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Procedia Engineering 67 (2013) 295 – 302

Procedia Engineering

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7th Asian-Pacific Conference on Aerospace Technology and Science, 7th APCATS 2013

Ground Effect on Flapping Wing

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Abstract

The ground effect on flapping wing is investigated numerically based on the immersed boundary-lattice Boltzmann method. A NACA0012 airfoil is considered in this work. The airfoil executes oscillation along vertical direction near ground. The simulations have been carried out for some parameters including the distance between the foil and the ground and frequency of oscillation as well. The ground effect on the force behaviors and vortex structures is analyzed. The results achieved in this work can shed physical insight into the understanding of aerodynamics and flow structures for air vehicle flying near the ground or water surface.

Selection and peer-review under responsibility of the National Chiao Tung University

Keywords: Ground effect, flapping wing, thrust force, lift force, vortex structure

Nomenclature

u_θ	velocity in the direction of (m/s)
A	radius of (m)
B	position of
C	further nomenclature continues down the page inside the text box
Greek symbols	
γ	stoichiometric coefficient
δ	boundary layer thicknesses(m)
Subscripts	
r	radial coordinate

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doi:10.1016/j.proeng.2013.12.029

1. Introduction

Due to high aerodynamic performance, the study about insect flight has drawn continuously increasing attention. Different from terrestrial animals which can walk or stand on the land by using solid friction and fixed support, the insects implement moving forwards or hovering by flapping their wings to produce the necessary thrust and lift forces [1, 2]. As compared to airplanes which are propelled by ejecting high-speed air from the propeller or the jet engine, the insects benefit from the reverse Karman vortex street generated from the flapping motion of wing. Up to now, numerous efforts have been devoted to studying insect flight via numerical simulation and experimental measurement [3-8].

It is known that a wing in ground effect can achieve a significant enhancement in lift and a drop in induced drag. The cause is that the pressure on the lower side of wing is increased as the wing comes close to the ground. However, the current study related to ground effect mainly focuses on the fixed wing. There are only limited works about the ground effect on flapping wing. The first attempt was conducted by Moryossef and levy [9] who numerically investigated the flow field about oscillating airfoil in close proximity to the ground. Thereafter, a few similar studies have been performed. Nevertheless, these works concern about the situation at high Reynolds number with turbulent flow.

In this paper, the ground effect on flapping wing at low Reynolds number, which corresponds to the flight condition of insect, is numerically studied. To perform the numerical simulation, the developed immersed boundary-lattice Boltzmann method [10] is adopted. A NACA0012 airfoil, which executes heaving motion, is considered in this work. 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 flapping wing on the aerodynamic forces and vortex structures is analyzed. It is expected that the present study can shed physical insight into the understanding of aerodynamics and flow structures for air vehicle flying near the ground or water surface.

2. Problem Definition and Numerical Methods

Figure 1 diagrams the sketch of two-dimensional viscous and incompressible flow over a NACA0012 airfoil. The airfoil carries out vertical oscillation near the ground. Consequently, its motion equation is

$$h(t) = h_0 + A_m \cos(2\pi f t) \tag{1}$$

where h is the distance between the center of airfoil and ground, h_0 is the mean position, A_m is the amplitude of oscillation and f is the oscillating frequency. Based on the free stream velocity u_∞ and double amplitude of motion $2A_m$, the Strouhal number of heaving motion is defined as

$$St_h = 2 f A_m / u_\infty \tag{2}$$

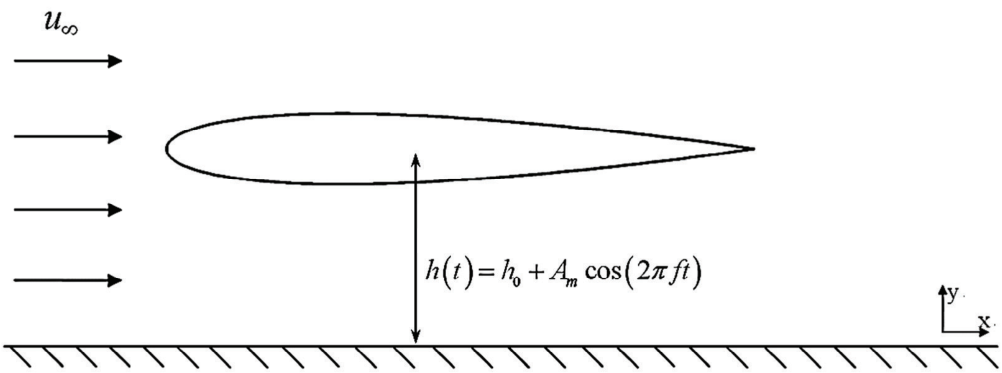

Fig.1 Flow over a NACA0012 airfoil with heaving motion near the ground

To solve such kind of moving boundary flow problems, the immersed boundary-lattice Boltzmann method (IB-LBM) [10] can be employed, which has the following governing equations

$$f_\alpha(\mathbf{x}+\mathbf{e}_\alpha\delta t, t+\delta t) - f_\alpha(\mathbf{x},t) = -\frac{1}{\tau}\left(f_\alpha(\mathbf{x},t) - f_\alpha^{eq}(\mathbf{x},t)\right) + F_\alpha \delta t \tag{3}$$

