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Effects of local oscillation of airfoil surface on lift enhancement at low Reynolds number

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ABSTRACT

A numerical computation for flow around an airfoil with local oscillation is presented at low Reynolds number to study the effect of the local oscillation on aerodynamic performance of the airfoil. Coupling with unsteady low Reynolds number flow, the local oscillation is considered as a harmonic function varying both in temporal and spatial domains. The effects of the oscillation on lift enhancement and flow patterns are studied parametrically. In particular, three essentials for the oscillation, i.e., frequency, amplitude and equilibrium, are discussed in order to provide a deep understanding for effective active flow control strategy. The results show that the frequency and amplitude of the oscillation are the two key factors for lift enhancement. As the primary frequency of flow equals to the oscillating frequency, and the secondary frequency of the flow is twice than the first one, i.e., frequency lock-in occurs, a series of separation bubbles and vortices are evolved close to the leading edge and moving downstream. These vortices enhance the vorticity around the airfoil and maintain a low pressure distribution on the upper surface, which improve the lift remarkably. The amplitude is related to the input energy transferring from the oscillation into the fluid near the leading edge, which induces a perturbation propagating downstream and enhances the influence on the vortex formation. Moreover, there exists an optimal amplitude range for the oscillation to achieve better controllability with less energy input. The pre-deformed equilibrium of the oscillation is not a necessary factor for the lift enhancement, but it improves the effect of the oscillation on lift enhancement significantly by reducing negative pressure near the leading edge on the upper surface.

1. Introduction

Micro-air vehicles (MAVs) have drawn much attentions due to its great potential for a wide range of applications for civilian and military purposes (Pines and Bohorquez, 2006; Shyy, 2008; Shyy et al., 2010). Since its characteristic size and velocity are much smaller than convectional aircrafts, the flow characteristics are quite different from those at high-Reynolds number. In low-Reynolds number flow regime, unsteady flow separation the wing surface caused by the viscous effect may lead to sudden increase of drag and loss of lift and thrust for MAVs (Shyy, 2008). What is worse, because of very low flight speeds, the aerodynamic conditions of MAV may dramatically be altered by any disturbance from the flight

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environment like gusts. These unique aerodynamic challenges have severely stunted the practicability of MAVs. In order to achieve better aerodynamic efficiency and high maneuverability, suitable flow control techniques are required for the design of MAV.

Inspired by bio-flight, flexible wings provide a novel idea for flow control of MAVs. The flexible wing is made of thin walled structure with large deflection. It is coupling with unsteady flow during the flight and can adaptively change the aerodynamic shape by the aeroelastic coupling to gain the improvement of aerodynamic performance. Smith and Shyy (1995) established a model of membrane airfoil coupling with unsteady flow at Reynolds number 4000. Since then, Shyy's group focused on the aerodynamics and aeroelasticity of MAVs. Excellent reviews on flexible and flapping wings of MAVs can be referred to as Shyy et al. (1999, 2010). The results from numerical simulations and experiments (Lian et al., 2003; Mueller and DeLaurier, 2003; Song and Breuer, 2007; Rojratsirikul et al., 2009; Gordnier et al., 2013) have shown that flexibility of structure gains the potential of shape adaptation for severe flow condition and improves aerodynamic performance. In these works, the whole lift surface of wings was modelled as flexible structure. Such design demands high quality of structure materials, and may result in irreversible damage during strongly fluid–structure coupling.

