# On the existence of uniform momentum zones in a turbulent boundary layer

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Instantaneous velocity fields in the $x$-$y$ plane of a zero pressure gradient turbulent boundary layer are measured using particle image velocimetry. It is found that there exist random, time-varying zones in the $u$-$v$ fields in which the streamwise momentum is remarkably uniform. The largest dimension of a typical zone is proportional to the boundary layer thickness. The zone closest to the wall contains viscous-inertial inclined structures similar to those found in low Reynolds number wall turbulence. A second zone is located above the wall zone in a region that coincides roughly with the logarithmic layer. The wake region of the boundary layer contains a complicated, time-varying pattern of several nearly-constant-momentum zones. The zones are separated from each other and from the free stream by thin viscous shear layers that contain concentrations of spanwise vorticity. © *1995 American Institute of Physics.*

Although many elements of the turbulent boundary layer have been identified,[1–8] its complexity continues to elude simple description, and a physical model which unifies all of the known elements is yet to be found. This letter reports experimental observations that identify two new structural features that modify several aspects of the current picture of the boundary layer. The observations are based on particle image velocimeter (PIV) measurements in the streamwise-wall normal ($x$-$y$) plane of a zero pressure gradient boundary layer on a smooth, flat plate at three Reynolds numbers (based on free-stream velocity $U_\infty$ and momentum thickness $\theta$): $\mathrm{Re}_\theta=930$, 2370, and 6845.

The first observation is that large, time-varying, irregularly shaped zones with nearly constant streamwise momentum exist throughout the boundary layer. Streamwise momentum is "nearly constant" in the sense that fluctuations within a zone are generally small and almost always less than the changes in velocity between adjacent zones. The two zones closest to the wall are long and layer-like, and they contain various elements that are associated with the viscous-inertial wall layer and the logarithmic layer. In the wake region, there may be more than one zone, each occupying a fraction of a turbulent bulge.

The second observation is that the constant momentum zones are bounded by thin viscous-inertial shear layers in which spanwise vorticity is clumped into concentrated vortical regions. The viscous superlayer, which is the thin region separating the free stream from the turbulent zones, also contains of vorticity. This observation suggests that the viscous superlayer should be viewed as a collection of vortices on a sheet-like domain, in contrast to the classical view of the super layer as a convoluted, but continuous, vortex sheet.[1]

The PIV measurements were made using a double-pulsed, high-image density, photographic PIV system similar to that described in Ref. 9. Several hundred instantaneous $u$-$v$ velocity vector fields in the streamwise-wall-normal plane over a 120×150 mm field of view were obtained. Each field typically contained 10 000 to 26 000 velocity vectors. The accuracy of each vector measurement was better than $0.01U_\infty$, and the spatial resolution ranged from 9 to 52 viscous wall units, depending on the Reynolds number and the interrogation parameters. Although the velocity field was not fully resolved, the measurements were adequate to resolve most of the energy in the vorticity field. Tests performed on the lowest spatial resolution case (i.e., the highest Reynolds number) showed that decreasing the measurement dimension from 52×52 viscous units to 36×25 affected the root-mean-square (RMS) vorticity by less than 5%. Details are given in Ref. 10.

For brevity only one velocity field from the highest Reynolds number data set, $\mathrm{Re}_\theta=6845$, is presented. In Fig. 1, the spanwise vorticity, $\omega_z$, is shown by the gray-shaded regions, and the velocity vector field is shown in a frame of reference in which $0.9U_\infty$ is subtracted from the streamwise velocity component. The coordinates are normalized by the boundary layer thickness, $\delta$, defined at $0.99U_\infty$. In the free stream, labeled FS, the $u$ component is nearly constant, the $v$ component is negligible, and the level of vorticity fluctuation approaches the noise level of the measurements.

Since the frame of reference is chosen to be $0.9U_\infty$, the zones with streamwise velocities close to $0.9U_\infty$ (i.e., zones labeled III–VI) are displayed with near zero velocity vectors, causing them to be highlighted. In regions where the $u$ component is significantly different from $0.9U_\infty$, the longer lengths of the vectors tend to darken the map. The zones labeled I and II clearly have lower momentum than zones III–VI, while the free stream clearly has higher momentum than zones III–VI. The set of four zones labeled III–VI forms a layer bounded from above by the free stream and from below by zone II. Each one of the zones labeled III–IV contain perceptibly different values of streamwise momentum.

