Vortex Dynamics in Transitional and Turbulent Boundary Layers

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The dynamics of transitional and turbulent boundary layers is explored via a hybrid vortex filament/finite volume simulation scheme in which vortical structures are identified without the constraints imposed by the traditional assumption that they are synonymous with rotational regions. Vortex furrows consisting of elongated, streamwise-oriented, raised perturbations to the wall vorticity layer overlying low-speed streaks are found to be the principal structural element appearing during the Klebanoff type transition. A number of dynamical properties of the furrows are considered here providing new insights into such questions as why both one and two-legged hairpins appear, why and how low-speed streaks form and why they persist, why hairpin-like rotational regions form, and why mushroom-like shapes and “pockets” are found in smoke visualizations of boundary layers. Consideration of the relationship between vortex furrows and the complex vortical structures appearing within the fully turbulent zone provides some insights into why turbulence in the boundary layer is self-sustaining.

I. Introduction

That vortical structures play a major role in the dynamics of transitioning and turbulent boundary layers is well supported by evidence obtained from physical experiments and numerical simulations of turbulent wall-bounded flows. For example, rotational motion that likely has a vortical origin is visible directly in boundary layers using smoke or particles\textsuperscript{1–5} and coherent, swirling motions appear in velocity data over three-dimensional grids produced in numerical boundary layer simulations.\textsuperscript{6} Coherent regions of rotating velocity are also revealed to be present via isosurfaces of several scalar indicators of local swirl\textsuperscript{7–9} when applied to grids of three-dimensional velocity data taken from numerical simulations\textsuperscript{10–13} and physical experiments.\textsuperscript{14–18} The presence of vortices is also indirectly indicated in such phenomena as low-speed streaks,\textsuperscript{19} ejections and sweeps,\textsuperscript{20} and “pockets”.\textsuperscript{21} Identifying what the structures are and how they contribute to the dynamics of the boundary layer has long been a primary aspect of boundary layer research.

For the most part it has been customary to assume that coherent vortical structures in the boundary layer can be distinguished from the background flow by their primary property of having a distinct local swirling or rotating motion. Thus, the concept of “organized vortical structures” has become largely synonymous with “regions of rotational motion.” From this point of view, the most commonly observed structures in transitioning and turbulent boundary layers have a form that may be described as that of a “hairpin” consisting of one or two streamwise-oriented “legs” connected downstream via an “arch” or “horseshoe” vortex. One-legged hairpins are often referred to as “canes.” It has also been observed that hairpins often occur in groups called “packets”\textsuperscript{22}

In a variety of contexts\textsuperscript{6,23} it is known that the vorticity within hairpin-shaped regions of rotational motion in the boundary layer does not consistently have an orientation along the axis of the structures. To
some extent this is a natural consequence of the presence of considerable ambient spanwise vorticity generated at the wall surface that is ultimately the source of the vorticity within the hairpin structures themselves. When the local vorticity and the axis of the structures are misaligned, there is reason to suspect — by virtue of the extension of the vortex filaments to the surrounding flow — that vorticity outside the structures may have some significant kinematic or dynamical connection to the vorticity within the structures. Consequently, by limiting the idea of structure to just the regions of rotational motion, the potential exists to overlook the true form taken by the local vorticity that acts as a coherent entity within the boundary layer.

The practice of using isosurfaces of a scalar marker to denote the position and shape of coherent structures within the flow field — and thus the need to decide on an appropriate contour level — adds an additional level of subjectivity to that inherent in the definition of vortical structure as regions of rotational motion. While some ability to track structures defined this way through the flow has been achieved, in situations where the rotational strength of a structure varies in space and/or time, as during its first appearance in the flow, it may be difficult to arrive at an objective understanding of the underlying phenomena. Closely related is the problem of discerning the true physical nature of multiple vortical objects that lie within close proximity to each other. Different parts of a structure are likely to have differing magnitudes of rotation besides the fact that there may be invisible, non-rotational vorticity connecting the separate objects.

The ambiguity inherent in the definition of structure according to its rotational field often means that multiple irreconcilable explanations for phenomena are possible. For example, the presence of low-speed streaks has been explained as due to the action of the lift-up mechanism produced by streamwise vortices as well as the kinematic consequence of hairpin vortices organizing into packets. The appearance of new hairpins in the flow is accounted for as the end result of a secondary instability on low-speed streaks as well as due to autogeneration processes in which hairpins beget more hairpins. In a similar vein, an explanation in terms of hairpins for such phenomena as the appearance of both one and two-legged hairpins, and retrograde vortices does not preclude the possibility that such flow objects can be explained via a different set of physics based on a more comprehensive notion of what vortical structures consists of.

One means for visualizing the complete set of vorticity belonging to structures is to simulate the boundary layer using a vortex filament scheme. In this, the flow field is represented via gridfree vortex tubes forming filaments that freely agglomerate to form large scale structures that can be identified by inspection. For example, in jet flow simulations vortex rings possessing various structural subtleties are readily depicted via filaments. Likewise, in the case of shear layers, filament patterns in the form of roller/rib, chain-link fence and oblique rollers with partial pairing are evident. Such forms match those seen in physical experiments.

In a previous work, boundary layer flow was studied using a generalization of the filament scheme that accurately accommodates the production of vorticity at solid surfaces. Consistent with grid-based studies, hairpin-shaped regions of rotational motion were evident in transition, but they were found to represent the rotational signature of structures that may be best described as “vortex furrows” — elongated streamwise-oriented, raised folds in the surface vorticity layer. Some of the basic kinematical properties of the furrows were explored in this work with just limited attention to the dynamics. The present study is focused on the dynamical aspects of furrows with a view toward answering questions concerning a variety of the flow phenomena that have long been observed in boundary layers. Among the latter are issues surrounding the causes of one and two-legged hairpins, low-speed streaks, mushroom-shaped and pocket-like smoke images as well as the mechanisms by which the turbulent field is self-sustaining.

The next two sections briefly review aspects of the numerical scheme and the computational problem that is solved. Following this the basic makeup of the furrows is considered followed by a number of developments related to their dynamics. Lastly, some discussion of the role of structures in the fully turbulent field is given followed by conclusions.
II. Vortex Filament Scheme

The hybrid vortex filament scheme employed in simulating the boundary layer flow is the same as has been previously described in detail.\textsuperscript{43} It combines a finite volume solution to the full viscous vorticity equation on a thin prismatic mesh adjacent to the wall surface with a vortex filament calculation away from the boundaries. The vortex filaments are formed out of short, straight vortex tubes linked end-to-end with each tube defined by its end points and circulation. Vortex tubes on a common filament share the same circulation. At each time step new vortices are created at the top layer of prisms from vorticity that has accumulated there from the wall-layer mesh computation. The circulation and orientation of the new tubes is set by requiring that the far field velocity produced by the vorticity in the prisms and tubes should be identical. Some small local distortion in the velocity field is inevitable in this process.

