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Study on Mass Transports in Evolution of Separation Bubbles Using LCSs and Lobe Dynamics

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Abstract. The lobe dynamics and mass transport between separation bubble and main flow in flow over airfoil are studied in detail, using Lagrangian coherent structures (LCSs), in order to understand the nature of evolution of the separation bubble. For this problem, the transient flow over NACA0012 airfoil with low Reynolds number is simulated numerically by characteristic based split (CBS) scheme, in combination with dual time stepping. Then, LCSs and lobe dynamics are introduced and developed to investigate the mass transport between separation bubble and main flow, from viewpoint of nonlinear dynamics. The results show that stable manifolds and unstable manifolds could be tangled with each other as time evolution, and the lobes are formed periodically to induce mass transport between main flow and separation bubble, with dynamic behaviors. Moreover, the evolution of the separation bubble depends essentially on the mass transport which is induced by lobes, ensuing energy and momentum transfers. As the results, it can be drawn that the dynamics of flow separation could be studied using LCSs and lobe dynamics, and could be controlled feasibly if an appropriate control is applied to the upstream boundary layer with high momentum.

AMS subject classifications: 35Q35, 35Q30, 76G25, 93D05, 86-08

Key words: Mass transport, separation bubble, Lagrangian coherent structures, lobe dynamics.

1 Introduction

Flow separation is a kind of common phenomenon in flow over airfoil, building or blade etc., and it usually leads the airfoil or blade to stall, resulting in negative effects on the aerodynamic performance of airfoil or blade. However, flow separation is still one of the

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main problems in aerodynamics, and there is a rich variety of nonlinear phenomena in flow separation, such as the evolution of separation bubble.

Some studies have been carried out on the separation of laminar flow since Horton [1] described initially the structure of classical two-dimensional laminar separation bubble. These studies are mainly focused on the formation of separation bubble and the change of lift with angles of attack [2], the structures and behaviors of laminar separation bubbles [3, 4], the vortex shedding phenomena in the flow over airfoil [5,6], the stability of laminar separation bubbles in the flow over airfoil [7-9] and other properties or phenomena in separation bubbles [10-12].

Indeed, for the flow around a body in turbo-machinery and aerospace engineering, the mass transport between separation bubble and main flow has an important influence on the aerodynamic performance of blade and airfoil near stall, and such kind of transport is a dynamic behavior. The nature for such phenomenon is still open, and hence it is necessary to study the evolution of the mass transport between separation bubble and main flow in depth, from viewpoint of dynamics. However, none of the above studies analyzed the separation bubble from the viewpoint of mass transport and energy exchange in the generation, evolution and breaking of the separation bubble. Most of traditional flow field numerical methods are based on Eulerian perspective. However, for the unsteady flow, Eulerian description can only describe the instantaneous state of flow but couldn't reveal the dynamic properties. In fact, flow over a body is a kind of nonlinear dynamic system. Flow separation, which is a kind of Lagrangian behavior, means that the fluid particles are separated from the boundary wall. Conventional Eulerian description is not sufficient to describe and analyze the unsteady flow anymore. Nevertheless, the transport process between the separation bubbles and the free stream can be captured from viewpoint of Lagrangian dynamics.

Recently, using Lagrangian description of the fluid and nonlinear dynamics to study the dynamic behaviors is indeed becoming more and more popular. Van Dommelen [13] studied the boundary layer equation in Lagrangian frame, and he also put forward the flow separation criterion on the basis of Lagrangian dynamics. From the point of view of dynamics, the phenomenon of periodic vortex shedding from the wake of flow over cylinder is numerically analyzed by Shariff et al. [14]. Duan and Wiggins [15] quantitatively described the mass transport between the separation zone and the free stream around circle cylinder by lobe dynamics. However, traditional manifolds in nonlinear dynamics can only be available in infinite-time flow. For the finite-time flow, the concepts of finite-time manifolds and Lagrangian Coherent Structures (LCSs) are proposed by Haller [16] to define the separatrix of different basins in finite-time flow. Haller [17] and Shadden [18] proposed using LCS as the transport boundary. Following that, Lei [19] numerically simulated the mass transport in transient flow over impulsively started circular cylinder by LCS. Currently, the LCS has been widely used to study the various flow phenomena, such as separation [20, 21] oceanic flow [22], turbulence [23] and atmospheric flow [24], etc.

In this paper, the flows over NACA0012 airfoil are studied numerically, and La-