The vorticity field in the turbulent boundary layer is filled with many regions of concentrated high and low vorticity, which are interpreted to be sections through vortex tubes if the streamlines surrounding them are approximately circular when viewed in a frame of reference convecting with the vorticity. Roughly circular regions of vorticity are

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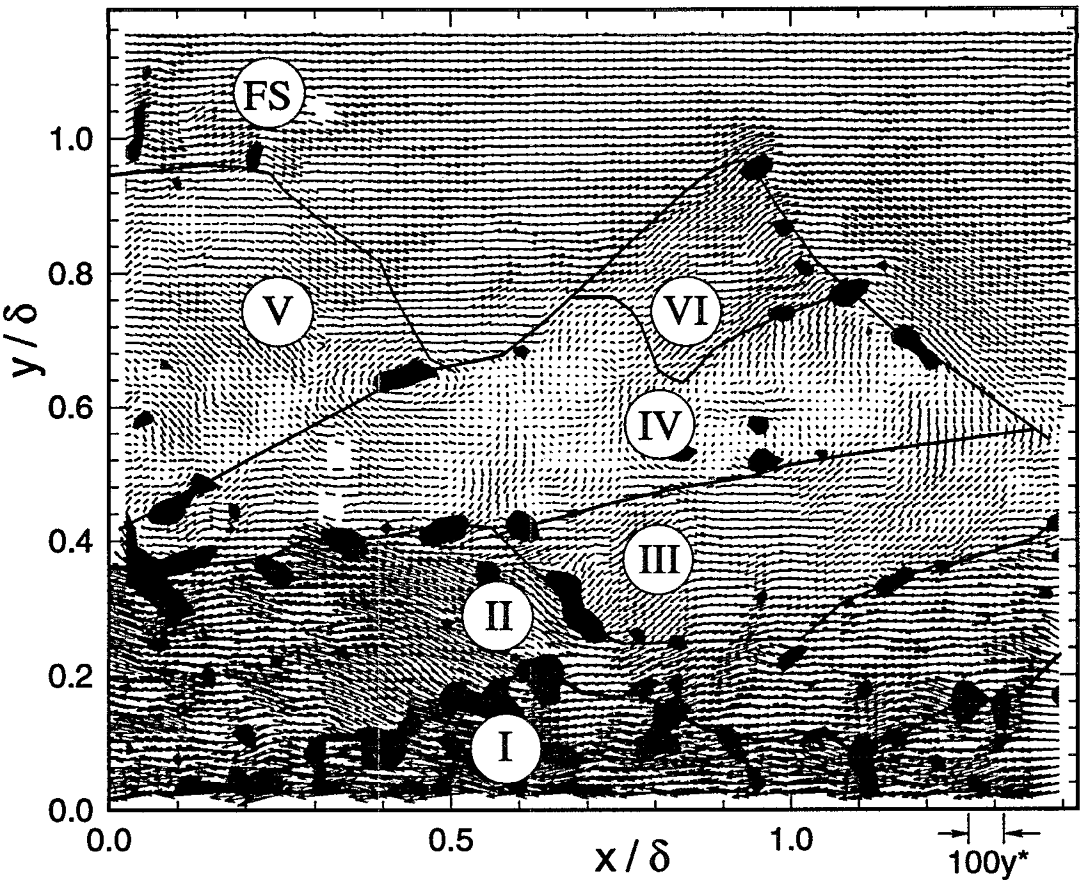


FIG. 1. Instantaneous velocity field in the streamwise-wall-normal plane of an $\mathrm{Re}_\theta=6845$ boundary layer viewed in a frame convecting at $0.9U_\infty$. The black lines indicate the approximate boundaries of zones in which the streamwise momentum is nearly constant. The dark-gray shaded areas denote regions where spanwise vorticity, nondimensionalized by the friction velocity $u_\tau$ and the viscous wall length scale $y^*=\nu/u_\tau$, is less than $-0.03$.

considered vortical by this definition, while elongated regions are not.

To illustrate the relationship between constant momentum zones and clumped regions of strong negative spanwise vorticity, the regions where the spanwise vorticity, $\omega_z \nu/u_\tau^2$, is less than $-0.03$ are indicated with dark-gray in Fig. 1. By inspection, the change in streamwise velocity from $U_\infty$ to $0.9U_\infty$ occurs along a locus of small, strongly negative vortices that outline the turbulent region. Since there is no significant vorticity above this envelope, it is reasonable to identify it as the layer that separates the free stream from the turbulent zone. Similar layers of vortices are observed throughout the boundary layer to coincide with the edges of uniform momentum zones. These vortical layers (denoted by black lines in Fig. 1) are also characterized by strong vertical changes in streamwise velocity.

Zones I and II, which are close to the wall, are layer-like, i.e., the streamwise extent of each zone, which exceeds one $\delta$, is significantly greater than the thickness. The average streamwise velocity in zone I is about $0.6U_\infty$. It contains inclined structures whose $x$-$y$ plane signatures are similar to those seen in direct numerical simulations of low Reynolds number wall flows, suggesting that zone I is essentially related to the viscous-inertial wall layer which contains many hairpin-like or cane-like structures and inclined shear layers, as summarized by Robinson.[8] The Reynolds number characteristic of the inclined structures and the maximum height to which zone I grows is of order several hundred $\nu/u_\tau$, consistent with accepted wall layer Reynolds numbers and mean thickness. Zone II extends from the top of zone I to a random height that may reach $0.6\delta$. The location of zone II and the velocity within it, about $0.7U_\infty$, suggest that it is associated with the logarithmic layer, although from the mean velocity profile the height of the logarithmic layer at the highest Reynolds number is only $0.25\delta$.