The use of a grid next to solid walls is motivated by the need to accurately compute the steep vorticity gradients at the surface that control the viscous flux of new vorticity into the flow. A near-wall grid is generated outwards from the surface triangularization and covers the region out to approximately $y^+ = 50$, where $y^+ \equiv y U_\tau / \nu$ and $U_\tau$ is the friction velocity. Since the Reynolds number is meant to be a real parameter in the simulations, the resolution of the boundary mesh aims towards that of a direct numerical simulation (DNS).

In the filament computation the vortex tubes translate, stretch and reorient according to the movement of their end points. Their circulation is taken to remain constant in time according to the approximate applicability of Kelvin’s theorem, it being assumed that the Reynolds number is sufficiently high to make this a reasonable model in the flow removed from solid boundaries. Tubes that stretch beyond a limit are subdivided. While viscous diffusion is not explicitly computed for the vortex filaments, vortex loop removal\textsuperscript{45–47} is used to provide spatially and temporally intermittent dissipation at inertial range scales, with the important benefit of limiting the growth in the number of vortex tubes to manageable levels. The principle invoked here is that removing the loops – that naturally form to accommodate the boundedness of the energy as it flows to small dissipation scales – dissipates local energy that otherwise would be destined for removal at finer scales. Loop removal thus sidesteps the great expense of treating details of the motion including viscous vorticity diffusion at the tiniest scales.

The velocity field is recovered from a summation over the contributions of vortex prism sheets and vortex tubes by application of the Biot-Savart law. A potential flow derived from a distribution of surface sources is included as a means of enforcing the non-penetration boundary condition. The computation of velocities is made affordable by the use of a parallel implementation of the Fast Multipole Method\textsuperscript{48, 49} that scales linearly with the number of vortex tubes. Excellent parallel efficiency is achieved for up to approximately 22 processors.

III. Numerical Problem

The numerical simulation of the boundary layer performed in this study is in many respects similar to that considered previously.\textsuperscript{43} In this, spatially developing flow is computed on both sides of a wide flat plate of length 1.5, thickness 0.1 and span 2.5 in the streamwise, vertical and spanwise ($x$, $y$, $z$) directions, respectively. The streamwise extent over which the computed boundary layer is in the laminar, transitional or turbulent regimes depends on the assigned Reynolds number as well as properties of the geometry such as the shape of the leading edge. For the purposes of the present study two main calculations are performed from which the structure of the boundary layer is analyzed. The first has Reynolds number $R_e = 120,000$ at the rear edge, transitions relatively quickly and reaches turbulent flow conditions by $x = 0.5$. The second calculation, which is designed to have a relatively long transition region, has a more streamlined front edge than the first case and a lower Reynolds number, $R_e = 75,000$. Turbulent flow conditions are delayed until approximately $x = 0.9$ in this case. The number of surface triangles used to represent the plate in the two calculations are respectively, 74,274 and 98,080.

The flow in the central part $|z| \leq 0.25$ of the plates constitutes a test section that has mean statistics
independent of spanwise position and is the exclusive focus of the following analyses. The test section in both cases is more than 5 boundary layer thicknesses wide and has dimensions in wall units of \((\Delta x^+, \Delta z^+) = (6177, 2059)\) for the higher Reynolds number case and \((4890, 1630)\) for the lower Reynolds number case. Velocity statistics are computed from a time average of points distributed over the span of the central test section.

In both calculations a prismatic mesh is erected from the surface triangles containing 11 layers with a layer of half-width adjacent to the boundary. Taking \(y = 0\) at the plate surface, the mesh extends to \(y = 0.012\). The number of surface triangles is more than fifty percent higher than in the previous study yet still somewhat less than the degree of resolution normally associated with a high quality DNS near the surface. For example, typical values of the thickness of the half-sheet on the wall surface for the present grids are, respectively, \(\Delta y^+ = 2.60\) and 2.06 which implies that the spacing between triangles is approximately \(\Delta z^+ = 45\) and 31. Finally, the maximum length of vortex tubes is taken to be 0.005 and 0.01 in the low and high Reynolds number flows, respectively. These scale to approximately 20 – 30 in wall units.

The boundary layer simulation begins from an impulsive start of the flow and runs in time until an equilibrium state is achieved. For example, in the simulation at \(Re = 75,000\) a leveling off in the number of vortex tubes occurs at approximately time \(t = 2\), with a slow relaxation to an equilibrium in the flow conditions well established by time \(t = 2.85\). Once the equilibrium state is reached, the flow is computed for an additional 2.2 time units \((\Delta t^+ = 484)\) for the higher Reynolds number case and 1 time unit \((\Delta t^+ = 213)\) for the lower Reynolds number case. To limit the number of vortices in the calculation, a downstream boundary is defined such that all filaments passing this point are removed from the flow. The missing vorticity has some effect on the adjacent part of the flow just upstream. Consequently, attention is confined here to the flow upstream of \(x = 1.2\). For the two simulations the number of vortex tubes in equilibrium is 26 million and 40 million, respectively.

Some evidence for the innate physicality of the computed boundary layer flow is provided in Figs. 1 and 2 containing plots of the mean velocity field computed as an average over data points within the fully turbulent zone \(0.6 \leq x \leq 0.7\) for the simulation at \(Re = 120,000\). In this region the local value of the Reynolds number based on momentum thickness \(R_\theta\) varies between 602 and 623. The computed constants in the log law \(\overline{U}^+ = 1/\kappa \log(y^+) + B\) are \(\kappa = 0.404\) and \(B = 4.986\) that agree well with a wide range of studies. In Fig. 2 the comparison to DNS data is made for mean velocity scaled by the far field velocity and here the agreement is quite excellent. Both of these results show that there is a relatively small and ultimately inconsequential distortion to the mean velocity in the neighborhood of \(y^+ \approx 50\) deriving from the switch between prisms and tubes at this location.

