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Influence of a flexible tail on the performance of a foil hovering near the ground: Numerical investigation

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ABSTRACT

The influence of a flexible tail on the performance of a foil hovering near the ground is numerically investigated in this study. A NACA0015 foil arranged in close proximity to the ground is imposed with a synchronous harmonic translation and rotation. A flat plate attached to the trailing edge of the foil is adapted to model a tail. The tail is either rigid or passively deformable. To conduct numerical simulations, a robust immersed boundary-lattice Boltzmann method is employed. At a Reynolds number of 100 and the position of the rotating axis at third chord, the influences of the mass and flexibility of the tail as well as the distance between the rotating axis and the ground on the aerodynamic performance are systematically examined. Based on the results established, it is found that for the case of a flexible tail both the drag reduction and lift enhancement are observed compared to the case of a rigid tail. In addition, high ratios between the lift and the drag as well as between the lift and the power input are found when the mass and flexibility of the tail are low.

1. Introduction

Biological flyers (generally refer to birds and insects) seen in nature possess marvelous flight characteristics, which are fascinating and of agelong human interest. From the physical point of view, they mainly utilize oscillatory motions with wings to perform flight [1,2]. Therefore, the studies on flapping foils have attracted increasing attention, and subsequently some important conclusions have been drawn. In particular, some of them are related to the hovering flight. Based on series of experimental visualizations, Ellington et al. [3] revealed that the high lift generation depends on the leading edge vortex (LEV) created by the translational mechanism that is termed the "delayed stall". Later on, Dickinson et al. [4] indicated that the extra lift can be produced during stroke reversals, which is found to be attributed to the rotational circulation and the wake capture. By conducting two-dimensional numerical simulations, Wang [5] found that the leading order mechanism of lift generation is the creation of a downward dipole jet of counter-rotating vortices.

Besides these findings, another important issue that has been frequently considered is the structural flexibility. To numerically take the flexibility of flapping foils into account, there are two categories, namely active control and passive deformation [6]. In the type of active control, the profile of a flexible foil is usually described by using a mathematical formulation [7,8]. In the type of passive deformation, a flexible foil is either simply modeled as a structure with different segments connected with a torsional spring [9–12] or assumed to be an isotropic plate-like structure that is elastic and nearly inextensible [13–16]. It is noted that the latter one can be viewed as a more realistic model to represent a flexible foil. Based on the numerical results obtained, it is found that the foil flexibility can significantly improve the aerodynamic performance. More recently, Dewey et al. [17] performed experiments on rigid and flexible panels flapping in a fast water flow, and used scaling laws to interpret their measurements. It is reported that flexible panels can give a clear amplification of thrust production and propulsive efficiency compared to rigid panels. In addition, through theoretical analysis, Moore [18] found exact solutions for the kinematics of a flexible wing flapping in an inviscid fluid, showing how flexibility can improve propulsion and under what circumstances. For a wing in nature, it is observed that most of the bending occurs near one end. Therefore, it is reasonable to represent such structure system as a rigid foil with a flexible tail, in which the tail is attached to the foil.

On the other hand, the ground effect has still been limitedly taken into account in the study of flapping foils. The underlying

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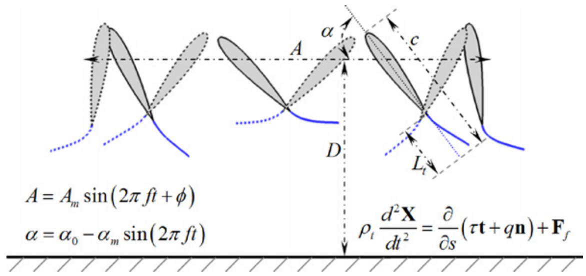

Fig. 1. A flapping foil with a flexible tail hovering near the ground.

mechanism of the ground effect is that the pressure on the lower surface of the foil is increased as the foil is placed in close proximity to the ground. The first work considering the ground effect on the flapping foil was implemented by Moryossef and levy [19] who numerically investigated the flow field about vertically oscillating airfoils near the ground. Gao and Lu [20] later examined the ground effect on the one-winged insect hovering flight at Reynolds number of 100, which was also extended to the two-winged situation by Liu et al. [21]. More recently, Truong et al. [22] measured the aerodynamic forces and flow structures of a single flapping wing. By utilizing the ground effect, it is noted that the aerodynamic forces of the flapping foil can be enhanced. However, the flexibility of the foil has not yet been considered in the ground effect study.

This paper numerically investigates the aerodynamic performance of a flapping foil with a flexible tail hovering near the ground. The simulations are conducted by using the recently developed immersed boundary-lattice Boltzmann method (IB-LBM) [23]. A NACA0015 airfoil is used in this work to represent the rigid foil. Its flapping motion is activated through synchronous harmonic translation and rotation. A flat plate that is attached to the trailing edge of the foil is employed to model a tail. Meanwhile, the tail either is rigid or can deform passively due to the exerted aerodynamic forces. After selecting the Reynolds number and location of rotating axis, the effects of the mass and flexibility of the tail as well as the distance between the rotating axis and the ground on the aerodynamic performance are systematically studied. Based on the numerical results obtained, the influences of the flexible tail on the force behaviors and flow patterns of the flapping foil and tail are demonstrated.

