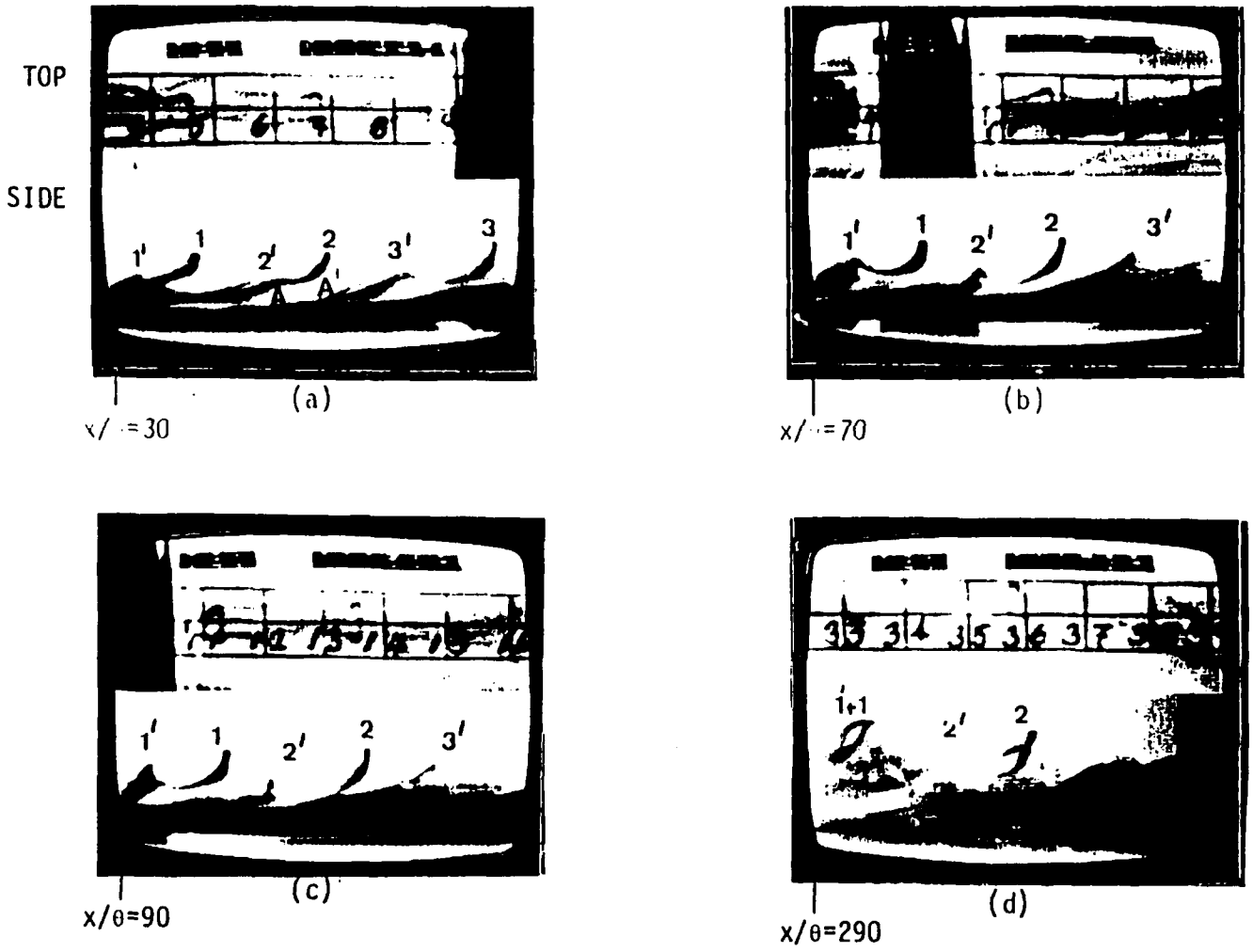


Figure 2.25 Generation of secondary vortices on the plane of symmetry. Re_θ=150, Re_{V_W}=17, V_W/U_∞=.126

exactly the location previously discussed in this section.