![Figure 1. Semilog plot of \(\overline{U}^+\).](image1)

![Figure 2. \(U/\overline{U}_{max}\).](image2)
IV. Vortex Furrows

The vortex filaments used in representing the flow outside the immediate wall vicinity can be made the basis for visualization of flow structures that are not readily depicted from traditional grid-based distributions of velocity and vorticity. For example, Fig. 3 provides a view of the computed vortex filaments in the boundary layer simulation at $R_e = 75,000$ from an overhead vantage point. The view includes the top surface of the plate from the leading edge at $x = 0$ to the position $x = 1.2$ at the right. The lateral boundaries are between $z = -0.25$ and 0.25. At the left the incoming flow is laminar with spanwise aligned vortex filaments. Transition begins upstream of $x = 0.4$ with a faint spanwise undulation to the vortices that gains in strength until elongated streamwise structures appear – the vortex furrows – in the region $0.4 \leq x \leq 1.0$. The average spanwise spacing of the furrows varies between approximately $\Delta z^+ = 150$ to 225 in viscous units and they are approximately 1000 viscous units in length. Beyond $x = 1$ the flow becomes increasingly turbulent and the organization of the filaments into furrows is less distinct.

Some idea of how the structure in Fig. 3 fits in with a more traditional view of the boundary layer is given in Fig. 4 where isosurfaces of the streamwise velocity fluctuation demarcating low- and high-speed fluid ($u = -0.3$ in blue and $u = 0.15$ in red) are displayed together with isosurfaces of rotational motion marked using $\lambda_2 = -100$ (in green). Here, $\lambda_2$ is the second eigenvalue of the matrix $S^2 + W^2$ where $S = (\nabla U + \nabla U^T)/2$ is the rate-of-strain tensor, $W = (\nabla U - \nabla U^T)/2$ is the rotation tensor and $(\nabla U)_{ij} = \partial U_i / \partial x_j$. The rationale for using $\lambda_2$ to mark rotational regions, as well as its effectiveness in doing so has often been noted.\textsuperscript{7,9} In the present case $\lambda_2$ is found by first evaluating the velocity field on a mesh and then computing the necessary derivatives via finite difference formulas. Within the main part of the transition region before the onset of turbulence, Fig. 4 shows that the volumes of rotating fluid revealed by isosurfaces of $\lambda_2$ are in the form of either one- or two-legged hairpins. These straddle low-speed streaks as seen in the Klebanoff type transition and have a one-to-one correspondence with the furrows. The elongated regions of high-speed fluid are located adjacent to and outside the furrows. In a number of instances arch vortices are seen to connect the hairpin legs.

Among the hairpin-like objects in Fig. 4, some are in the form of nested arch vortices that have a resemblance to “hairpin packets.” Considerable weight has been attached to the hairpin and hairpin packets in previous attempts at explaining the dynamics of transitional and turbulent boundary layers.\textsuperscript{22} The evidence in Figs. 3 and 4 as well as prior studies\textsuperscript{33,44} suggest that while the hairpins are the rotational signature of the furrows, it is only the latter that are complete structures suitable for analysis of the boundary layer physics. Consequently, the primary focus of the following discussion will center on elucidating the role of the furrows in a variety of phenomena associated with boundary layers, while the hairpins will be of subsidiary interest.
Figure 4. Isosurfaces of $\lambda_2$ (green), low-speed fluid (blue) and high-speed fluid (red) for the same time, domain and simulation as that in Fig. 3.

primarily because of their usefulness in identifying the location and rotational properties of the furrows.

Some idea of the interior of a typical furrow is given in Fig. 5 showing the vortex tubes from an end-on perspective at different positions along its length. The profile taken by this particular furrow at fixed $x$ locations is seen to proceed from an arch-like form at $x = 0.58$ to a mushroom-like shape by $x = 0.7$. The similarity of the latter with the mushroom-like images in smoke-filled boundary layers is unmistakable, and perhaps more closely aligned to what is observed than the traditional inference that the mushrooms seen in experiments are caused by hairpin vortices. By $x = 0.88$ there is the beginnings of a noticeable distortion away from the mushroom-like profile that signals the ending of transition. In this figure vortex tubes are nominally indicated by black, though those whose orientation is within $\pi/16$ radians of the streamwise direction are indicated as red or blue depending on whether their vorticity is pointing downstream or upstream, respectively. The lobes of the mushroom-like parts of the furrow clearly contain significant amounts of streamwise-oriented vorticity.

The connection between furrows and the rotational volumes used in more conventional analyses of boundary layer structure is given succinctly in Figs. 6 and 7. The first of these shows the upstream end of a furrow where it has an arch-like form — indicated by the filaments on three cuts through the furrow — together with the isosurfaces of rotation. For the sake of clarity the latter is rendered somewhat transparently. It is seen that the hairpin legs are associated with the sides of the arches for which the filaments are forward tilted and thus possessing streamwise vorticity that generates counter-rotating motion. This swirling flow is what gets represented graphically by the hairpin legs in the figure. The filaments at the most downstream location in Fig. 6 are close to acquiring the mushroom-like shape that dominates the continuation of this furrow in the streamwise direction as shown in Fig. 7. Here, vortex tubes with a streamwise orientation have become established within the lobes of the mushrooms as have the hairpin legs that represent the rotational motion produced by the streamwise vorticity. Thus, vorticity that only has a streamwise component due to tilting of filaments at the beginning of a furrow becomes fully oriented in the streamwise direction when the furrow acquires a mushroom-like form.

Figures 6 and 7 help make clear the distinction between the vortex furrows that represent self-contained and complete vortical structures on the one hand and the hairpin vortices that represent just that part of the furrows having to do with their rotational motion. Non-rotational vorticity, both in the stem and across the top of the mushroom-shaped profiles plays seemingly essential roles in producing a structure that contains rotational motion in the form of hairpins. Below it will be seen that the form taken by the furrows, including the specific arrangement of vorticity within them, is determined by the dynamical process by which
streamwise oriented vorticity is produced in the flow field.

On many occasions single-legged hairpins are observed in the filament simulations as, for example, in Fig. 4 at $x = 0.6, z = 0.16$. Examination of the filament field underlying a typical example of this occurrence, as shown in Fig. 8, explains why just a single leg is visible and not two. Thus, in this case the filaments comprising the furrow, as seen on spanwise planes at three locations, are tilted to one side with the mushroom lobe closest to the wall being the location of the single hairpin leg. Evidently, the roll-up process that forms the lobes and with it hairpins essentially atrophies on the side of the furrow tilted away from the wall while the side closest to the ground plane strongly interacts with the wall vorticity leading to the development of a single streamwise column of rotational motion. As before, there is significant streamwise vorticity within the now single lobe of the mushroom. Despite having only one sense of rotation, low-speed fluid accumulates beneath the tilted furrow forming a streak and is ejected outwards very much the same way as happens for
a symmetric mushroom having two hairpin legs.

