THE SIGNIFICANCE OF HAIRPIN VORTICES IN TURBULENT BOUNDARY LAYERS

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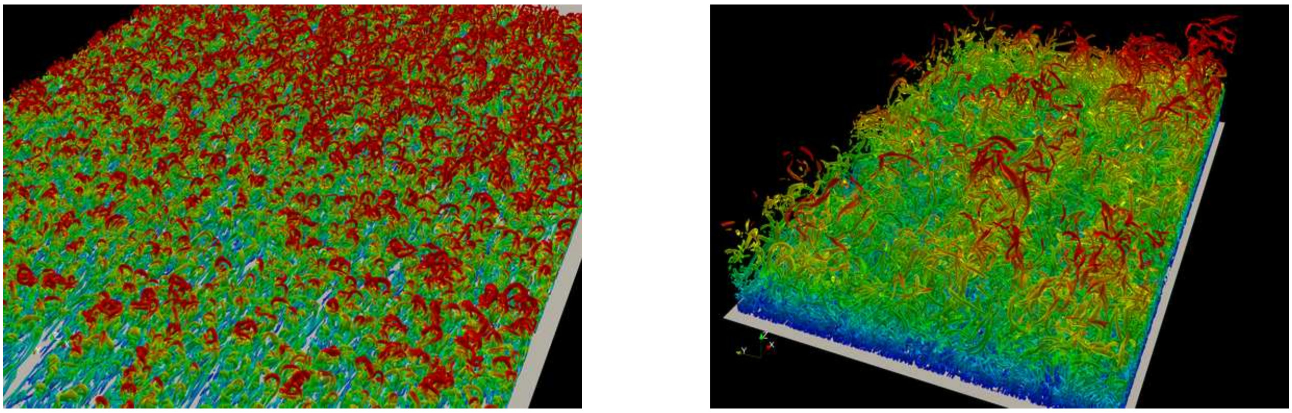
Abstract The elementary question whether hairpin vortices constitute an inherent, universal structure of wall turbulence at moderate and high Reynolds numbers (Re) is addressed in this study. The downstream evolution of a single, artificial hairpin vortex is first studied in a mean shear flow to investigate possible decay and package-creation processes under high Re conditions. In a second step, hairpin-dominated flow in a transitional turbulent boundary layer is considered, whereas the lifetime of individual vortices and possible connection mechanisms are evaluated. The statistics obtained from this flow regime will be compared with reference data from turbulent-boundary-layer studies employing different transition mechanisms. Vortex eduction will be applied to comprehend the evolution from a well organized to a more chaotic state. The results could explain discrepancies in boundary-layer data close to transition and will contribute to the discussion about the relevance of hairpin-like structures in fully developed wall turbulence.

Besides the statistical description of turbulent shear flows, models for inherent vortical motions and coherent structures have become very important. In this context, wall-attached, hairpin-shaped vortices have been suggested to be the main sustaining flow pattern in turbulent boundary layers (TBL) [7, 10]. Models using superpositions of attached eddies succeed in explaining several features of wall turbulence like mean velocity profile, distribution of Reynolds stresses, and energy spectra. The existence of large-scale coherent structures is comprised by considering packets of hairpin vortices aligned in streamwise direction, whereas every hairpin above a certain size generates new loop-shaped vortices upstream and downstream of its own position [6, 13]. These formations have been observed in experiments and numerical simulations of a single hairpin in laminar shear flow and in low Reynolds number (Re) turbulent channel flow [1, 13] being consistent with some forms of experimental data from channel and flat-plate boundary layer flows [2, 3, 4].

However, actual evidence for such universal structures "in the wild" is still limited – especially at moderate to high Re – and spatial and evolutionary details as well as statistical relevance remain controversial. Definitely, hairpin structures are evident in turbulent flow close to transition, as shown by the early visualizations by Head and Bandyopadhya [4], and the simulations by Wu and Moin who even report a "forest of hairpins" in their TBL direct numerical simulations (DNS) [11, 12]. On the other hand, DNS data at higher Re indicate that hairpins are not a clear feature of fully developed near wall-turbulence [8] (cf. Figs. 1a and 1b). Three-dimensional visualizations like in Fig. 2 indicate that two-dimensional experimental data might be misinterpreted regarding the occurrence of hairpin packages.