This type of pairing of secondary and primary hairpin vortices has also been observed by Haidari and Smith (1988). By controlled fluid injection from a streamwise slot, they were able to stimulate the formation of a short sequence of hairpins of varying strengths. As these hairpin vortices evolved and convected downstream, they were often observed to amalgamate or "pair", yielding subsequently larger hairpin vortex structures.

2.6 Streak Reinforcement

One feature that is observed in turbulent wall layers is the phenomenon of streak reinforcement (Smith,1984) and this will be discussed in this section. It has been previously argued that a low-speed streak is the trail of a convected hairpin vortex. As the vortex moves over the wall, it finally induces an eruption of the viscous flow near the wall; in the process a secondary vortex is created and the streak is momentarily obliterated. Smith and Metzler (1983) have observed that shortly thereafter, the streak re-appears in much the same spanwise location, but somewhat further downstream and they refer to this as "streak reinforcement". This phenomenon can also be explained in terms of hairpin vortices (Smith,1984). To illustrate this consider the simulation carried out by Hon and Walker (1987) which is shown in figure 2.26 and 2.27. Here it was assumed that a secondary hairpin vortex H1 has just been created through a viscous-inviscid interaction caused by hairpin H2 convecting in a shear flow. The assumed initial configuration as shown in figure 2.26. Calculations were then carried out using the Biot-Savart law to determine the subsequent trajectories of the vortices in the shear flow. It may be seen (figure 2.27) that the two vortices intertwine and interact to become essentially one stronger hairpin. As this process occurs, a new streak may then appear in much the same spanwise location as the original streak but somewhat further downstream, or the amalgamation process may simply act to reinforce and redevelop the initial streak from which the hairpins initially evolved.

2.7 The Origin of Hairpin Vortices

To this point, it has been argued that once vortices of the hairpin-type are present in a shear flow near a wall, they are able to multiply themselves in the spanwise direction and create new vortices through an interaction with the viscous flow near the wall. Thus once the process starts, it feeds on itself and becomes regenerative. However one question worthy of discussion is associated with how the hairpin vortices can develop in the first place. The studies of Acarlar and Smith (1987a,1987b) show that this process can initiate directly from small surface disturbances, either solid protruberances or injection of low momentum fluid, in an otherwise laminar