The connection between hairpin legs and furrows provided by Figs. 6 – 8 has the beneficial consequence of offering a relatively simple and unified explanation for why both one and two-legged hairpins are observed in boundary layers. In fact, in all cases they are the rotational signature of furrows, but sometimes the furrows acquire a tilt to one side or the other that promotes the growth of only a single leg. Why furrows tilt away from the symmetric state appears to be a result of an intrinsic instability, as will become evident below when considering the flow at the end of transition. It thus appears that noisy flow conditions (e.g. due to sound or other disturbances\textsuperscript{55}) may promote a tendency for tilted mushrooms that shows up as single-legged hairpins when rotational regions are mapped out.

V. Dynamics

Observation of the simulated flow fields reveals that the furrows occupy relatively stable positions within the flow showing only minor shifts up and downstream or laterally during extended time periods. The furrows persist for a relatively long time before moving off downstream to be replaced by another furrow. Despite the stability of the furrows as a whole, the filaments of which they are composed experience a variety of changes as they rapidly convect downstream within the furrows. This suggests that the physics of the flow associated with the furrows may be considered from both the point of view of the furrows in their entirety including their formation and life cycle as well as from the perspective of the processes affecting the development of the vorticity within them. How the two aspects of the furrows are related to each other can be understood after considering each of the dynamical properties separately.

V.A. Within the Furrows

The existence of a favored convection velocity that may be associated with coherent events within the boundary layer has often been measured and used in describing the evolution of structures.\textsuperscript{22} In the present context, it is of interest to discern if there is a specific convection speed that may be associated with the movement of filaments along the plate and specifically within the furrows. One way to compute such a speed, if it exists, is by the translation along the plate of peaks in appropriate space-time velocity correlations. Specifically, the velocity at a given position, say \( x = x_0, y = y_0 \) at time \( t_0 \), can be correlated with upstream
velocities at an earlier time via

\[
R_{vv}(x_0, y_0, t_0; x, y, t) = \frac{\sum_{i=1}^{N_z} v(x_0, y_0, z_i, t_0) v(x, y, z_i, t)}{\sqrt{\sum_{i=1}^{N_z} v(x_0, y_0, z_i, t_0)^2} \sqrt{\sum_{i=1}^{N_z} v(x, y, z_i, t)^2}}
\]  

(1)

where \(v(x, y, z, t)\) is the wall-normal velocity in the boundary layer, \(t \leq t_0\) and the sums are over \(N_z\) equally spaced points covering the span of the test section. A typical result for \(R_{vv}\) in the late transition region at \(x_0 = 0.336, y_0 = 0.026\) for the \(Re = 120,000\) simulation is shown in Fig. 9. The presence of a favored correlation between upstream velocities at a given time and downstream velocities at earlier times is evident in the downstream shifting of maximum correlation with increasing time delay. Fig. 10 shows the locations of the correlation peaks as a function of time. Evidently, to good accuracy the translational speed of the peak is constant in time and so there is little ambiguity in determining the implied convection velocity from a least-square fit to the data. The convection speed in this case is computed to be 0.735 and values close to this may be computed for a wide range of nearby locations. If the data used in establishing the correlation is limited to the narrow region within a single furrow, then a similar result occurs as in Figs. 9 and 10 with the primary difference being a somewhat slower decay in peak correlation amplitude and a lower convection velocity, typically around 0.67, that no doubt reflects the fact that low-speed streaks are centered within the furrows. The convection speeds computed here are in the same range as has been found in many prior studies.

By plotting the filaments in a furrow from the perspective of an observer moving with the previously determined convection speed, it becomes possible to see the general outlines of what the dynamics of the vorticity field looks like within the furrows. A view from above of the filaments in a furrow at four consecutive times is given in Fig. 11. As before, vortex tubes with a high degree of orientation in the streamwise direction are colored either red or blue depending on their sense of rotation. The accumulation and concentration of significant streamwise vorticity along the length of the furrow is evident. To see how the vortex filament field develops in time within the furrow, an end-on view is provided in Fig. 12 of the vorticity within the small region outlined in green in Fig. 11 that is convecting downstream at speed 0.7. From this perspective the vorticity is seen to pass through a sequence of states from arch to mushroom-like forms, the same as existed at a fixed time along the length of a furrow in Fig. 5. The distance over which the change in Fig. 12 takes place is approximately \(\Delta x^+ = 575\).

It may be concluded that during the lifetime of the furrow, which is substantially longer than the time interval captured in Figs. 11 and 12, vorticity passes through it as if in an assembly line undergoing a continuous transformation from arch-like to mushroom-like forms. While this process occurs, the furrow
Figure 11. Overhead view of vortex filaments in a furrow as it evolves in time: (a), $t^+ = 0$; (b), $t^+ = 10.9$; (c), $t^+ = 23.9$; (d), $t^+ = 43.4$. Window outlined in green moves at speed 0.7.

Figure 12. Evolution in time of the filaments within the moving window in Fig. 11. (a), $t^+ = 0$; (b), $t^+ = 10.9$; (c), $t^+ = 23.9$; (d), $t^+ = 43.4$. 
shifts slowly in position as does the location separating arch-like and mushroom-like forms. In the example shown in Fig. 11 it is also the case that the furrow is subject to transitory disturbances that cause tilting of the mushroom structure. The sequence of images shows a distortion to the furrow that moves downstream with the result that the furrow returns to a symmetric form in the last view. This suggests that the furrows do not feed a steady stream of identically shaped mushroom-like vortical forms into the post-transitional flow downstream, but rather a continuously changing array of structures that vary in angle and other qualities. This viewpoint will be seen to be supported by the analysis of the late transition considered below.

The sequence of images in Fig. 12, or equivalently, the images in Fig. 5 at a fixed time, give some insights into how the mushroom-shapes are created. For example, wall-normal vorticity contained within the two sides of the arch-like structures at the upstream end of the furrows is initially separated in the spanwise direction with a low-speed streak between them. As the arch-like structures move downstream, the wall-normal vorticity at their sides is pushed toward the center by the counter-rotating motion associated with the furrow that includes the ejection of low-speed fluid outwards from the middle of the furrow. As the process continues the relatively narrow stems of the mushroom-shaped vortices are formed as is also the general mushroom shape of the furrow itself. How the lobes acquire streamwise vorticity is a question that will now be considered.

V.B. Creation of Streamwise Vorticity

While the mushroom-like profiles of the furrows appear to be a natural expression of the underlying counter-rotating motion associated with them, it is clearly the presence of streamwise vorticity in the lobes that drives the process forward by creating the counter-rotating motion in the first place. Thus, explaining the mechanism by which streamwise vorticity accumulates in the mushroom lobes so as to reinforce the counter-rotating motion first induced by forward-tilted vorticity within the arch-like structures, is a key step in understanding how the boundary layer works during transition and possibly also under turbulent flow conditions.