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

$$\rho\mathbf{u} = \sum_\alpha \mathbf{e}_\alpha f_\alpha + \frac{1}{2}\mathbf{f}\delta t \tag{5}$$

Here, f_α is the distribution function and f_α^{eq} is its corresponding equilibrium state; τ is the single relaxation time; δt is the time step; $\mathbf{e}_\alpha$ is the lattice velocity and w_α are coefficients. $\mathbf{f}$ is the force density which is determined from satisfaction of no-slip boundary condition. Besides the velocity, the other macroscopic variables are calculated by

$$\rho = \sum_\alpha f_\alpha, \quad P = \rho c_s^2 \tag{6}$$

where c_s is the speed of sound. More details and extensive validations of IB-LBM have been performed in [10-12].

3. Results and Discussions

In this section, we systematically investigate the ground effect on flapping wing. The effects of parameters including the mean distance between the center of airfoil and ground h_0 and the Strouhal number of heaving motion St_h are researched. In current study, the laminar flow is considered, and the Reynolds number based on the chord c of $Re = 150$ is chosen. At the same time, the amplitude of oscillation is selected as $A_m = 0.25c$. Firstly, we fix the mean distance at $h_0 = c$. Five different values of St_h ranging from 0.1 to 0.5 are considered. Thereafter, the influence of h_0 from 0.5c to 2c is checked.

3.1. Effect of Strouhal Number

By changing St_h, the forces on the airfoil as well as flow patterns could be significantly affected. Figure 2 plots the variation of mean drag coefficient $\overline{C}_d$ and mean lift coefficient $\overline{C}_l$ on the airfoil as the function of St_h. For the reference, the result of stationary airfoil ($\overline{C}_d$ = 0.3577, $\overline{C}_l$ = 0.094) is also presented in the figure shown by the dash line. From this figure, it is obvious that the heaving motion can significantly change the force behaviors. For mean drag coefficient, as shown in Fig. 2(a), it monotonously decreases as St_h increases. As compared with the stationary airfoil, the drag is always reduced for oscillating airfoil. Moreover, when St_h > 0.3, $\overline{C}_d$ becomes negative, which means that thrust force is produced. For mean lift coefficient, as shown in Fig. 2(b), it first decreases smoothly and reaches the minimum value ($\overline{C}_l$ = -0.334) at St_h = 0.3. As St_h further increases, $\overline{C}_l$ jumps to a large positive value and keeps increasing. Based on the obtained results, it is known that there is a critical frequency of oscillation, which determines whether thrust force and positive lift force can be generated or not.

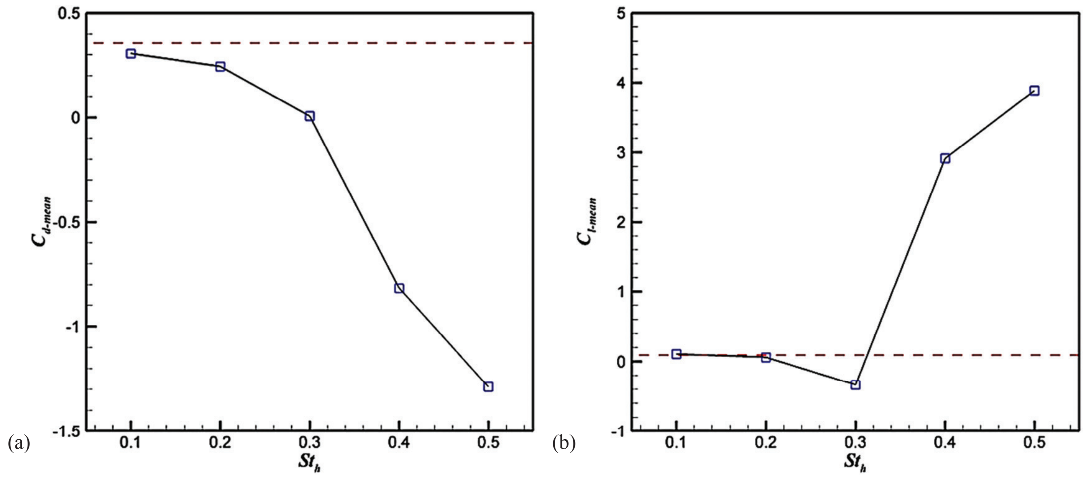

Fig.2 Variation of mean force coefficients with St_h at $h_0 = c$. (a) mean drag coefficient, (b) mean lift coefficient