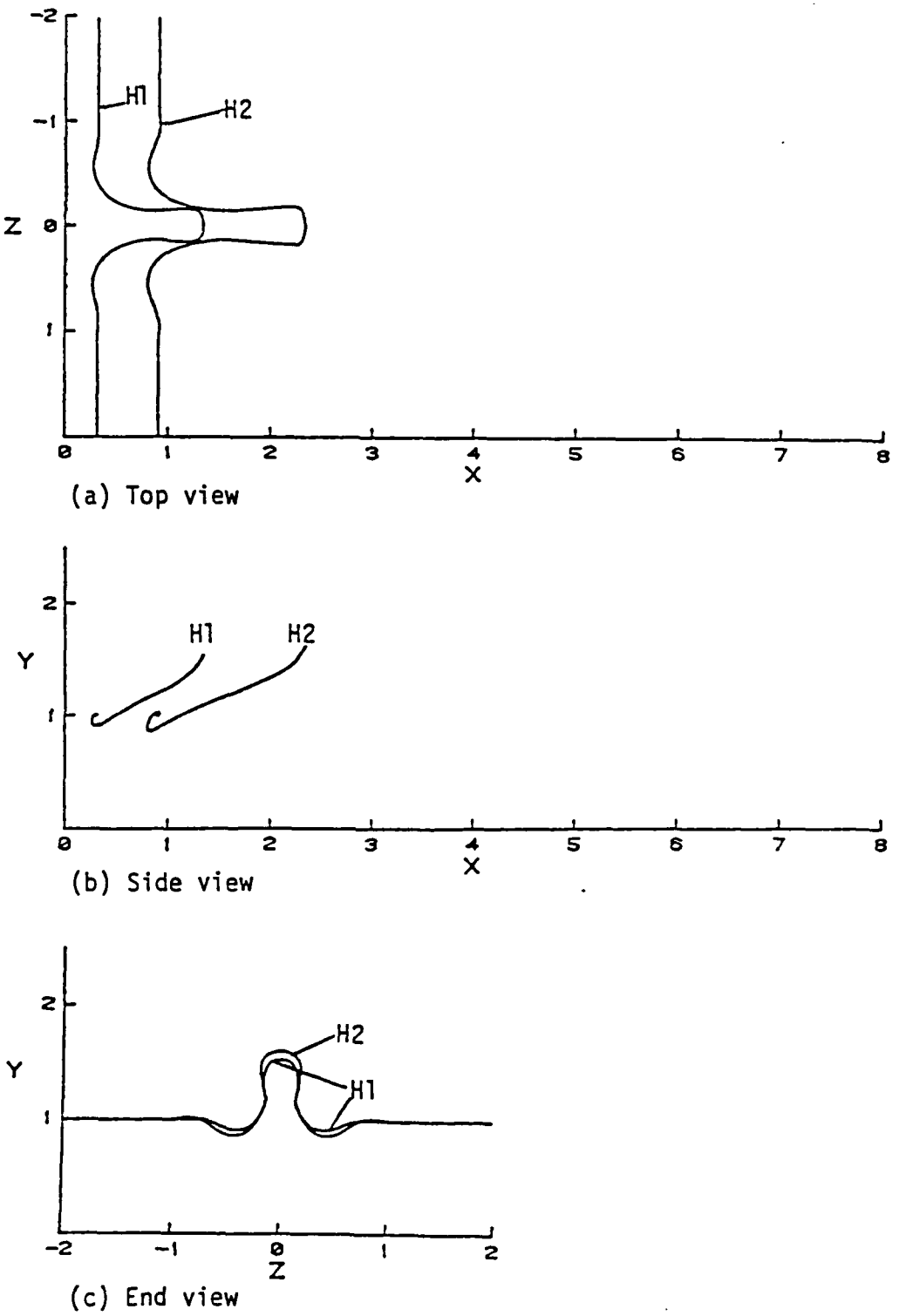
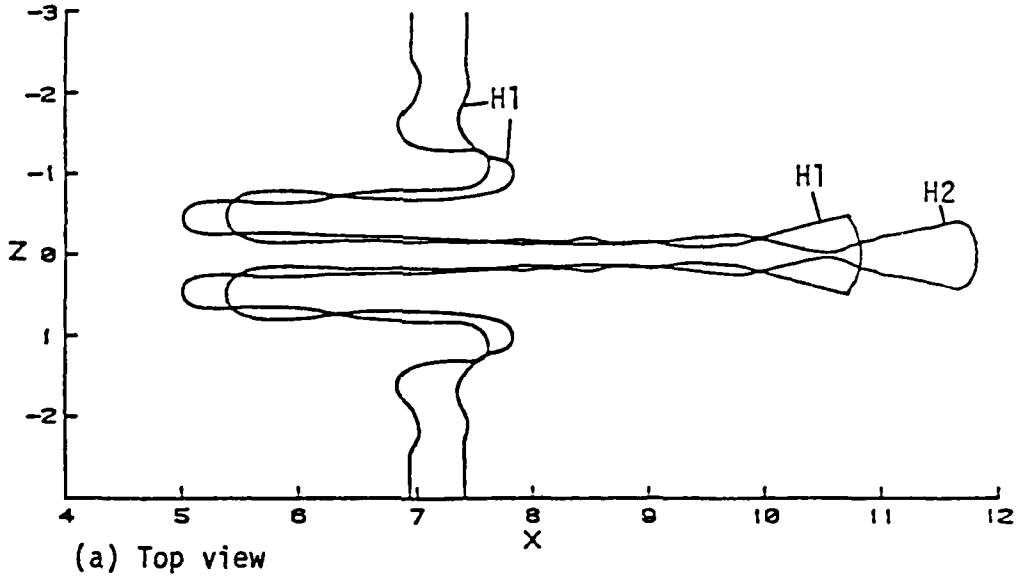
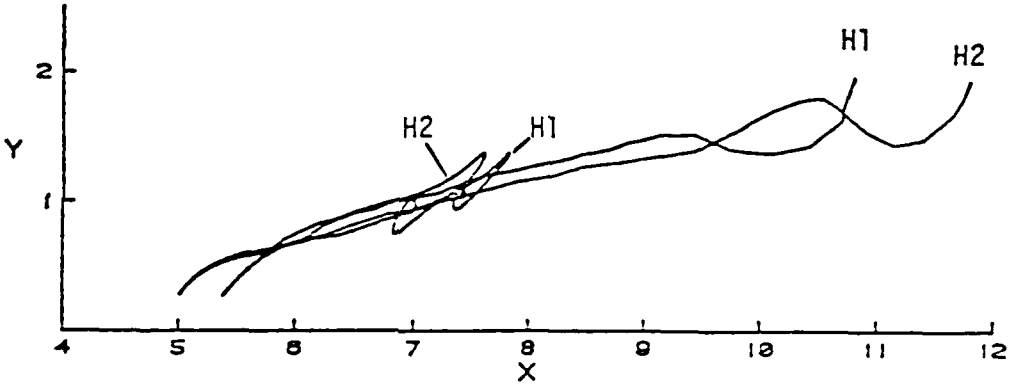