A view of the process by which streamwise vorticity is generated can be had by following the time history of initially spanwise lines of tracer particles in the vicinity of furrows. With a sufficiently fine grained coverage the tracers well account for the reorientation and stretching of material lines as they move in the flow. If it is assumed that the tracers are sufficiently far from the wall, so that the direct influence of viscosity can be neglected, then the material lines may be taken to also represent the convection of vortex filaments in the same locations. Note that the neglect of viscosity among the filaments within the numerical scheme is justified through the same set of assumptions. Analysis of the creation of streamwise-orientation from initially spanwise aligned material lines can go far toward explaining from whence streamwise vorticity appears within the furrows.

Figure 13 shows the evolution of an initially spanwise material line at $x = 0.5$ that is purposefully chosen at an altitude and spanwise position that strongly interacts with a furrow, in this case the furrow that is highlighted in Figs. 6 and 7. Tracer particles on the material element are initially equally separated so that the extent of localized stretching can be intuited from the subsequent spacing of elements. Places along the material curve that have a significant streamwise orientation are indicated in cyan or red, depending if they are within $\pi/4$ or $\pi/8$, respectively, of the streamwise direction. From the end-on perspective in Fig. 13 the material line is seen to initially rise upwards as part of the ejecting low-speed fluid that is contained within the central part of the furrow. As the tracers rise they curl up inside the lobe area of the flow due to the influence of the counter-rotating motion centered in the top part of the furrow. Substantial stretching of the material line across the top of the furrow is evident.

By the third image in Fig. 13 some streamwise orientation of the tracers begins to take hold at locations to either side of the rounded upward ejecting central part of the line. The positions where streamwise orientation becomes visible are where the high-speed sweeping fluid carried wallward due to the counter-rotating velocity field most closely encounters the ejecting low-speed fluid. The extent and degree of streamwise orientation grows in the subsequent views in Fig. 13 with the lobes of the mushroom-shapes becoming the central
Figure 13. End on view of material line element. (a) – (f) correspond to equally spaced times over an interval of length $\Delta t = 0.192 \ (\Delta t^* = 40.9)$. Tracers are colored cyan or red if they are within $\pi/4$ or $\pi/8$, respectively, of the streamwise direction, respectively.

Top and side views of the tracers in Figs. 14 and 15, respectively, for the same times as those shown in Fig. 13, give a clearer view of the way in which the material line reorients into the streamwise direction. In particular, Fig. 15 shows how the tracers are initially pushed backwards as they rise since they are immersed in ejecting low-speed fluid. At the same time, the rising tracers encounter faster moving fluid and begin to be uniformly pushed forward, except at the points on the side where the high-speed fluid curves in toward the central plane of the furrow. Here, the large differential in streamwise velocity between the ejecting fluid in the center of the furrow and the sweeping fluid coming inward from outside pulls the tracers into the streamwise direction. Initially the turning of the line segment is caused primarily by the retarded fluid as in the third and fourth images in Figs. 14 and 15, but subsequently the figures show that the lengthening into the streamwise direction is also driven by faster moving fluid. This may be a consequence of the continual rise in the streamwise line segments as seen in the last images in Fig. 15, which would act to increase the effect of the fast moving fluid relative to that of the slow moving fluid. The gathering of the rising streamwise tracers in the lobes fits in with the upwards downstream tilt of the mushroom-shaped furrows as seen in Fig. 7.

Figure 14. Top view of material line element as it moves downstream at times corresponding to those in Fig. 13.

Figure 15. Side view of material line element as it moves downstream at times corresponding to those in Fig. 13.

The physical model suggested by Figs. 13 – 15 of how initially spanwise material lines develop a streamwise component may account for the creation and augmentation of streamwise vorticity within the
furrows. Thus, if vorticity initially aligned in the negative \( z \) direction after having been created by shearing at the solid surface develops similarly to the material line element just discussed, then it is not hard to see that the plus and minus streamwise orientations of the vorticity arriving in the final positions in Fig. 14 are exactly what is required to generate the counter-rotating motion that drives the process forward. In essence, the counter-rotating motion generated by the arch-like structures that first appear in transition, causes the production of more streamwise vorticity that enhances the counter-rotating motion and thus causes the emergence of the mushroom-shaped structures with streamwise-oriented vorticity within their lobes. The phenomenon is thus self-reinforcing, and a good candidate to be prevalent in boundary layer transition as well as under turbulent flow conditions.

In the case of tilted mushrooms associated with a single hairpin leg, as in Fig. 8, streamwise vorticity appears to develop according to the same general mechanism as for a symmetric furrow. For example, Figs. 16 and 17 illustrate the motion of an initially spanwise material line as it interacts with the tilted furrow in Fig. 8. The end-on view in Fig. 16 shows that the rising tracers roll up into the one lobe of the mushroom. As before, the differential in speed between ejecting low-speed fluid and high-speed fluid sweeping around the mushroom lobe tilted toward the ground is most severe at a point just below the lobe. Here, tracers are redirected into the streamwise direction as they aggregate within the mushroom lobe as seen in the sequence in Fig. 17.

Figure 16. End-on view of material line element associated with the single-lobed vortex in Fig. 8. Figures (a) – (f) correspond to equally spaced times over an interval of length \( \Delta t = 0.192 \) (\( \Delta t^+ = 40.9 \)).

Figure 17. Top view of material line element, moving downstream, at times corresponding to those in Fig. 16.

V.C. Creation of Furrows

The boundary layer calculations performed in this study begin by applying an impulsive start to the flow field. As time progresses, an instability appears in the developing laminar flow that leads to the appearance of the furrows and eventually the fully developed turbulent field that forms downstream of the point where the furrows succumb to instability. Once established, the furrows appear to be relatively long lived in the sense that, for example, over the time \( \Delta t^+ = 320 \) of the simulation at \( Re = 75,000 \), a single furrow is
observed to move off downstream and disappear with a new furrow taking its place. The specifics by which the changeover in furrow occurs is shown in Fig. 18. Firstly, the furrow that has reached the end of its life cycle is centered at $z = 0.075$. During the elapsed time between the two images in the figure, $\Delta t^+ = 38$, its upstream end moves from approximately $x = 0.6$ to 0.7. Secondly, indicated by the arrows, a new furrow grows from a relatively short disturbance extending over the interval $0.5 \leq x \leq 0.7$ in the first image to a much longer streamwise interval $0.5 \leq x \leq 0.85$ in the second image.

