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# Effects of a dynamic trailing-edge flap on the aerodynamic performance and flow structures in hovering flight

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ABSTRACT

To examine the effects of wing morphing on unsteady aerodynamics, deformable flapping plates are numerically studied in a low-Reynolds-number flow. Simulations are carried out using an in-house immersed-boundary-method-based direct numerical simulation (DNS) solver. In current work, chord-wise camber is modeled by a hinge connecting two rigid components. The leading portion is driven by a biological hovering motion along a horizontal stroke plane. The hinged trailing-edge flap (TEF) is controlled by a prescribed harmonic deflection motion. The effects of TEF deflection amplitude, deflection phase difference, hinge location, and Reynolds number on the aerodynamic performance and flow structures are investigated. The results show that the unsteady aerodynamic performance of deformable flapping plates is dominated by the TEF deflection phase difference, which directly affects the strength of the leading-edge vortex (LEV) and thus influences the entire vortex shedding process. The overall lift enhancement can reach up to 26% by tailoring the deflection amplitude and deflection phase difference. It is also found that the role of the dynamic TEF played in the flapping flight is consistent over a range of hinge locations and Reynolds numbers. Results from a low aspect-ratio ($AR=2$) deformable plate show the same trend as those of 2-D cases despite the effect of the three-dimensionality.



## 1. Introduction

Flapping-wing offers unique force-producing mechanisms over conventional flight methods for designing micro air vehicles (MAVs), especially in the low Reynolds number (Re) regime. The inherently unsteady nature of flapping kinematics is responsible for the primary force production (Dickinson et al., 1999), and also differentiates flapping-wing motion from conventional fixed- and rotary-wing configurations. In recent years, increasing attention has been paid to the aerodynamics of deformable wings. Several studies have shown that the unsteady aerodynamic phenomena of the flapping mechanism are not only sensitive to variations in the wing kinematics but also to the wing morphing (Valasek, 2012; Wang et al., 2003). The results also reveal that a dynamically adjustable wing surface may potentially provide new aerodynamic mechanisms (Shyy et al., 2011; Zhao et al., 2011) of force production over fully rigid wings (Dickinson et al., 1999; Sun and Tang, 2002) in flapping flight. Further research (Dai et al., 2012; Shoele and Zhu, 2013) has illustrated that the performance of a rigid flapping wing can be significantly improved by adding some level of flexibility to the wing surface. For achieving the

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performance enhancement, both passive and active flow control mechanisms have been studied, and some examples are reviewed here.

In order to understand the effects of chord-wise flexibility on aerodynamics of flapping motion, a hinge connected two rigid components model is commonly used because of its simplicity and well preservation of the flexibility characteristics in chord-wise (Toomey and Eldredge, 2008). Through this passive deformable model, Eldredge et al. revealed that wings with moderate flexibility have better power efficiency compared to the rigid wing in hovering flight, nevertheless very flexible wings will degrade its aerodynamic performance (Eldredge et al., 2010). Using a similar model, Vanella et al. showed that if parameters are chosen appropriately, the chord-wise flexibility can result in an enhancement of up to 28% in the lift-to-drag ratio and a 39% increase in the lift-to-power ratio over a rigid plate (Vanella et al., 2009). Wan et al. studied the effect of chord-wise flexibility over a range of hovering kinematic parameters using a hinged-plate model (Wan et al., 2012). Their results indicate that the maximum lift-to-drag ratio can be achieved by placing the hinge at the three-quarter chord position from the leading edge.

