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Unsteady Flow Separation and High Performance of Airfoil with Local Flexible Structure at Low Reynolds Number

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Abstract. The unsteady flow separation of airfoil with a local flexible structure (LFS) is studied numerically in Lagrangian frames in detail, in order to investigate the nature of its high aerodynamic performance. For such aeroelastic system, the characteristic-based split (CBS) scheme combined with arbitrary Lagrangian-Eulerian (ALE) framework is developed firstly for the numerical analysis of unsteady flow, and Galerkin method is used to approach the flexible structure. The local flexible skin of airfoil, which can lead to self-induced oscillations, is considered as unsteady perturbation to the flow. Then, the ensuing high aerodynamic performances and complex unsteady flow separation at low Reynolds number are studied by Lagrangian coherent structures (LCSs). The results show that the LFS has a significant influence on the unsteady flow separation, which is the key point for the lift enhancement. Specifically, the oscillations of the LFS can induce the generations of moving separation and vortex, which can enhance the kinetic energy transport from main flow to the boundary layer. The results could give a deep understand of the dynamics in unsteady flow separation and flow control for the flow over airfoil.

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Key words: Unsteady flow, moving separation, aeroelastic structure, lift enhancement, Lagrangian coherent structures.

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1 Introduction

Flexible structures, such as shell, plate, shallow arch and membrane etc., have been used widely in the high-performance aircraft, especially in micro air vehicles [1–3]. Many experiments and numerical researches have shown that the flexible airfoil, compared with the rigid one, can delay flow separation, enhance lift and reduce drag efficiently [2,4–8]. At low Reynolds number, flow separation can easily occur for laminar flow, and result in complex unsteady separated flow, even the transition to turbulence. In such flow, small perturbation, such as the oscillation of flexible structure, can change the flow structure and airfoil performance dramatically. Chimakurthi et al. [6] presented a computational aeroelasticity framework for the flapping wing micro air vehicles, and investigated both rigid and flexible wing. Lee et al. [7] studied the two-dimension insect flapping wing, and found that structural flexibility has a significant impact on aerodynamic performance. Also, some key physical phenomena, such as vortex pairing and vortex staying, were observed. Kang et al. [8] introduced the local flexible structure to control the flow, and improved the aerodynamical performance significantly. Compared with the fully flexible wing, local flexible structure is easier to implement active control, and can be used in normal or large size airfoil. However, airfoil with flexible structure usually involves strong and complicated fluid-structure interaction, giving rise to a variety of phenomena relevant to the high aerodynamic performance. The unsteady flow separation, however, is generally the original source of many complex flow structures, such as vortex formation, wake flow etc. Therefore, a deep understanding of the unsteady flow separation and related flow structure can lead to a way to explain many complicated phenomena in unsteady flow.

Usually, the Eulerian descriptions of the flow are used to study the flow separation and flow structure, such as the streamline pattern, pressure and vorticity fields. However, there are many Lagrangian phenomena in the unsteady flow, such as flow separation, transient flow processes. These unsteady flow phenomena can be well described by the Eulerian description, yet their dynamic properties (e.g. fluid transport and mixing) are still hidden under Eulerian description. The Prandtl's criteria for flow separation, which are Eulerian description, indicate that the separation point is the point of vanishing wall-shear. However, in unsteady flow, vanishing wall shear does not denote separation in any meaningful sense [9]. As the development of nonlinear dynamics, Lagrangian description for flow has been increasingly appreciated by many researchers. Van Dammelen [10] first studied boundary layer separation in Lagrangian frame, and gave the flow separation criteria from Lagrangian viewpoint. Duan and Wiggins [11] applied the lobe dynamics into the flow over circular cylinder to study the transport and mixing of vortex shedding in the near wake of circular cylinder in the point of dynamic view, and some new results have been found. Recently, it is shown that Lagrangian Coherent Structures (LCSs) proposed by Haller [12] become a useful tool to study flow structures in general unsteady flow from Lagrangian viewpoint. The LCSs are the transport barriers in unsteady flow, and hence it is convenient in the studies of transport in general unsteady