INVESTIGATION OF LAGRANGIAN COHERENT STRUCTURES IN A WAKE-INDUCED BOUNDARY LAYER TRANSITION

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Abstract The evolution of coherent structures in a flat plate boundary layer transition induced by the cylinder wake is investigated using the particle image velocimetry (PIV) technique. The finite-time Lyapunov exponent (FTLE), which characterizes the amount of stretching about the flow trajectory, is used to extract the Lagrangian coherent structures. It is revealed that secondary vortex is induced by the cylinder wake vortices in the near wall region, which would evolve into hairpin vortex as it convects downstream. The subsequent evolvement of the hairpin vortex, characterized by the regeneration of offspring hairpin vortex upstream of it, leads to the appearance of the hairpin packet and the boundary layer finally reaches a turbulent state.

INTRODUCTION AND EXPERIMENTAL METHODOLOGY

The effects of blunt body wake on a wall-bounded shear layer are often encountered in engineering applications, such as multi-airfoil configuration in high-lift system and compressor blade interaction in turbo-machinery. A better understanding of this process is important in the design of these machines in terms of high aerodynamic performance or heat transferring characteristics.

The present experimental investigation was conducted in a low-speed water tunnel with free-stream velocity U_∞=67mm/s and turbulence intensity *Tu* less than 0.8%. Figure 1 illustrates a sketch of the experimental model and the coordinates definition. A flat plate with a 8:1 elliptical leading edge and a size of 10mm × 500mm × 2500mm (thickness × width × length) was horizontally positioned in the middle of the water tunnel. A circular cylinder with diameter D=20mm was horizontally placed over the whole span of a flat plate. Two-dimensional time-resolved digital particle image velocimetry (PIV) was used to provide quantitative information of the flow. The attention of the present paper was focused on the Lagrangian coherent structures in the flow, which was identified with the finite-time Lyapunov exponents (FTLE) method. FTLE can be used to find separatrices in time-dependent systems, which are often analogous to stable and unstable manifolds of time-independent systems [1]. These separatrices are called Lagrangian Coherent Structures (LCS).

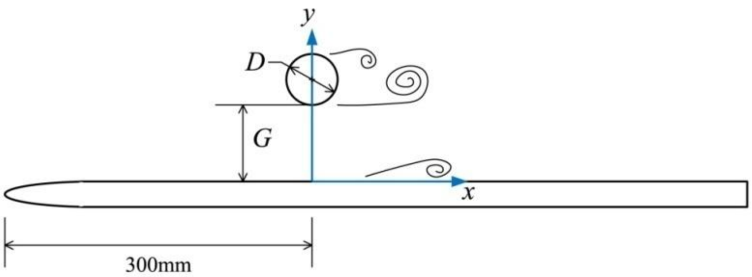

Figure 1. Sketch of the experimental model and the coordinates definition.

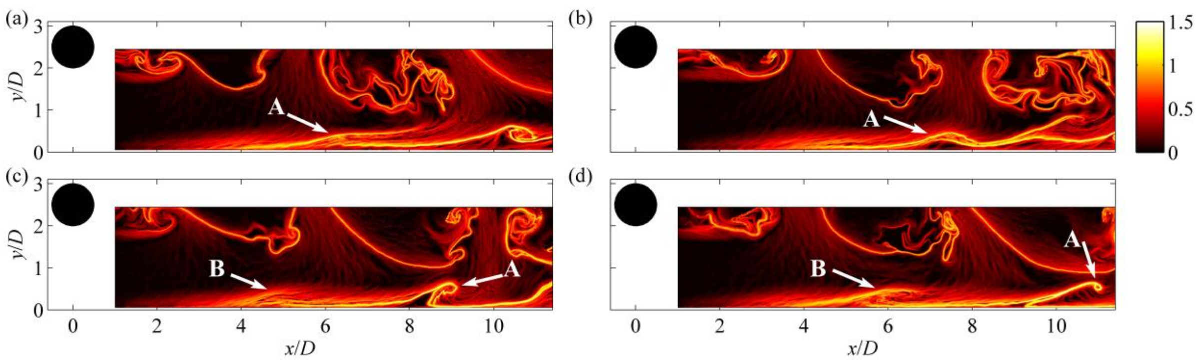

Figure 2. Lagrangian coherent structures revealed by FTLE in the boundary layer downstream of the cylinder. Arrows A and B indicate the secondary vortices induced by the wake vortices. The integration time length is T= -4.0s (backward integration).

