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Using Lagrangian coherent structure to understand vortex dynamics in flow around plunging airfoil

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ABSTRACT

In this study, the Lagrangian coherent structures (LCSs) of the flow around two-dimensional airfoil with a plunging motion are numerically investigated, in order to reveal the physics of the unsteady aerodynamics in the flapping wings. The present study, in which only low Reynolds (*Re*) flows are considered, focuses on two typical unsteady flows at zero angle of attack, respectively induced by slow and fast plunging motions. To simulate such unsteady flows, the Characteristic Based Split (CBS) scheme combined with Arbitrary Lagrangian–Eulerian (ALE) framework are applied. After that, the LCSs are introduced to study the dynamic properties in the unsteady flow and by using the finite-time Lyapunov exponent (FTLE), the evolution of the vortex structures in the two distinct flow patterns are determined. By presenting the dynamic evolution of the Lagrangian behaviors, such as the formation and transport of the flow patterns, as well as the flow separation, it proves that LCSs can describe the Lagrangian dynamics properly. Moreover, during investigating the formation of leading-edge vortex (LEV), the time-dependent separation profile is found to play a major role. To be specific, within the slow plunging motion, the flow is rolled up to form a LEV downstream the separation point where the unstable manifold attaches. In contrast, within the fast plunging motion, a transfer barrier is generated upstream the leading edge, causing the LEV to form upstream the separation point. It is also found that by studying the dynamic behavior of the intersection between the unstable manifold and the stable manifold, the evolvement of the vortex structures, including the formation and the shedding of them, is more clear. Compared to the traditional visualization techniques, the Lagrangian analysis based on LCSs can provide a deeper insight into the dynamics of the vortex, which plays an important role in understanding the high performance of the unsteady flow induced by flapping wings.

1. Introduction

Micro Aerial Vehicles (MAVs) have received a lot of attention because of their wide variety of applications for civilian and military purposes. However, the flow characteristics are quite different from those at high Reynolds number, since the length scale and flight speed of MAVs are much smaller than convectional aircrafts. Specifically, with low Reynolds numbers, the separated and vortical flows due to the viscous effects may lead to sudden increase of drag and drop of lift and thrust for MAVs (Shyy et al., 1999). Inspired by biological flight, flapping wings provide an idea to improve the aerodynamics performance of MAVs, and hence the flapping wings are investigated systematically in recent decades, as stated in review articles (Shyy et al., 1999; Platzer et al., 2008; Shyy et al., 2010). On the other hand, there still exist some challenges in the full understanding of complex phenomena in unsteady flapping

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aerodynamics, such as the generation of unsteady force, the formation of the flow pattern and the relationship between them, etc.

The researches on flapping airfoils are concentrated on pure plunging motion, pure pitching motion or combined pitching–plunging motion. As one of simplified models of flapping wings, the studies of pure plunging airfoil have a long history. In the 1910s, the sinusoidally heaving airfoils were analyzed to explain the generation of unsteady force by Knoller and Verein (1909) and Betz (1912) independently. In the past few decades, there is renewed interest in heaving airfoil after the water-tunnel experiments and numerical simulations by Jones et al. (1998). Their studies show that the topologies of wake structures and velocity profiles are changed with varying parameters. In particular, an interesting phenomenon, which is nonsymmetric, deflected wake pattern induced by the symmetric heaving motion, has been found at high Strouhal number. Since then, Lai and Platzer (1999), Lewin and Haj-Hariri (2003) and Lua et al. (2007) study the flow patterns of heaving airfoil over a broad range of reduced frequencies and dimensionless heave amplitudes. Their results show that the symmetric and periodic flow pattern can be found at low Strouhal numbers. Further, the asymmetric pattern appears with an increasing Strouhal numbers. As a result, they conclude that the aperiodic, quasi-periodic and asymmetric patterns are common phenomenon in the flow with high Strouhal numbers.