In addition to above passive mechanisms explorations, active flow control via wing surface morphing has been widely adopted in both fixed-wing and rotary-wing aircraft design. These include articulated flaps and/or slats (Lee and Su, 2011b), surface flow control devices (Ho and Tai, 1996) and continuously deforming surfaces (Brian et al., 2002). Among them, the flow control via trailing-edge flap (TEF) is presumed to be more applicable to novel flapping-wing micro air vehicles (MAVs) designs, in terms of simplicity of moving surface control, weight of MAVs and so on. Liu et al. experimentally studied the effect of actively controlled trailing-edge flaps on the flow control of translational plates (Liu et al., 2013). Their results have shown that force and flow characteristics strongly depend on the timing of trailing-edge flap deflection rather than translational speed. Li et al. (Li et al., 2014) and Xu et al. (Xu et al., 2015) further studied the effect of the trailing-edge flap on the aerodynamic performance of a 2-D flapping wing via a computational approach. It is found that the aerodynamic forces can be significantly affected by controlling the timing of the flap deflection in a flapping cycle. More extensive reviews of the studies on deformable wings can be found in (Kang et al., 2011; Shyy et al., 2010; 2008).

However, there is still a lack of effort on quantitative evaluating the possibility of active flow control in flapping-wing MAVs design. To this end, the aerodynamic performance of deformable flapping wings via dynamic trailing-edge flap is deserved to be investigated. In this paper, the unsteady aerodynamics of 2-D and 3-D flapping plates with a controllable trailing-edge flap are computationally studied. Through a systematic parametric study, the effects of TEF deflection amplitude, deflection phase difference, hinge location, and Reynolds number on the near field and far field flow structures and their associated aerodynamic performance are investigated. Both instantaneous and cycle-averaged forces productions are examined to provide quantitative descriptions of the TEF effects. The rest of the paper is organized as follows: Section 2 presents the problem formulation, numerical method, and code validation; Section 3 discusses the simulation results and analysis on aerodynamic performance and vortical structures; and finally, the conclusions of this work are given in Section 4.

## 2. Problem definition and numerical approach

### 2.1. Problem definition

In the present paper, a thin rigid plate attached with a TEF is considered as the model of deformable flapping wing, as shown in Fig. 1(a). The methodology of handling this thin (0.04 chord-length thickness) plate is demonstrated in (Mittal et al., 2008). As shown in Fig. 1(b), the harmonic kinematics is used to prescribe the flapping motion in a Cartesian coordinates system. Specifically, the main plate is constrained to move in a horizontal stroke plane according to the function defined by Eqs. (1) and (2)

$$x(t)=\frac{A_0}{2}\cos(2\pi ft),\quad y(t)=0, \tag{1}$$

$$\theta_L(t)=\beta_L sin(2\pi f t), \tag{2}$$

where, $x(t)$ and $y(t)$ denote the position of the leading edge of the chord, $\theta_L(t)$ is the orientation of the main plate relative to the vertical direction, $f$ is the flapping frequency, $A_0$ and $\beta_L$ are the amplitudes of translation and rotation, respectively.

The deflection angle ($\theta_T$) of TEF is defined by Eq. (3). In the current study, the deflection phase difference ($\varphi$) controls the TEF deflection timing, and thus forms a different camber patterns. The choices of these design parameters are in line with other TEF studies on fixed/rotary wing aerodynamics (Gerontakos and Lee, 2008; Lee and Gerontakos, 2006; Lee and Su, 2011a). By changing the deflection phase difference, the plate will either form a positive camber with $\varphi \in (-90^\circ, 90^\circ)$, or form a negative camber with $\varphi \in (90^\circ, 270^\circ)$ which is presented as the sum of $(90^\circ, 180^\circ)$ and $(-180^\circ, -90^\circ)$ in the following discussions. Fig. 1(c and d) present the typical samples of a positive camber configuration at $\beta_T=60^\circ,\ \varphi=60^\circ$ and, a negative camber configuration at $\beta_T=60^\circ,\ \varphi=-120^\circ$, respectively.

$$\theta_T(t)=\beta_T sin(-2\pi f t+\varphi), \tag{3}$$

where, $\beta_T$ is the amplitude of deflection, and $\varphi$ is the phase difference between the main plate rotation and trailing-edge deflection.