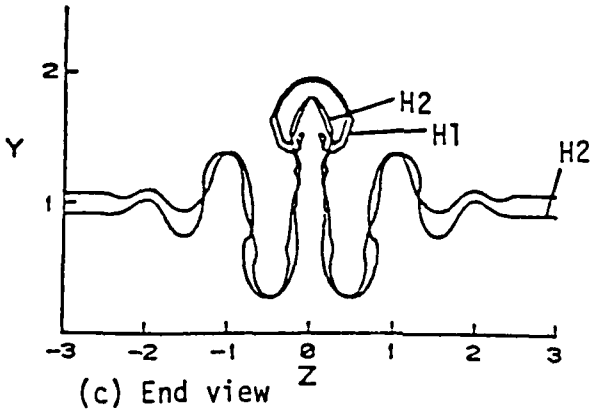
Figure 2.26 - Initial configuration for two hairpin vortices in shear.



(a) Top view



(b) Side view



(c) End view

Figure 2.27- Development of the two hairpin vortices at t=.04.

boundary layer. Disturbances in the transition zone are also thought to be of the hairpin vortex type. The central point is that once the flow speed and shear near the wall are large enough, even small three-dimensional disturbances in the flow can be expected to grow in the streamwise direction (c.f. figures 2.6 and 2.8) and to multiply through the processes described in this section.

2.8 The Outer Flow

The large rollers observed in the outer region of turbulent boundary layers are considered here to be large recirculations of smaller hairpin vortices. Indeed as previously discussed, hairpin vortices within a controlled sequence are observed to amalgamate (Haidari and Smith, 1988); there is every reason to believe that this process will continue to larger scales. It may be verified, in a number of ways, that large numbers of elementary vortices will agglomerate in such a manner as to give the impression of a large overturning zone of vorticity. The outer part of the boundary layer may be regarded as a "graveyard" for vorticity, since as the hairpins move away from the wall they decay and become relatively inactive. The recirculation in the large rollers may on occasion act to bring the hairpin vortices back toward the wall where they become stretched and active again in the production process. An indivdual hairpin vortex in the outer portion of the boundary layer may be expected to undergo a spiral type motion in the downstream direction. Thus time averaged measurements in the outer zone might lead to the impression that there exist large streamwise vortices in the outer layer (Nagib and Guezennec, 1987); however this outer region recirculation is not directly related to the important production events which occur near the wall.