An examination of the filaments on crosssections of the new furrow in Fig. 18(a) shows that it is composed entirely of arch-like vortices. In contrast, a short while later the downstream part of the new furrow in Fig. 18(b) has developed mushroom-like vortices while the upstream part remains arch-like. It may be concluded that simple arch-like perturbations in the background spanwise vorticity progress downstream acquiring mushroom-like forms and leaving fully developed furrows in their wake. In other words, the same process discussed in the previous section by which vortices travelling along the surface within a furrow turn from arch-like to mushroom-like forms is also responsible for the creation of new furrows.

Since low-speed streaks underlie the furrows as was illustrated in Fig. 4, the process by which furrows develop in the flow also explains how and why low-speed streaks develop. In the first instance, the furrows have the capacity to concentrate low-speed fluid beneath their positions by virtue of the counter-rotating motion that is integral to their construction. As furrows develop in length and become elongated so too will the spatial extent of the low-speed fluid that they foster. Thus, low-speed streaks of considerable streamwise extent are produced. By similar reasoning, the observed persistence of streaks for relatively long times in the flow corresponds to the similar persistence of the furrows.

An often cited supposition\textsuperscript{28,36} maintains that low-speed streaks are created by counter-rotating motion produced by the legs of hairpin vortices that are themselves created in the wake of downstream convecting arch or horseshoe vortices. An alternative model suggests that low-speed streaks are created as the kinematical consequence of the formation of hairpin packets.\textsuperscript{22} In fact, the first of these ideas is essentially an indirect way of describing how the streamwise growth of furrows leads to the creation of streaks. Thus, since hairpin legs naturally appear as the rotational signature of furrows, the connection between hairpin legs and low-speed streaks may be viewed as a byproduct of the prima facie connection that furrows have with the streaks.
V.D. Pockets

Smoked-marked boundary layers, when viewed from above, have been observed to contain “pockets” consisting of distinctively shaped regions that are largely devoid of smoke. Such structures are also visible in numerical boundary layers by using sufficiently large number of tracer particles to model the appearance of smoke. Explanations that have been given to account for the existence of pockets tend to require the action of a variety of special vortical objects whose existence has yet to be firmly established. Thus, it is of interest to discover if pockets are present in the filament simulations of the boundary layer, and if so, find out what connection they might have with the vortex furrows.

To model the presence of smoke in the computed boundary layer at \( R_e = 120,000 \) equally spaced tracers on a line spanning the test section at \( x = 0.2 \) and \( y^+ = 50 \) were released at uniform time intervals. At this location, which is within the transition region, a series of furrows exist very much the way they do in Fig. 3 at the lower Reynolds number. Releasing particles into the flow at this location is a convenient means of seeing if a connection exists between furrows and pockets, since the former is the only kind of vortical structure in the flow in this region. In fact, the computed motion of the tracers, as shown in Figure 19 over the time interval \( \Delta t^+ = 30.4 \), shows that structures with the appearance of pockets form for each of the furrows in the field of view. In this, lines oriented mainly in the flow direction represent streamlines while spanwise lines connect groups of particles that are placed into the flow at the same time step. Characteristic of pockets the structures contain regions largely scoured of tracers. The structures are also reminiscent of tracer marked objects seen in a previous computation of a spatially developing transitioning boundary layer. Below it will be seen that a connection between furrows and pockets is also present to some extent in the fully turbulent region.

![Figure 19. Image of tracer particles modeling smoke in the boundary layer reveal the presence of pockets corresponding to vortex furrows. Direction of flow is upwards.](image)

A three-dimensional view of how the counter-rotating motion associated with a furrow causes the appearance of a pocket is given in Fig. 20. In this, the tracers inside the furrow decelerate while ejecting outward through the center while tracers to the side are accelerated downwards toward the wall. The stretching across the top of the furrow that was evident in Fig. 13(f) is responsible for clearing away tracers toward the sides where they roll-up in the lobes to create the distinctive edging of the pockets. The essential motion is highlighted by the red line that represents the set of particles that were first released into the flow. The characteristic shape of the pockets can be attributed to the fact that the sideways spreading of the smoke precedes the cumulative effect of the roll-up in gathering particles into the region of the lobes. The demarcated boundary of the pockets tapers downstream since the longer a particle is influenced by the velocity field produced by the furrow the more it has circulated through the lobe. For some of the pockets, such as the second one from the right in Fig. 19, roll-up of the tracers occurs on just one side suggesting that the underlying furrow is tilted and has just a single hairpin leg.
V.E. Hairpins

Hairpin vortices as revealed by isosurfaces of rotation often contain arch-like regions that either connect the two legs of a symmetric hairpin or form the top part of a one-legged “cane” vortex. Normally, the rotational motion in the arch-like part of the hairpin is taken to be the direct consequence of vorticity aligned along the axis of the structure. Such an explanation is compatible with the tendency of hairpins to project outwards above the intense spanwise vorticity lying adjacent to solid surfaces. In the same vein, the hairpin packet model interprets the appearance of multiple arch-like regions of rotation as the signature of multiple hairpins that have developed together to form a packet. Since hairpin legs were shown previously to represent the rotational signature of furrows, it is of interest to see in what way the arch-like regions of rotation in hairpins might also fit in with the underlying presence of furrows.

It may be noticed at several positions in Fig. 4 (e.g., \((x, z) = (0.9, 0.1), (0.9, -0.15), (1, -0.08)\)) that arched vortices positioned over low-speed streaks seemingly connect the adjacent hairpin legs. Thus, the present simulations share this kind of rotational structure with many boundary layer simulations and experiments.\(^{13, 28, 55}\) A close-up view of the isosurfaces of rotation for a typical event of this kind taken from the \(R_e = 120,000\) simulation is given in Fig. 21. A well formed hairpin is seen to be present in the foreground with a second one attached to it and situated just downstream. Traditionally\(^{13}\) this arrangement tends to be interpreted as meaning that two hairpin vortices are present that likely originated out of a common disturbance to the upstream boundary layer. The vortex filaments underlying this pair of hairpin-like regions of rotation is shown in Fig. 22 from the same perspective as in Fig. 21. In addition to the red and blue vortex tubes indicating a streamwise alignment, green is used to show vortices oriented largely in the spanwise direction. The object that is revealed from the filaments is seen to be a somewhat perturbed furrow in which some spanwise vorticity has accumulated at those positions where the apparent arch vortices in Fig. 21 are visible. Perhaps the most notable aspect of the figures is the subtlety with which the positioning of filaments leads to quite distinctive regions of rotation.

The concentrated formations of streamwise vorticity visible as red and blue in Fig. 22 are indicative of a mushroom-like profile to the furrow that persists through the locations where the arch vortices occur. The regions where spanwise vorticity concentrates on the top of the furrow may thus be viewed as having arisen...
Figure 21. Isosurfaces of $\lambda_2 = -60$ suggesting the presence of two hairpin vortices in the $Re = 120,000$ simulation.

