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Fluid Dynamics of Flapping Insect Wing in Ground Effect

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Abstract

The fluid dynamics of flapping insect wing in ground effect is investigated numerically in this study. To model the insect wing cross-section in forward-flight mode, the laminar flow over a NACA0012 airfoil animated by a combination of harmonic plunge and pitch rotation is considered. To implement the simulation, the proposed immersed boundary-lattice Boltzmann method is employed. By fixing the Reynolds number and the amplitude of motion, we systematically examine the influences of the distance between the foil and the ground and the flapping frequency on the flow behaviors. As compared to the situation out of ground effect, the forces for foil placed in close proximity to the ground show some differences. The mean drag coefficient is increased at low frequency and decreased at high frequency. Meanwhile, the mean lift coefficient is increased at both low and high frequencies and decreased at middle frequency. Moreover, an interesting phenomenon with oblate vortices due to vortex interaction with the ground is observed.

Keywords: flapping insect wing, ground effect, drag reduction, lift enhancement

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1 Introduction

Since possessing the excellent manoeuvrability and the aerodynamic performance, the study about the insect flight can date back to 1500s and has attracted continuously increasing attention. Different from the terrestrial animals using the solid friction to walk on the land, the insects implement flight by flapping their wings to generate the thrust and lift from the surrounding fluids[1,2]. As compared to the man-made fixed-wing air vehicle, which is usually propelled by ejecting the high-speed air from propeller or jet engine, the locomotion of insects is mainly attributed to the reverse Karman vortex street generated by the flapping wing. Due to the highly unsteady features of the flow over a flapping wing, it was not until 1920s that the basic mechanism of thrust generation was demonstrated by Glauert[3] via a classical linear theory about a vertically oscillating wing in the inviscid flow. Recently, Ellington *et al.*[4] experimentally observed the intense leading-edge vortex in the axial flows around the insect wing, which explained the high lift generated by the insects. By solving the 3D incompressible laminar Navier- Stokes equations, Liu and Kawachi addressed the numerical modeling of insect flight[5]. So far, numerous studies have been made on the insect flight through the numerical simulations and the experimental measurements[6–9].

When a wing is placed in close proximity to the ground, higher lift and drop in induced drag would be produced as compared with the free stream case. This is known as the Wing In Ground (WIG) effect[10]. The underlying mechanism is that the pressure on the lower surface of wing is increased as the wing comes close to the ground. The WIG effect has been well applied to the ground effect craft and the racing car. However, the current study related to the ground effect mainly focuses on the fixed wing. The works about the ground effect on the flapping wing are very limited. The first attempt was conducted by Moryossef and Levy[11] who numerically investigated the flow field about the vertically oscillating airfoils near the ground. Both inviscid and viscous turbulent flow simulations were performed in their study. When the airfoil is in close proximity to the ground, the flows are dominated by the viscous effects at the low

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reduced frequencies, whereas the inviscid flow behaviors are acceptable at the high reduced frequencies. Later, Molina and Zhang[12] investigated the aerodynamics of an inverted airfoil in ground effect under the heaving motion. Three fundamental features, which were dependent on the frequency, were identified: ground effect, incidence effect and added mass effect. Nevertheless, it is noted that these works concern about the high Reynolds number flow associated with the turbulent effect. For the insect flight, the Reynolds number is relatively low. The most related work was done by Gao and Lu[13] who examined the ground effect on the insect normal hovering flight at Reynolds number of 100. They found that the force behavior could be divided into three typical regimes according to the ground clearance: force enhancement, force reduction and force recovery.

In this paper, the ground effect on the flapping insect wing in the forward-flight mode is investigated. To perform the numerical simulation, the recently developed Immersed Boundary-Lattice Boltzmann Method (IB-LBM)[14] is adopted, which has been successfully employed to simulate various moving boundary problems[15,16]. A NACA0012 airfoil, which models the insect wing cross-section, is considered in this work. It executes a combined motion of harmonic plunge and pitch rotation. After fixing the Reynolds number and the amplitude of motion, the influences of two parameters including the distance between the foil and the ground together with the frequency of oscillation are examined. Based on the numerical results, the ground effect of the flapping wing on the aerodynamic forces and vortex structures is analyzed. It is expected that the present study can dig into the mechanism of fluid dynamics for the flapping Micro Air Vehicles (MAVs) flying near the ground or the water surface.

