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Lagrangian Identification of Coherent Structures in Wall-Bounded Flows

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Abstract. In this paper, Lagrangian tracking of a specific material surface and Lagrangian-averaged vorticity deviation (LAVD) are applied to experimental data sets of two kinds of wall-bounded flows to detect coherent structures. One for laminar boundary layer with wall-mounted hemisphere, the other for turbulent boundary layer. Lagrangian coherent structures detected in a hemisphere protruded laminar boundary layer show some similarity with Eulerian-detected hairpin vortices. However, the LAVD-based vortices and the evolution of material surface demonstrated in turbulent boundary layer are different from the patterns in the wake of the hairpin shedding hemisphere. The wavelike deformed material surfaces appear to support the importance of three-dimensional wave structures in the near-wall turbulence production process. The Lagrangian methods provide another perspective in understanding coherent structures in wall-bounded flows.

AMS subject classifications: 76F40, 76D17, 76M23

Key words: Lagrangian coherent structure, tomographic PIV, turbulent boundary layer, hairpin vortices.

1 Introduction

Over the past half century, joint numerical and experimental efforts have been devoted to identifying the coherent structures in turbulent flow. Up to now, a large number of flow structures have been observed by various identification techniques [1–20]. The pioneering finding of low-speed streaks by Kline [3] advanced the investigations of structures in turbulent boundary layer. Since then, most of the early works were based on the flow visualizations. Hama and Nutant used the hydrogen bubble lines parallel and normal to the flat plate to study the structures in shear flow [2], and they found the kink structures in near-wall region. Similar techniques were applied by Standford group [21, 22], they

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found that bursting cycle with ejection-sweep events are closely related to the behaviour of flow structures. Smith and his colleagues improved the visualization technique and implemented a series of "kernel" studies, which characterized the dynamic of low-speed streak and hairpin vortex in detail [5,7,23,24]. It worth noting that Acarlar and Smith [23] conducted experiments to measure the wake of a wall-mounted hemisphere in a laminar boundary layer, the visual hairpin like patterns they observed were very similar to those found in near-wall region of turbulent boundary layer, which supported the importance of hairpin vortices in the turbulence production. The hairpin vortex was also identified by laser illuminated smoke visualization in the air [25] at a wide range of Reynolds numbers. Flow structures at transitional boundary layer were obtained by smoke visualization by Saric [26]. Then later, Lee and his colleagues applied the hydrogen bubble visualization to systematically investigate the flow structures in transitional boundary layer, and a three dimensional wave structure was observed at the low-speed region, which was called solitonlike coherent structure (SCS) [9, 11, 27–33].

The above visualized structures were also verified by quantitative methods. The early methods were based on techniques of mutual or automated image processing on pictures taken from single view or dual-view visualization system [21, 23, 34]. Hot-wire (film) anemometry was also used to characterize the flow behaviour [6, 9, 23], thus the conditional sampled techniques were developed [34, 35]. With the advancement of laser technology and computer performance, particle image velocimetry (PIV) and direct numerical simulation (DNS) became the main tool to extract flow structures. Adrian et al. used the planar PIV to investigate the structures in outer region of turbulent boundary layer, and they identified uniform-momentum zones and hairpin packets based on instantaneous velocity vector map [10]. In the last decade, tomographic PIV (Tomo-PIV) was also applied to verify turbulent structures at different Reynolds numbers [36–38]. Most of these works mainly reconstructed structures based on Eulerian view, which considered only localized and instantaneous velocity field. However, Lagrangian detecting techniques that are based on the velocity fields with a finite-time interval also show their superiority [39–41]. Recently, evolution of material surface was extracted from DNS data of channel flow by using Lagrangian approach [42, 43], and the evolution from triangular bulge to hairpin-like structures was reported. Also a method named Lagrangian-averaged vorticity deviation (LAVD) was developed by [44], the vortices detected by which are objective, i.e., remain unchanged under time-dependent rotations and translations of the coordinated frame. However, this method was mainly used in geostrophic flows, where rotationally coherent vortices is apparent. Since the LAVD method is able to trace the persistent structures and to identify the interaction between vortices in complex flows, which appears be a good tool in detecting structures in wall-bounded shear layers. This motivates us to apply the LAVD method in the current investigation.

This paper firstly describes the methods of Lagrangian identification in Section 2, and then introduces the experimental set-up in Section 3. Next, Lagrangian tracing of material surface and LAVD-based vortices are reconstructed from Tomo-PIV data sets of hemisphere wake and turbulent boundary layer in Sections 4 and 5. Finally, results are