Figure 22. Vortex filaments underlying the event in Fig. 21 seen from the identical angle. Red and blue vortex filaments are approximately aligned in the streamwise direction while green vortex filaments are approximately aligned in the spanwise direction.
from shear layer roll-up due to interaction with the high-speed outer flow. In this case, the arched vortices appearing in Fig. 21 have a very different interpretation than that of being the top part of well defined hairpin vortices.

An example of another commonly observed rotational structure in the filament simulation is depicted in Fig. 23. Here, three arch- or cane-like rotational regions are connected with a single hairpin leg. Such structures are suggestive of the organization that is often associated with a hairpin packet, but the underlying filaments, shown on several cuts in Fig. 24, reveal that the causative flow structure is a tilted furrow. In fact, images similar to those in Fig. 24 can be seen at any crosssection of the structure in Fig. 23 with the main variation being that the size of the tilted mushroom depends on whether the cut is within or outside one of the bulges. For example, the structures in (d) and (e) appear larger than the others since they are within the arch segments and the others are not. As in the case of Fig. 21, the three spanwise-oriented arch-like regions in Fig. 23 result from roll-up of the highly stretched spanwise vorticity at the top of the furrow and cannot be regarded as independent arch vortices.

Figure 23. Isosurfaces of \( \lambda_2 = -30 \) suggesting the presence of three arch-like vortices in the \( R_e = 120,000 \) simulation.

The specific examples of arch-like structures considered in Figs. 21 and 23 are representative of many other similar events seen in the filament simulations. Evidently, whether or not the furrows are symmetric or tilted, they can project substantial spanwise vorticity into the fast moving outer flow where shear layer instabilities promote the roll-up of vorticity into a form whose rotational signature is that of single or nested hairpin-like structures. Once such processes start, the potential increases for the furrows to devolve into complex forms and the flow becomes turbulent. Some basic aspects of this process as it affects the breakdown of furrows into turbulence is now considered.

VI. Breakdown to Turbulence

The shear instability out of which the rotational regions in Fig. 21 and 23 appear may be viewed as an initial stage in a sequence of dynamical events by which furrows breakdown toward a turbulent state. Ever more complex distortions of the vorticity in the furrows beyond the point illustrated in the previous section occurs as the vorticity in the furrow moves into the turbulent region. Some indication of this is evident in
Fig. 3 where the furrows spread laterally and interact with neighboring furrows creating structures of greater complexity than those upstream.

A different perspective on the processes at work at the end of transition and into the turbulent region is provided by Fig. 25 in which the profiles of the filaments at several streamwise positions in the $Re = 75,000$ simulation are shown at a fixed time. The organization into mushrooms that is largely intact in the most upstream location at $x = 0.8$ is virtually non-existent by $x = 0.95$. Individual mushrooms are seen to follow different paths to a more chaotic state over the spatial extent in the figure. Thus, those centered at $z = -0.23, -0.04$ and $0.225$ tilt over until they are almost upside down and are intensely interacting with the surface vorticity. Others, at $z = -0.175$ and $0.01$ appear to twist sideways while those at $z = 0.1$ and $0.16$ tilt toward each other initiating a strong mutual interaction. It may be concluded that the furrows are either intrinsically unstable or are sensitive to the disruptive influence of nearby perturbations that promote the likelihood of breakdown. As mentioned above, the predilection for tilting when disturbed provides an explanation for why single-legged hairpins are more prevalent than two-legged hairpins in noisy flow conditions.

An interesting side light to the tendency for furrows to tilt is the effect that this may have on their rotational signature. For example, Fig. 26 illustrates a case where extreme tilting of a furrow towards the ground plane is accompanied by twisting of the hairpin legs that have developed within the mushroom lobes. Without knowledge of the underlying filament field very different explanations for the appearance of the crossed hairpin legs can be imagined. In fact, such structures appearing in rotational fields play an important role in recent analyses of the growth of secondary instabilities on low-speed streaks leading to breakdown.\cite{29,33} Clearly the evidence in Fig. 26 warrants reinterpretation of streak breakdown from the point of view of the downstream development of instabilities in the furrows.

In a number of different ways the previous discussion has made clear that the literal interpretation of structure via isosurfaces of rotation is likely to oversimplify the nature of the true vortical forms giving rise to rotation in the first place. The capacity for distortion can only increase as the flow becomes fully chaotic in the downstream turbulent zone and the shapes taken on by regions of strong rotation, such as those depicted at the downstream side of Fig. 4, give little clue as to what may be inferred about the underlying vorticity field. Note, as well, that in this case the vorticity filament field itself, such as that shown in Fig. 3, is not readily
Figure 25. Filaments at a fixed time showing progression to turbulent flow at the end of transition. (a), $x = 0.8$; (b), $x = 0.85$; (c) $x = 0.90$; $x = 0.95$.

Figure 26. Twisting of a furrow near the end of transition.
interpreted in terms of simple vortical objects.

Despite these obstacles, some general observations can be made about vortical structures in the turbulent region. In particular, Fig. 3 suggests that vorticity enters the turbulent zone in groups of somewhat affiliated structures that form along the furrows during their breakdown, rather than as a continuous stream of vorticity. In other words, segments of the post-transitional furrows detach in some sense from the more stable upstream parts and become self-contained structures in the immediate wake of the transition region. The forms taken by these vortices are far more varied than the simple arches and mushrooms that dominate transition, since the result of interacting with neighboring vortices and the wall leads to an endless variety of structural forms. Differences in structures from one place to another depend on how the vorticity in the furrows tilts, twists and bends and whether it detaches from the wall layer or interacts with the ground plane.

Vortical structures that share a common origin in a particular furrow can be imagined to maintain some degree of self-coherency within the boundary layer as they convect for some distance downstream. A sense of this organization is visible in Figs. 3 and 4 as a continuing delineation between vortices originating in neighboring furrows, that only slowly lessens with downstream distance. Eventually, as depicted in a prior simulation,\textsuperscript{43} this kind of coherency is no longer obvious to the naked eye. The downstream maintenance of coherency from vortices that have derived from a particular furrow may be related to the internal coherency attributed to hairpin packets as they grow due to the multiplication of hairpin vortices.\textsuperscript{12} The difference between the present result and packets is that the underlying structure formed out of furrows is not readily describable in the simple terms of a collection of nested hairpin vortices.

