SCALE INTERACTIONS AND 3D CRITICAL LAYERS IN WALL-BOUNDED TURBULENT FLOWS

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Summary Phenomena related to scale interaction in wall-bounded turbulent flows were considered through the lens of critical layer analysis. A 3D critical layer formulation was used, with the 3D critical layer associated with a particular structure defined as the height where the instantaneous velocity field composed of the large scales and the mean velocity matched the convection velocity of that structure. Characterization of the velocity field surrounding the 3D critical layer in wall-bounded turbulent flows led to conclusions consistent with previously observed phenomena including the shape of the interface defining uniform momentum zones (UMZs) [1] [2] and amplitude modulation of the small scales by the large scales [5]. The use of a 3D critical layer formulation in wall-bounded turbulent flows may lead to improved modeling of small scale activity in reduced order models and LES.

The 3D critical layer has previously been considered in wall-bounded turbulent flows in the context of self-sustaining, exact solutions to the Navier-Stokes equations [3]. The present work links phenomena related to a critical layer and current observations of scale interaction in wall-bounded turbulent flows. The shape of the interface outlining UMZs in instantaneous snapshots of turbulent boundary layers has been observed to lie along an isocontour of velocity [1] [2], which can be considered to constitute an instantaneous 3D critical layer. Additionally, observations that large scales in the flow can modify the local wall shear stress [4] and the amplitude of the local small scales [5], can be considered through the perspective of the 3D critical layer analysis. Considering physical and statistical features of wall-bounded turbulent flow through a critical layer framework allows for improved understanding of scale interactions and may lead to improved modeling of these phenomena.

Figure 1 offers an illustration of a 3D critical layer identified in PIV data. 2D Gaussian filters were used to identify distinct scales in the PIV velocity data, and Taylor's hypothesis was used to visualize a larger field of view than is available in the data. Large-scale velocity structures corresponding to instantaneous velocity higher than the mean velocity are shown to correspond to depressions in the 3D critical layer towards the wall (relative to the 2D critical layer corresponding to the location where the *mean* velocity is equal to the structure convective velocity) and are correlated (both visually and statistically) with energetic small scales at lower heights in the flow, while those leading to instantaneous velocities slower than the mean velocity are shown to correspond to raised regions of the 3D critical layer and are associated with energetic small scale activity at higher heights in the flow.

The resolvent analysis of McKeon and Sharma [6] has been used to model this simplified definition of the 3D critical layer in wall-bounded turbulent flows. A single velocity response mode from resolvent analysis superimposed with the mean velocity profile leads to a 3D critical layer signature that qualitatively matches observations of 2D PIV data.

In summary, the utility of the 3D critical layer to describe a range of phenomena that have been observed in the literature is demonstrated and exploited.

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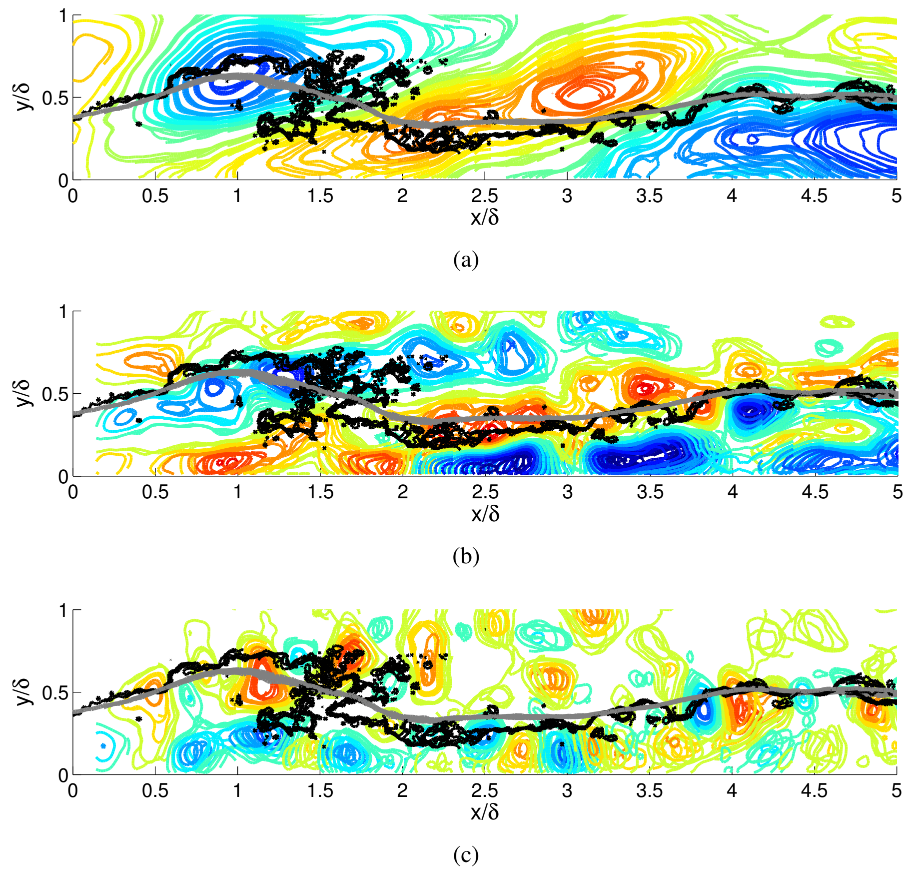

Figure 1: A visualization of a 3D critical layer is shown using PIV observations of a turbulent boundary layer. The streamwise large-scale (a), streamwise small-scale (b), and wall-normal small-scale (c) fluctuating velocity structures are identified from PIV velocity data using 2D Gaussian filters. The black contour line in each figure is an instantaneous contour of $u = 0.83U_\infty$ in the full, unfiltered flow field. The grey contour line is the same velocity isocontour identified from the velocity field of the superposition of only the mean and the large scales, and represents a 2D cut through the 3D critical layer corresponding to the large scale structure. The similarity of the black and grey contour lines suggests that the large-scale streamwise velocity structure identified in (a) is largely responsible for the shape of the full velocity isocontour. The small scales in (b) and (c) are seen to follow the black and grey contour lines closely, potentially identifying the source of the well-characterized amplitude modulation effect. Note that Taylor's hypothesis has been applied to all velocity contours using a convection velocity of $0.83U_\infty$ to show a larger field of view than is available in the data. Adjacent images are overlapped to visualize the accuracy of Taylor's hypothesis.