2 Description of methodology

In this section, the adopted numerical method, *i.e.* the boundary condition-enforced IB-LBM[14–16], will be described simply. In the framework of IB-LBM, as shown in Fig. 1, the governing equations for the two-dimensional viscous and incompressible flow with the embedded body can be written as[14]

$$f_\alpha(\boldsymbol{x}+\boldsymbol{e}_\alpha\delta t,t+\delta t)-f_\alpha(\boldsymbol{x},t)=-\frac{1}{\tau}\left(f_\alpha(\boldsymbol{x},t)-f_\alpha^{\mathrm{eq}}(\boldsymbol{x},t)\right)+F_\alpha\delta t, \quad (1)$$

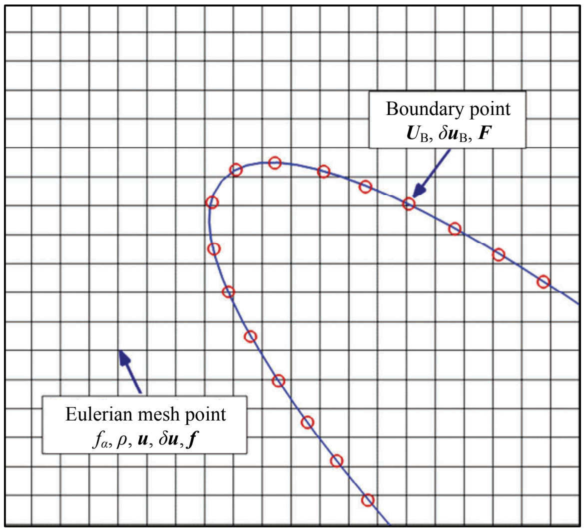

Fig. 1 Sketch of embedded body in flow field.

$$F_\alpha=\left(1-\frac{1}{2\tau}\right)w_\alpha\left(\frac{\boldsymbol{e}_\alpha-\boldsymbol{u}}{c_s^2}+\frac{\boldsymbol{e}_\alpha\cdot\boldsymbol{u}}{c_s^4}\boldsymbol{e}_\alpha\right)\cdot\boldsymbol{f}, \quad (2)$$

$$\rho\boldsymbol{u}=\sum_\alpha\boldsymbol{e}_\alpha f_\alpha+\frac{1}{2}\boldsymbol{f}\delta t, \quad (3)$$

where f_α is distribution function and f_α^{eq} is its corresponding equilibrium state, τ is single relaxation time, δt is time step, $\boldsymbol{e}_\alpha$ is lattice velocity, w_α are coefficients, c_s is sound speed, and $\boldsymbol{f}$ is force density which is determined by the boundary force density.

To satisfy the no-slip boundary condition, the force density $\boldsymbol{f}$ in Eqs. (2) and (3) is set as unknown and resolved via enforcing the boundary condition[14–16]. As a result, the force density $\boldsymbol{f}$ would be related to the fluid velocity correction $\delta\boldsymbol{u}$, which can be obtained from the boundary velocity correction $\delta\boldsymbol{u}_B$. The final equation system about $\delta\boldsymbol{u}_B$ is written as[14]

$$\boldsymbol{AX}=\boldsymbol{B}, \quad (4)$$

where $\boldsymbol{X}=\left\{\delta\boldsymbol{u}_B^1,\delta\boldsymbol{u}_B^2,\cdots,\delta\boldsymbol{u}_B^m\right\}^{\mathrm{T}}$,

$$\boldsymbol{A}=\begin{pmatrix}\delta_{11}&\delta_{12}&\cdots&\delta_{1n}\\\delta_{21}&\delta_{22}&\cdots&\delta_{2n}\\\vdots&\vdots&\ddots&\vdots\\\delta_{m1}&\delta_{m2}&\cdots&\delta_{mn}\end{pmatrix}\begin{pmatrix}\delta_{11}^B&\delta_{12}^B&\cdots&\delta_{1m}^B\\\delta_{21}^B&\delta_{22}^B&\cdots&\delta_{2m}^B\\\vdots&\vdots&\ddots&\vdots\\\delta_{n1}^B&\delta_{n2}^B&\cdots&\delta_{nm}^B\end{pmatrix},$$

$$\boldsymbol{B}=\begin{pmatrix}\boldsymbol{U}_B^1\\\boldsymbol{U}_B^2\\\vdots\\\boldsymbol{U}_B^m\end{pmatrix}-\begin{pmatrix}\delta_{11}&\delta_{12}&\cdots&\delta_{1n}\\\delta_{21}&\delta_{22}&\cdots&\delta_{2n}\\\vdots&\vdots&\ddots&\vdots\\\delta_{m1}&\delta_{m2}&\cdots&\delta_{mn}\end{pmatrix}\begin{pmatrix}\boldsymbol{u}_1^*\\\boldsymbol{u}_2^*\\\vdots\\\boldsymbol{u}_n^*\end{pmatrix},$$