2.9 The Logarithmic Law

One of the features of the turbulent boundary layer which is most thoroughly documented is the logaritmic behavior of the mean velocity profile near the wall. There are many arguments that have been put forth for this law (Millikan, 1927; Lighthill, 1963) but at present there is no sound physical explanation as to the sequence of events in the turbulence which give rise to this behavior. It is not possible here either to give a mathematical derivation of the logarthmic behavior. However it is possible to understand the general shape of the mean profile on the basis of the events occuring at the wall. As the bursting occurs via a hairpin-induced eruption, relatively high-speed flow from the outer portion of the boundary layer penetrates very close to the wall. During the quiescent state, the wall layer slowly grows outward with high streamwise velocity at its outer edge. During the relatively long quiescent period, the instantaneous velocity streamwise velocity profile near the wall clearly contains the logarithmic behavior (Lu and Smith, 1988). Thus on average the

streamwise flow near the wall is high speed and this is reflected in the mean profile distribution there. It is the continual collapse of the wall-layer region due to the bursting event that permits the high speed flow to approach the wall, thus giving rise of the relatively large values of the mean profile close to the wall.

2.10 Summary

In this section, an overall model of the important dynamical processes in a turbulent boundary layer has been put forth. This conceptual model is based on a considerable body of supporting experimental and theoretical studies which at present indicate that the convected hairpin vortex is the most important dynamical feature in the turbulent boundary layer.

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4. ASSOCIATED PUBLICATIONS, PRESENTATIONS, AND THESES

(During the present AFOSR contract period)

A. Publications

1. Ersoy, S. and Walker, J.D.A., "Viscous flow induced by counter-rotating vortices," Physics of Fluids, vol. 28, p. 2687 (1985).

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25. Smith, C.R., "Computer-aided flow visualization," Chapter in Handbook of Flow Visualization, ed. W.J. Yang, Hemisphere Pub. Co. (in press).

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B. Presentations

C. R. Smith

1. "A combined visualization-anemometry study of trianguler drag reducing mechanisms of triangular surface modifications," AIAA Shear Flow Control Conference, March 13, 1985.

2. "The effects of cylindrical surface modifications on turbulent boundary layers," AIAA Shear Flow Control Conference, March 13, 1985.

3. "An experimental study of hairpin vortices as a causative agent of near-wall turbulent flow structure," Invited Lecture, 22nd Society of Engineering Sciences, Penn State University, Oct. 7, 1985.

4. "Hairpin vortices in turbulent boundary layers: the implications for reducing surface drag," Invited Talk, DOD Drag Reduction Symposium, National Academy of Sciences, Washington, D.C., Oct. 23, 1985.

5. "A correlation of velocity flow field behavior with flow visualization data during turbulent bursting," 38th meeting of div. fluid dynamics., Amer. Phys. Soc., Nov. 25, 1985.

6. "Search for structure in hydrodynamics: applications of flow visualization and image processing," Invited Seminar, Mechanical Engineering Seminar Series, Penn State University, Nov. 6, 1986.

7. "Three-dimensional vortices in the wake of circular cylinders," invited presentation, Workshop on Bluff-Body Near-Wake Instabilities, Ohio State University, November 22, 1986.

8. "The search for hairpin vortex flow structures in turbulent boundary layers," 39th meeting of div. fluid dynamics, Amer. Phys. Soc., Nov. 25, 1986.

9. "Wall-layer flow structure: Empirical simulation and evaluation," invited lecture, Workshop on Turbulent Wall Layers, University of Texas, 13 February 1987.

10. "Application of image processing of hydrogen bubble flow visualization for evaluation of turbulence characteristics and flow structure," Invited Seminar, Applied Mechanics Seminar, University of Southern California, April 10, 1987.

11. "Flow structure in the wall region of turbulent boundary layers including empirical simulations," Invited Seminar, Fluid Mechanics Seminar Series, Stanford University, April 14, 1987.

12. "Higher level processing of flow field data: some thoughts," NSF-Ohio State Image Processing and Analysis Workshop, 18 October 1987.

13. "The use of pattern-matching techniques to identify hairpin vortex flow structures in turbulent boundary layers," 40th meeting of div. fluid dynamics, Amer. Phys. Soc., 22 Nov. 1987.

14. "Pattern-matching techniques applied to hairpin vortex flow structure detection in turbulent boundary layers," Zaric International Seminar on Near-Wall Turbulence, Dubrovnik, Yugoslavia, 16 May 1988.