In order to deal with such issue, a flow control method that utilizes aeroelastic effects of locally flexible wing surface (LFWS) is proposed for adaptive control of unsteady flow separation at low Reynolds number (Kang et al., 2012). The flexible structure is located at the leading edge of the airfoil, and the perturbation raised by the aeroelastic coupling of LFWS can propagate downstream and change the flow pattern to improve aerodynamic performance of airfoil at low Reynolds number (Kang et al., 2014; Lei et al., 2014). The results in the works have highlighted the positive impact of LFWS on aerodynamic performance of the airfoil. However, the previous work focused on the modelling of the aeroelastic system of LFWS and its possibility for flow control. Detailed analysis for the underlying aeroelastic coupling needs yet to be done to obtain an optimization of oscillating parameters. Moreover, the control strategies like flexible wing and LFWS are passive control methods due to the absence of extra energy input. In the real environment, the flexibility of the wing may not reach a designated control state for aerodynamic performance improvement, in light of the dramatic change of flight condition such as a gust or wind, or mechanical flaw of the flexible structure. Therefore, active flow control is preferable for the compensation of the designated control state in a wider range of operating conditions.

Effective active flow control system needs to handle the complexity of the MAV system. An active flexible wing will involve a number of variable parameters, e.g., camber, stiffness distribution, location of actuator, actuating frequency and amplitude, flight conditions, which result in a large state space for optimization. A comprehensive review on this topic can be found in Ho et al. (2003) and Greenblatt and Wygnanski (2000). Whitehead and Gursul (2006) studied the synthetic jet for propulsion of MAVs. They found out that the separated shear layer reattached on the airfoil by the jet with optimum excitation frequency, which produces positive thrust. However, synthetic jet method requires more space for the generation of jet, which will be a limitation of the further miniature of MAV system. As a better choice of active flow control technique for MAVs, surface-integrated flow control methods such as microelectromechnical systems (MEMS), piezoelectric and plasma actuators are mostly considered due to less limitations of the weight and space for MAVs. Hak (2001) discussed the role of MEMS system as a flow control technique in lifting and control surfaces of fixed wing MAV. Göksel and Rechenberg (2006) proposed an active flow control method by surface smooth plasma actuator for Eppler E338 airfoil at low Reynolds number. Recently, Maqsood and Go (2010) developed a piezoelectric wing-driven flap actuation mechanism to generate the kinematic motion required for aerodynamic performance improvement. From viewpoint of dynamics, these flow control techniques essentially utilize the vibration of structure acting on the fluid to achieve better performance of MAVs. The vibration of the actuator consists of three essentials, the pre-deformed equilibrium, frequency and amplitude, which play an important effect on the improvement of aerodynamic performance of MAVs. In this study, a general model for local oscillation of the structure is presented including three essentials of the vibration for active flow control. The effects of these three factors on the flow patterns are clarified to provide a physical understanding for effective flow control strategy.

The paper is organized as follows. In Section 2, a model of the local oscillation is established, coupling with unsteady low Reynolds number flow. The model of local oscillation is simplified as a periodic motion with prescribed equilibrium. In Section 3, numerical method and its validation is presented for unsteady viscous flow. Subsequently, a parametric study is carried out to study the effects of the oscillation on flow evolution and aerodynamic performance in Section 4. The effects of frequency, equilibrium and amplitude of the oscillation on lift enhancement are highlighted. Finally, some conclusions are drawn in Section 5.

2. Model of local oscillation of airfoil surface

Fig. 1 shows the model of local oscillation of airfoil surface. The oscillation part is located at the leading edge of the upper surface, $x \in [0, 0.1]$, in light of the study of an airfoil with a dynamically deformed leading-edge (DDLE) shape (Sahin et al., 2003) and comments of Greenblatt's review on periodic excitation's location (Greenblatt and Wygnanski, 2000). According to the previous work (Kang et al., 2014; Lei et al., 2014), the vibration of the structure with simply supported boundary conditions can be expanded as the sum of mean deflection and a set of Fourier functions. During the coupling, the amplitude of the first mode is much larger than the other ones shown in Fig. 2 (Lei et al., 2014). Therefore, only one mode is chosen for the oscillation in this study. Accordingly, the motion of the actuation is considered as a harmonic motion of single mode varying both in temporal and spatial domains. If the pre-deformation is considered, the motion of the structure is expressed