To help answering the question whether hairpin-like structures represent a universal flow structure in TBL, and if they could consequently be used as a valid low-order model for boundary-layer turbulence, two approaches are pursued in the present study. Initially, a single, artificial hairpin vortex (generated in the spirit of Acarlar and Smith [1]) is induced in a mean shear flow corresponding to a high-Re TBL, and the vortex is tracked while extending downstream. This can be viewed as an extension of the work by Zhou et al. [13], but in a boundary layer with fixed turbulent profile. The observed dynamics will provide new details about the life-time of the streamwise and spanwise vortex constituents in a realistic environment. Furthermore, possible regeneration and package-creation processes are investigated in the context of TBL.

In a second step, the statistics of hairpin dominated flow is evaluated using TBL simulation data featuring a regular version of the "forest of hairpins" regime. We are re-simulating the transitional region of a boundary layer using an adapted trip forcing with low-amplitude random modulations which generates a regular pattern of hairpins [9]. This data is analyzed to answer a number of questions, e.g. how long individual hairpin vortices exist, whether span/streamwise connection mechanisms can be observed (see Adrian [2]), and how well the obtained turbulent statistics in this regular array of hairpins coincide with either canonical TBL [5, 8] or the bypass-transition flow by Wu and Moin [11]. Furthermore, the Reynolds number at the position of the tripping can be varied to understand Re-dependence. Vortex eduction is used to characterize the evolution of the boundary layer from the regular state to a more chaotic state further downstream. In particular the later steps, i.e. those related to feature extraction and interpretation of results, will be helpful to resolve one of the recent, important questions in the community, namely the relevance of hairpin vortices both at lower and higher Reynolds numbers.



(a) (b)

Figure 1. Three-dimensional visualization of vortical structures in a DNS of a turbulent boundary layer at (a) $Re_\theta \approx 600$ and (b) $Re_\theta \approx 4300$ [8]. The transitional region is characterized by individual hairpin vortices while no such regularity is evident at higher Re.

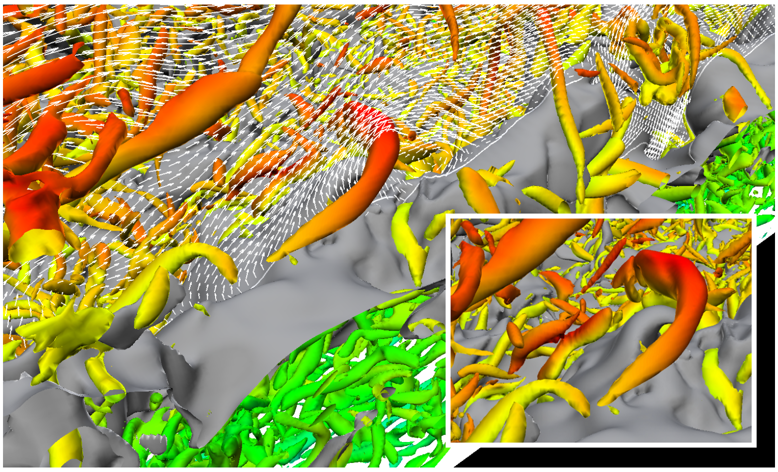


Figure 2. Snapshot of an ejection event in a DNS of a turbulent boundary layer at $Re_\theta \approx 4000$ [8]. Instantaneous vortical structures are visualized by λ_2 contours colored by streamwise velocity u. Vectors describe the velocity in a vertical plane ($0.75U_\infty$ subtracted) and the gray surface denotes $u = 0.7U_\infty$. The close-up shows a zoomed view of the most probable hairpin-vortex candidate.

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