15. "Flow conditioning: a new technology," invited presentation to Annual Meeting of ASME Committee on Fluid Metering, New York city, 3 Oct. 1988.

16. "Identification of hairpin vortex flow structures in turbulent boundary layers," 41st meeting of div. fluid dynamics, Amer. Phys. Soc., 22 Nov. 1988.

17. "Generation and growth of single hairpin vortices," 41st meeting of div. fluid dynamics, Amer. Phys. Soc., 22 Nov. 1988.

J. D. A. Walker

1. "Asymptotic theory of turbulence at a trailing edge," Invited presentation, Applied Mathematics Conference, Rensselaer Polytechnic Institute, June 1-2, 1985.

2. "Some aspects of turbulence modeling," Invited keynote address to the SSME Computational Third Working Group Meeting, George C. Marshall Space Flight Center, Alabama, June 11-14, 1985.

3. "The flow induced at a wall by a vortex pair," presentation at the 18th AIAA Fluid Dynamics, Plasma Dynamics and Laser Conference, Cincinnati, Ohio, July 16-18, 1985.

4. "The boundary layer induced by a three-dimensional vortex loop," presentation at the 38th Meeting of the American Physical Society, Division of Fluid Dynamics, University of Arizona, November 24-26, 1985.

5. "The evolution of a hairpin vortex in a shear flow," presentation at the 38th Meeting of the American Physical Society, Division of Fluid Dynamics, University of Arizona, November 24-26, 1985.

6. "Wall layer models for the calculation of velocity and heat transfer in turbulent boundary layers," presentation at the AIAA 24th Aerospace Meeting, Reno, Nevada, January 6-8, 1986.

7. "Boundary layer eruptions induced by vortex motion," Invited Seminar, NASA Lewis Research Center, Cleveland, Ohio, March 20, 1986.

8. Invited participant, Workshop on Atmospheric Turbulence Relative to Aviation, Missile and Space Programs, NASA Langley Research Center, Hampton, Virginia, April 2-4, 1986.

9. "Computational enhancements to viscous flow predictions" (with J.E. Carter, United Technologies Research Center), presentation to SSME Computational Fluid Dynamics Fourth Wroking Group Meeting, George C. Marshall Space Flight Center, Huntsville, Alabama, April 10, 1986.

10. "Turbulent flow at a sharp trailing edge," NASA Lewis Research Center, Cleveland, Ohio, August 7, 1986.

11. "Some aspects of three-dimensional vortex motion," NASA Lewis Research Center, Cleveland, Ohio, August 8, 1986.

12. "Calculation of turbulent flows near walls," NASA Lewis Research Center, Cleveland, Ohio, August 15, 1986.

13. "Mechanism for turbulence prediction near a wall," presentation at the 39th Annual Meeting of the American Physical Society, Division of Fluid Dynamics, Ohio State University, November 23-25, 1986.

14. "Viscous flow induced by a hairpin vortex convecting in a shear flow," presentation at the 39th Annual Meeting of the American Physical Society, Division of Fluid Dynamics, Ohio State University, November 23-25, 1986.

15. "Computational Enhancements to Viscous Flow Predictions," invited seminar (with J.E. Carter) at NASA Langley Research Center, December 3, 1986.

16. "Analysis and Prediction of the Turbulent Near Wake at a Sharp Trailing Edge," presentation at the AIAA 25th Aerospace Sciences Meeting, Reno, Nevada, January 12-15, 1987.

17. "Physical Mechanisms Leading to Wall Layer Erupitons," invited participant, Turbulent Wall Layer Workshop, U. of Texas, Austin, Feb. 12-13, 1987.

18. "An embedded function approach for turbulent flow prediction," AIAA 19th Fluid Dynamics Conference, Honolulu, Hawaii, June 8-10, 1987.

19. "An embedded function method for the calculation of turbulent flow near walls," NASA Lewis Research Center, Cleveland, Ohio, June 2, 1987.

20. "The influence of a moving hairpin vortex," R.T. Davis Symposium, invited paper, Cincinnati, Ohio, June 12, 1987.