RESULTS AND CONCLUSIONS

Figure 2 shows the FTLE field downstream of the cylinder. The FTLE is computed from the PIV data with integration time length of 4s. Backward integration is applied, so the attracting Lagrangian coherent structures have been extracted. The dominant structures in the wake region are the lower shear layer (*x/D*<4) and the shed lower wake vortices. In the near wall region, secondary vortices are induced by the wake vortices (see arrows A and B in Figure 2). Previous studies[2, 3, 4] have already shown that these secondary vortices would evolve into three dimensional structures as they convect downstream and become Λ vortices under the perturbation of wake vortices. Afterwards, the Λ vortex would evolve into a hairpin vortex downstream (see Figure 3), and hairpin packets are found further downstream as shown in Figure 4. In Figure 4, the head of a primary hairpin vortex is indicated by arrow A. It is followed by a lifted shear layer, which is the result of upward induction of the streamwise-stretched counter-rotating hairpin vortex legs. This lifted-up shear layer is unstable and leads to the formation of an offspring hairpin vortex (vortex B in Figure 4). The mean velocity profiles are also analyzed in this investigation (not shown here), and it is indicated that the boundary layer has already become turbulent downstream of *x/D*=48. This auto-regeneration process of the hairpin structure presented here is very similar to the description given by Zhou et al. [5] in their direct numerical simulation of hairpin vortex evolvement in channel flow.

Although Λ/hairpin vortices have been reported in previous studies [2, 3, 4] on wake induced bypass transition, they were revealed by qualitative hydrogen bubble visualizations or the quantitative Eulerian vector field. The Lagrangian coherent structures in the present study, which are derived from the quantitative measurement data, are presented as direct embodiment of the flow structures. This allows us to investigate the dynamics of the Lagrangian coherent structures, and to promote the understanding of their roles in the wake-induced boundary layer transition.

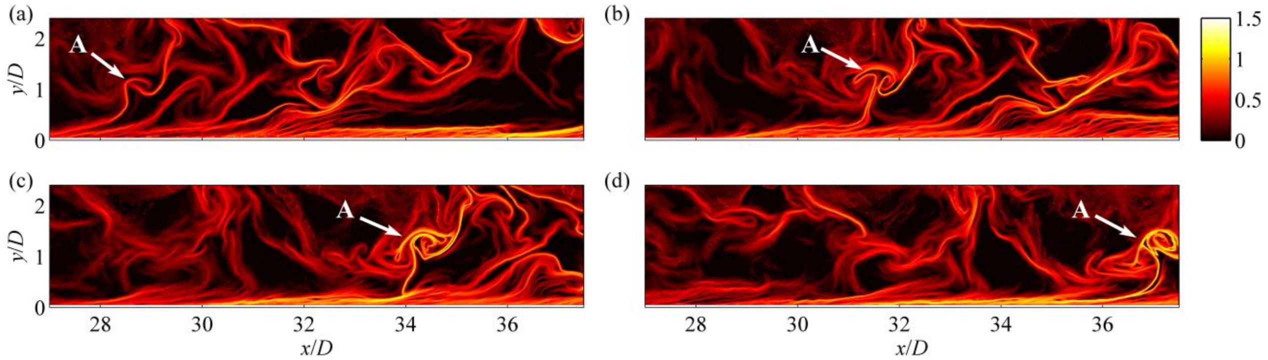

Figure 3. A single hairpin vortex in the transitional boundary layer. Arrow A indicates the head of the hairpin vortex. The integration time length is *T*= -4.0s (backward integration).

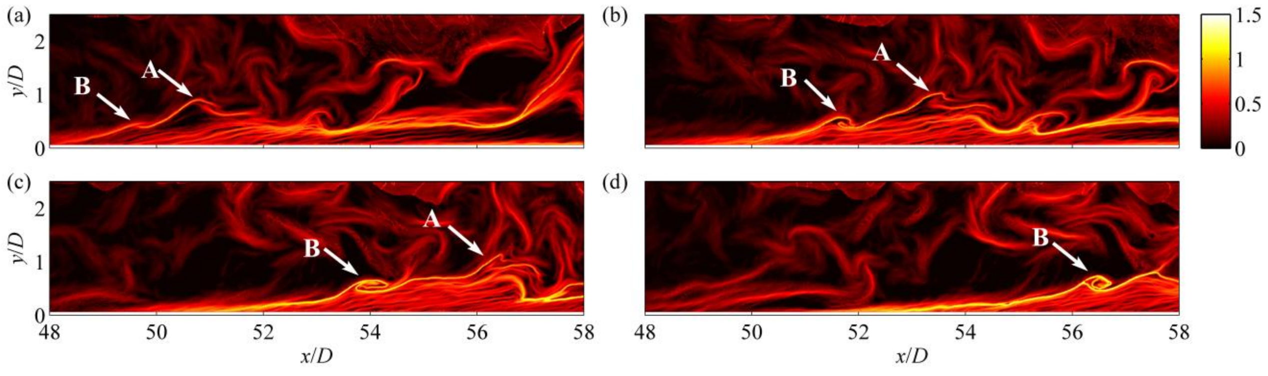

Figure 4. Hairpin vortex packet in the turbulent boundary layer. Arrows A and B indicate two successive hairpin heads in the packet. The integration time length is *T*= -4.0s (backward integration).

References

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