From above, it is clear that the flow patterns have significant impact on the generation of unsteady aerodynamic force. As one example, the formation of wakes attract much attention because it is believed that the qualitative structure of the wake is the principal factor on thrust generation. An experiment by von Ellenrieder and Pothos (2008) is carried out to study the asymmetric wake and they measure the deflected angle. Further Godoy-Diana et al. (2009) find that the symmetry breaking is related to the two counter-rotating vortices in a dipolar structure in theoretical works. Based on it, a criterion of symmetry breaking is proposed. Later, Zheng and Wei (2012) and Wei and Zheng (2014) develop the model of dipolar, showing that the deflection is determined by the competitions between the symmetry-breaking and symmetry-holding effective phase velocities.

Although the deflection of the wake patterns have been extensively investigated, there is little work on the dynamic behaviors of flow around the airfoil. These questions, such as how flow separates from the airfoil and how fluid particles move in flow around a plunging airfoil, are fascinating and need to be answered. Furthermore, it still needs to improve the understanding of the formation, shedding or breaking of the vortex based on the flow separation and transport. In fact, the study on them will play a crucial role in understanding the high aerodynamic performance of flapping wings. In the present study, the discussion is focused on the flow separation, fluid transport and the dynamics of the vortex in flow around plunging airfoil. It is convenient to apply the Lagragian method in studying the unsteady separation and fluid transport. In the recent years, the Lagrangian Coherent Structures (LCSs) are developed to study the intrinsic structures or properties within fluid flows that govern flow transport or mass transport (Haller and Yuan, 2000). Shadden et al. (2005) show that LCSs, which are one kind of invariant manifolds, can be defined by the ridge of finite-time Lyapunov exponent (FTLE) field. The results show that these manifolds, which represent dynamic transport barriers in the flow, reveal exact vortex boundaries, as well as the time-dependent separation and reattachment profiles. At present, the LCSs are widely used in studying the vortex shedding of airfoil (Lipinski et al., 2008; Cardwell and Mohseni, 2008), the onset and development of dynamic stall (Mulleners and Raffel, 2012, 2013), the flow separation of airfoil with local flexible structure (Lei et al., 2014), flapping motion with a large-amplitude low-frequency (Eldredge and Chong, 2010) and unsteady biological propulsion at intermediate Reynolds numbers (Pekarek et al., 2007; Gazzola et al., 2012; van Rees et al., 2013; Huhn et al., 2015). In other words, the LCSs are available and powerful in the Lagrangian analysis of unsteady flow.

In the present study, a numerical analysis of the unsteady flow induced by a plunging airfoil is carried out in order to gain a deep understanding of evolution of flow structure. In Section 2, a finite element algorithm is presented for simulating the unsteady aerodynamics of plunging airfoil. Furthermore, the theory and computational method of LCSs are introduced in Section 3 to analyze the Lagrangian dynamics. Subsequently, the LCSs in the flows induced by the two typical modes of plunging airfoil are discussed in Section 4. Finally, some conclusions are drawn in Section 5.

2. Numerical methods

2.1. Governing equations

Considering the low *Re* flows investigated in the present study, the laminar and incompressible flow is governed by the Navier–Stokes equations

$$\begin{cases} \dfrac{\partial u_i}{\partial x_i} = 0, \\ \dfrac{\partial u_i}{\partial t} + u_j \dfrac{\partial u_i}{\partial x_j} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x_i} + \dfrac{\mu}{\rho}\dfrac{\partial^2 u_i}{\partial x_j \partial x_j} \end{cases} \tag{1}$$

where ρ and μ are the density and dynamic viscosity of the air, respectively. Moreover, by defining the chord of the airfoil c to be the characteristic scale, and the freestream velocity u_∞ to be the characteristic velocity, a list of dimensionless parameters is used to re-scale the equations, given as

$$x_i^* = \frac{x_i}{c}, \quad t_i^* = \frac{u_\infty t}{c}, \quad p^* = \frac{c}{\rho_\infty u_\infty^2}, \quad u_i^* = \frac{u_i}{u_\infty} \tag{2}$$

In the following study, the * is dropped for the sake of simplicity. Furthermore, in consideration of the plunging airfoil, the boundary is considered to be a moving wall. To this end, by introducing the arbitrary Lagrangian–Eulerian (ALE) framework into