21. "Wall function methods for heat transfer," invited lecture, U. of Cincinnati, June 24, 1987.

22. "Mechanisms for wall layer eruptions," NASA Lewis Research Center, July 2, 1987.

23. "Effects of a hairpin vortex convected in a shear flow," NASA Lewis Research Center, July 9, 1987.

24. "The nature of turbulent flow near walls," invited presentation, Wright Patterson Air Force Base, Dayton, Ohio, September 28, 1987.

25. "Prediction methods for turbulent flows near walls," invited presentation, Wright Patterson Air Force Base, Dayton, Ohio, September 29, 1987.

26. "Eruption mechanisms for turbulent flows near walls," 2nd International Symposium on Transport in Turbulent Flows, Unviersity of Tokyo, Tokyo, Japan, October 25-29, 1987.

27. "Methods for the Calculation of unsteady separation," AIAA 26th Aerospace Sciences Meeting, Reno, Nevada, January 13, 1988.

28. "Eruption mechanisms in turbulent boundary layers," invited seminar University of Michigan, Ann Arbor, Michigan, February 17, 1988.

29. "Calculation methods for compressible turbulent flows near walls," NASA Langley Research Center, Langley, VA, April 25, 1988.

30. "Three-dimensional vortex interactions in turbulent boundary layers," AFOSR Contractors meeting, University of Southern California, June 28, 1988.

31. "Embedded function methods," NASA Lewis Research Center, July 12, 1988.

32. "Turbulence production near a wall," ICOMP seminar, NASA Lewis Research Center, July 25, 1988.

33. "Modelling of turbulence near a wall," invited presentation at ONR Workshop on "New directions in research on turbulent wall layers," University of Mschigan, Ann Arbor, Michigan, November 18, 1988.

34. "Production mechanisms for turbulent boundary layers," 41st Annual Meeting of the Division of Fluid Dynamics, American Physical Society, University of Buffalo, Buffalo, NY, November 22, 1988.

35. "Vortex-induced separation," 41st Annual Meeting of the Division of Fluid Dynamics, American Physical Society, University of Buffalo, Buffalo, NY, November 21, 1988.

36. "Modeling of the symmetric turbulent wake of a thin flat plate," 41st Annual Meeting of the Division of Fluid Dynamics, American Physical Society, University of Buffalo, Buffalo, NY, November 21, 1988.

C. Theses

Completed Theses

1. Ersoy, S., "The flow induced near a wall by counter-rotating vortex pairs and vortex loops," Ph.D., Lehigh University, June 1985.

2. Ece, M.C., "An analysis of turbulent thermal trailing edge flows," Ph.D., Lehigh University, June 1986.

3. Hon, T.-L., "An analysis of the motion and effects of hairpin vortices," Ph.D., June 1987.

4. Lu, L.J., "Image Processing of Hydrogen Bubble Flow Visualization for Quantitative Evaluation of Hairpin-type Vortices as a Flow Structure of Turbulent Boundary Layers," Ph.D., August 1988.

Theses in Progress

(expected completion date in parentheses)

1. Peridier, V., "Strong interactions in turbulent boundary layers," Ph.D. thesis (June 1989).

2. Haidari, A.H., "The three-dimensional flow field of single hairpin vortices," Ph.D. thesis (June 1989).

3. Taylor, B.K., "The effect of pressure gradients on the generation, development, and interaction of hairpin vortices," Ph.D. thesis (June 1989).

4. Sobrun, U., "The motion of hairpin vortices," Ph.D. thesis (December 1990).

5. PERSONNEL

A. Co-Principal Investigators

C. R. Smith, Professor of Mechanical Engineering

J. D. A. Walker, Professor of Mechanical Engineering

B. Student Research Assistants

		(Comp. date)
V. Peridier	Ph.D. Candidate	June 1989
A. H. Haidari	Ph.D. Candidate	June 1989
B. K. Taylor	Ph.D. Candidate	June 1989
J. G. Greco	M.S. Candidate	June 1990
U. Sobrun	Ph.D. Candidate	December 1990