2. Problem description and methodology

2.1. Problem description

In this study, a NACA0015 airfoil together with a tail is considered, in which the tail is attached to the trailing edge of the foil. As shown in Fig. 1, the system hovering in close proximate to the ground experiences synchronous translating and rotating motions. Similar to the previous studies [20,21], the flapping motion of the system is imposed. A simple harmonic motion mode is employed in this study. Thus, the governing equations for the system motion can be expressed as

$$A(t) = A_m \sin(2\pi ft + \phi) \tag{1}$$

$$\alpha(t) = \alpha_0 - \alpha_m \sin(2\pi ft) \tag{2}$$

where $A(t)$ is the instantaneous displacement of the rotating axis at time t, A_m is the translation amplitude; $\alpha(t)$ is the instantaneous rotating angle at time t, α_0 and α_m are respectively the mean angle of attack and rotation amplitude; f is the frequency of oscillation, and ϕ is the phase difference between translation and rotation. In the current study, the rotating axis is located at the third chord, and α_0 is fixed at 90°. The translation amplitude is fixed at $A_m/c = 1.25$, where the parameter c is the chord length of the system containing the foil and tail. In addition, ϕ is chosen as 90°, which has been proven to produce the optimal thrust coefficient [18] or the maximum propulsive performance [24]. The Reynolds number based on the characteristic translational velocity and the chord is chosen as $Re = 100$, in which the characteristic translational velocity is defined as $U = 2\pi A_m f$. In addition, the distance between the rotating axis and the ground is denoted as D.

To model the tail, a flat plate with the length of L_t can be used, which is either rigid or passively deformable. Although the tail length may have impact on the aerodynamic performance, it will not be considered in this work. Therefore, the tail length is simply chosen as $L_t = c/3$. If the tail is flexible, it can be viewed as an elastic and nearly inextensible structure, which is the same as that in the previous studies [13,16]. Then, its motion equation in the Lagrangian form can be written as

$$\rho_t \frac{d^2\mathbf{X}}{dt^2} = \frac{\partial}{\partial s}(\tau\mathbf{t} + q\mathbf{n}) + \mathbf{F}_f \tag{3}$$

where $\mathbf{X}$ is the position vector of the tail, s is the Lagrangian coordinate along the tail length, ρ_t is the linear density of the tail, $\mathbf{t} = \partial\mathbf{X}/\partial s$ is the unit tangent vector along the tail length, $\mathbf{n}$ is the corresponding unit normal vector, τ is the tension, q is the transverse stress, and $\mathbf{F}_f$ is the aerodynamic force distributed along the tail. The tension and transverse stress are respectively given by

$$\tau = K_s\left(\left|\frac{\partial\mathbf{X}}{\partial s_0}\right| - 1\right), \qquad q = K_b\frac{\partial\kappa}{\partial s} \tag{4}$$

where K_s is the stretching coefficient of the tail, s_0 is the Lagrangian coordinate in the unstretched state, K_b is the bending coefficient

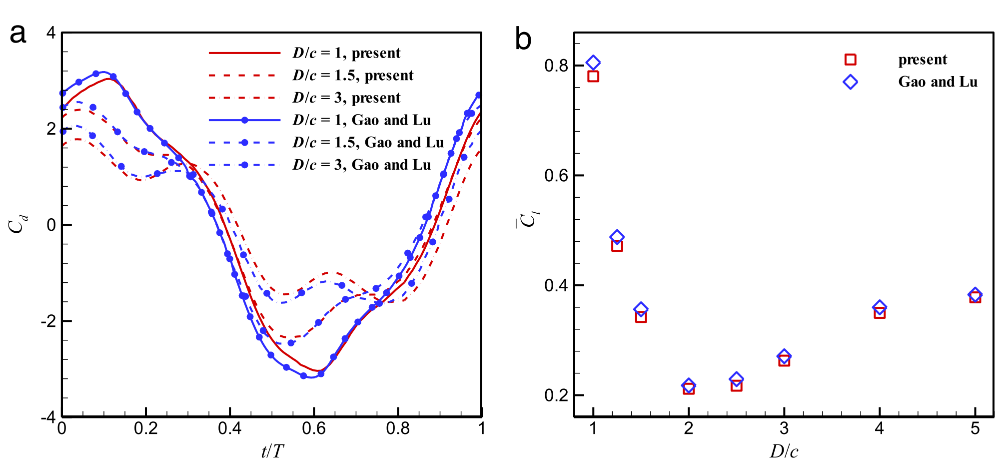

Fig. 2. (a) Time evolution of drag coefficient (C_d) over one stroke and (b) time-averaged lift coefficient ($\bar{C}_l$) with different ground clearances (comparison with Gao and Lu [20]).