Frequently, the wake region can be divided into several subzones, which are smaller in size than the $\delta$-scale zones, and have smaller changes in the streamwise velocity across their edges than the larger zones. The realization shown in Fig. 1 contains several subzones, denoted as zones III–VI, which lie in the wake region and which are clearly associated with a turbulent bulge. Because the changes in streamwise velocity between the subzones (i.e., zones III–VI) are weaker, the locations of the bounding shear layers are less certain than they are for zones I, II, and the super layer. It is common to observe all the large zones, but in some realizations the smaller zones are missing or not easily identified.

In Fig. 2, profiles of $u(x,y)$ at several horizontal loca-

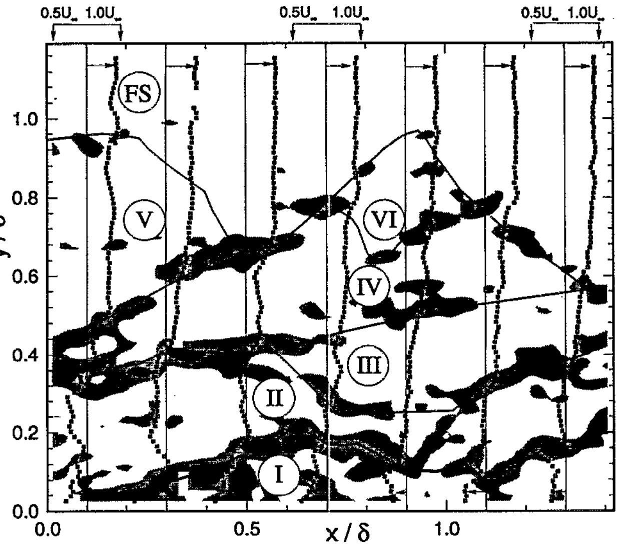


FIG. 2. Wall-normal profiles of total streamwise velocity show regions where the $u$-component of velocity is nearly constant. The solid black vertical lines indicate the $x$ location of each profile. The wall-normal profiles of streamwise velocity are overlaid on a map of $\partial u/\partial y$, where the light-gray and dark-gray shaded areas correspond to regions where $0.01<\partial u/\partial y<0.03$ and $0.03<\partial u/\partial y$, respectively. The regions where $\partial u/\partial y$ is large often coincide with the boundaries of the momentum zones and the shear layers. Black lines are used to denote zone boundaries, as in Fig. 1.

tions are overlaid on a map of $\partial u/\partial y$. The uniformity of the streamwise velocity within the zones is apparent, as are the jumps in velocity that occur across the layers separating one zone from another. Light-gray shading denotes regions in which $\partial u^+/\partial y^+$ is between 0.01 and 0.03, and dark-gray shading denotes regions in which $\partial u^+/\partial y^+$ is greater than 0.03. The contours of $\partial u/\partial y$ define boundaries between the constant momentum zones that are somewhat more continuous than the vorticity contours, suggesting that the boundaries are similar to shear layers. The Reynolds number of a typical shear layer, based on the velocity change across the layer and its thickness, is approximately 25–100. This number is approximately constant for all three Reynolds numbers, suggesting that the layers have a boundary layer character in which viscosity and inertia are in balance.

The vortical concentrations in the shears layers are qualitatively similar at all of the Reynolds numbers studied, despite the limited spatial resolution of the PIV measurements which must blur the shear layers at the higher Reynolds number. Rows of vortices within the shear layers could result from vortex roll-up of viscous shear layers due to classical instability. However, flow visualization suggests that the vortex roll-up is a more complicated process, which is frequently caused by time-dependent interactions where high-speed flow shears over a region of low-speed fluid, creating one or more horseshoe or arch-like vortices. The horseshoe vortices induce low-speed fluid under their arches. This induced low-speed fluid can form a shear layer with upstream high-speed fluid, forming another vortical arch. Direct numerical simulations at low Reynolds number show that one hairpin or arch can, in this way, create a succession of aligned hairpins.[11] The same mechanism offers a likely explanation for the formation of the long regions of uniform momentum in zone I. The long layers of retarded flow are simply caused by mutual induction from several arch vortices aligned coherently in the streamwise direction. The same mechanism might explain the large regions of uniform momentum found in zone II of these experiments, but further details are needed to complete this picture.

The zonal structure reported here offers some new ways of conceptualizing the structure of wall turbulence. The conventional decomposition of the boundary layer into a wall layer, a logarithmic layer and a wake region is based on time-averaged properties of regions of fixed vertical dimension. The zones, in contrast, are instantaneous, time-evolving entities, whose characteristics contribute to the mean properties of each of the conventional layers. The most interesting consequence of zonal structure is that, to the extent in which streamwise momentum is constant throughout each zone, the transport of momentum must occur only across the thin viscous-inertial layers which separate the zones, either by motion of the layers or by vortex induced flow across the layers. In either case, the scenario is rather different from eddy transport by homogeneously scattered eddies.

## ACKNOWLEDGMENTS

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