An example of the kind of coherency that is generally attributed to packets\textsuperscript{12,17,18,38,59} is shown in Fig. 27 which is taken from the simulation at $R_e = 75,000$. The isosurfaces appear to describe a series of hairpin vortices that develop together as they convect downstream. Moreover, a quiver plot in Fig. 28 of the velocity field relative to an observer translating at speed 0.8 computed on the central plane $z = -0.091$ in Fig. 27 reveals the presence of the kind of vortical motion that is often taken to be due to hairpin packets, specifically the “heads” of hairpin vortices.\textsuperscript{60,61} In fact, the vortices in Fig. 28 can generally be matched with hairpin-like structures in Fig. 27. It is of interest to see if justification for the packet model can be found in the underlying vortex filament field that is ultimately responsible for generating the rotational patterns in the figures.

The structures in Figs. 27 and 28 lie for the most part in the turbulent field where there is a steep rise in complexity of the underlying filaments compared to the relatively straightforward arrangements that were responsible for the arch vortices in Fig. 21 and 23 or the twisted vortices in Fig. 26. The contrast is evident in Figure 29 showing end-on views of the filaments on planes in the proximity of the significant vortical motions visible in Fig. 28. Focussing attention mainly in the vicinity of $z = -0.09$ it is seen that at best only a rough connection can be established between filaments and the rotational signatures. For example, the first few images in Fig. 29 show the presence of a growing arch-like to mushroom-like structure centered at $z = -0.09$, though neighboring structures in the form of one and two-lobed mushroom-like vortices are in very close proximity and presumably exert considerable influence on the rotational motion. Downstream of $x = 1.079$ the complex entanglements between vortices give way to the somewhat isolated mushroom-like structure in $x = 1.152$ that turns into a very complex form in the last image. The abundance of spanwise vorticity in the images of Fig. 29 is presumably related to the appearance of vortices in Fig. 28 and it is likely that vortex roll-up might have had some influence in this, though it is not a simple matter to establish this rigorously. A chief conclusion of this example is that there is likely no unambiguous way to relate the kinds of phenomena in Figs. 27 and 28 to the kind of orderly growth and development that might be seen in a series of hairpin vortices forming a packet.

One useful conclusion that can be drawn from Fig. 29 is that, despite the overall complexity of the turbulent vortices, it is often possible to identify individual arch or mushroom-like objects within the field. This is similar to the experience in smoke marked boundary layers where mushroom-like vortices are occasionally seen within much more complex patterns. This suggests that at least some aspects of the dynamical processes that produce the furrows in transition might very well have a role to play in the turbulent field as

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Figure 27. Isosurfaces of $\lambda_2 = -100$ revealing a complex group of arch-like vortices within the early stages of the turbulent zone.

Figure 28. Quiver plot of $u - 0.8, v$ on the plane $z = -0.091$ corresponding to the structure in Fig. 27. Positions denoted in blue correspond to planes in Fig. 29.
Figure 29. End-on view of vortex filaments on planes corresponding to the points indicated in blue in Fig. 28. (a), $x = 0.965$; (b), $x = 0.998$; (c), $x = 1.031$; (d), $x = 1.079$; (e), $x = 1.152$; (f), $x = 1.17$.

well. For example, to the extent that low-speed streaks and hairpin-like regions of rotation are present in the turbulent flow, it is very likely that vortex furrows in some form or another are locally present to produce them.

For the present simulations, examination of the turbulent flow near low-speed streaks often revealed the presence of flow structures that have distinctly furrow-like qualities. For example, Fig. 30 shows the characteristic mushroom-like and pocket-like behavior of tracer particles occurring over a low-speed streak in the turbulent region of the $Re = 120,000$ simulation. Unlike what was seen previously in transition, there are nearby structures whose presence is clearly felt in the somewhat more chaotic trajectories of the particles. Inspection of the filaments and isosurfaces contributing to the event in Fig. 30 confirms that a mushroom-like structure with two well formed rotational regions in the lobes is present in this place and time. The circumstances leading to the presence of furrows within the turbulent zone has yet to be determined with precision. However, in view of the self-reinforcing quality of the furrows, it may be the case that relatively quiescent regions that appear within the turbulent field are quickly populated by new furrows that grow out of perturbations to the wall vorticity. This can explain the self-sustaining nature of turbulence.

VII. Conclusions

This study has considered the structural aspects of boundary layer flow determined from simulations based on a hybrid vortex filament/finite volume scheme. The natural tendency of vortex filaments to agglomerate to form coherent structures allowed for the determination of structure unrestricted by the imposition of its traditional definition in terms of regions of rotational motion. Vortex furrows were found to be the dominate structural entity in the transitional boundary layer subject to Klebanoff type instability. Hairpin vortices that are widely touted as representing a dominant aspect of turbulent boundary layers are found to represent the rotational motion associated with furrows and have no standing as structures in their own right.

The view of the boundary layer dynamics provided by the furrows offers a unified and relatively simple explanation for a range of disparate phenomena that have been difficult to account for in a systematic way using the traditional view of structure as rotational regions. Thus, one- and two-legged hairpins represent the rotational signature of tilted and symmetric furrows, respectively. The intrinsic instability of the symmetric
mushroom-like form means that noisy flow conditions are likely to favor one-legged over two-legged hairpins. Low-speed streaks appear simultaneously with the furrows whose innate counter-rotating motion concentrates low-speed fluid beneath them. The length of the streaks coincides with the length of the furrows and the persistence of the furrows for long times is consistent with the persistence of low-speed streaks. Structures marked by smoke with the appearance of pockets and mushrooms are seen to reflect the direct influence that vortex furrows have upon smoke. The robust mechanism within the furrows that promotes the generation of streamwise vorticity can be seen as providing a basis for understanding how and why turbulence is self-sustaining. This process both creates furrows in the first place and maintains them over long time periods as vorticity passes through them from arch-like to mushroom-like forms.

The innate sensitivity of the furrows to disturbances leads to their breakdown and the commencement of the turbulent regime. Among the factors affecting the furrows is an apparent shear-layer type instability on the top surface exposed to the free stream velocity that causes roll-up of spanwise vorticity and the appearance of arch-like vortices in the rotational field. Other influences on the furrows lead to their tilting, twisting and interactions with neighboring structures and the wall vorticity. The complex mushroom-like forms produced by the furrows disperse into the post-transitional region as discrete collections of filaments. The lingering coherence of structures arriving into the turbulent field from particular furrows may be reflected in some of the organization taken to be that of hairpin packets. In general, the filament configurations underlying packet-like regions do not appear to be in the form of nested hairpin vortices. Finally, some evidence for the presence of furrow-like behavior in the turbulent region was observed, particularly surrounding low-speed streaks. A major goal of future work will be to better characterize and understand the nature of the complex filament field in the turbulent region.

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