Besides the variation of force behaviors, the flow patterns are also changed caused by oscillation of the airfoil. Figure 3 illustrates the instantaneous vorticity contours at different frequency. Due to heaving motion, the vortex shedding in the wake appears. At low frequency, as shown in Figs. 3(a) and 3(b), regular vortex street is formed behind the airfoil, which corresponds to the positive drag force in Fig. 2(a). As the frequency increases up to medium value (Fig. 3(c)), vortices are nearly compressed into a row. When the frequency continues to increase, as plotted in Figs. 3(e) and 3(f), the oscillating airfoil exchanges the positions of clockwise and counterclockwise vortices. As a result, a jet-like vorticity profile caused by the development of a reverse von Karman vortex street is observed. This clearly explains the appearance of thrust force in Fig. 2(a). Moreover, at high frequency, the strengthened leading-edge vortex (LEV) can be observed. It is known that LEV contributes to the generation of high lift according to the delayed stall mechanism [1, 13], which can be seen in Fig. 2(b). From the results in Fig. 3, it is shown that the structures of vortex also depend on the frequency of heaving motion.

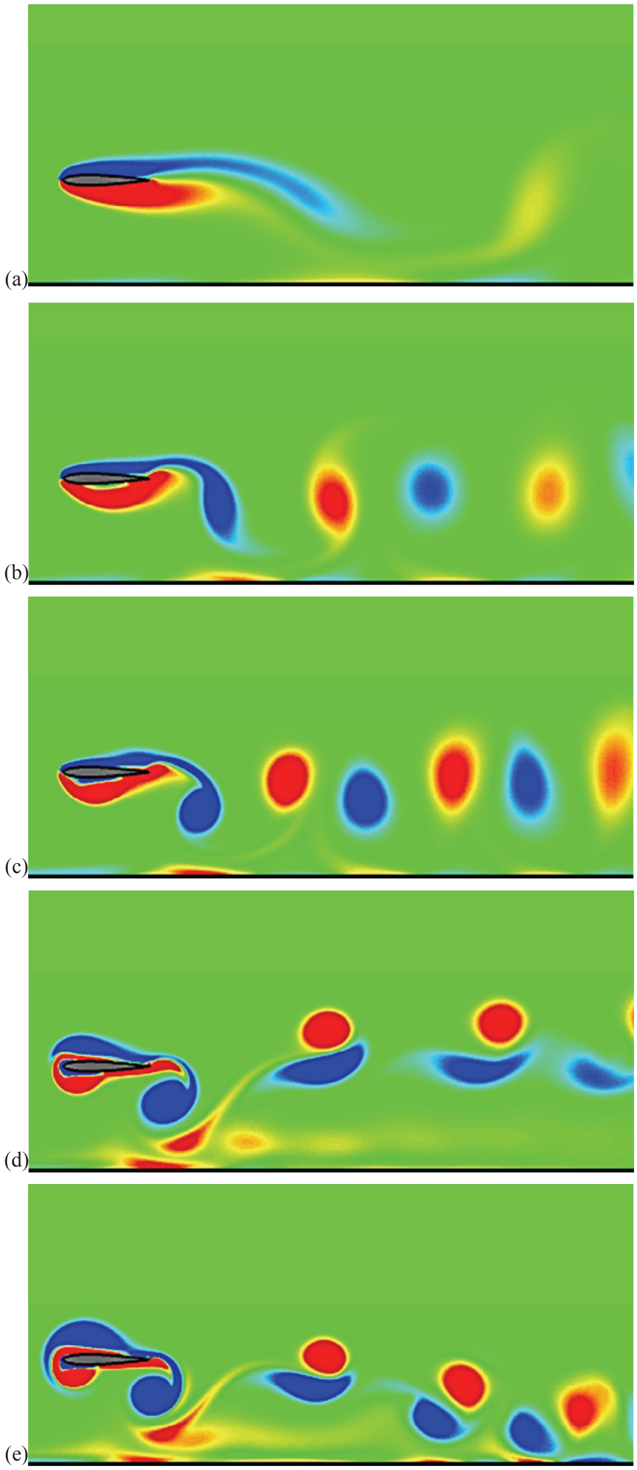

Fig.3 Flow patterns vary with St_h at $h_0 = c$. (a) $St_h = 0.1$, (b) $St_h = 0.2$, (c) $St_h = 0.3$, (d) $St_h = 0.4$, (e) $St_h = 0.5$

3.2. Effect of Mean Distance

After checking the influence of oscillating frequency, the examination of effect of mean distance is performed in this sub-section. Since the variation trend of force coefficients with respect to mean distance is similar at different frequency, the results only at St_h = 0.3 are presented. Figure 4 pictures the time histories of drag and lift coefficients for different h_0 in one cycle. To make comparison, the results out of ground effect are also included. For C_d as shown in Fig. 4(a), there are two peaks in one oscillating period. Particularly, when h_0 =0.5c, there is a perceptible difference between first peak value and second one, which is caused by the interaction between vortex and airfoil. Meanwhile, it can be seen that the mean thrust force is produced. As h_0 increases, the difference between two peaks becomes negligible and no mean thrust force is observed. On the other hand, for C_l (Fig. 4(b)), only one peak occurs. Its value gradually decreases with the increase of h_0.

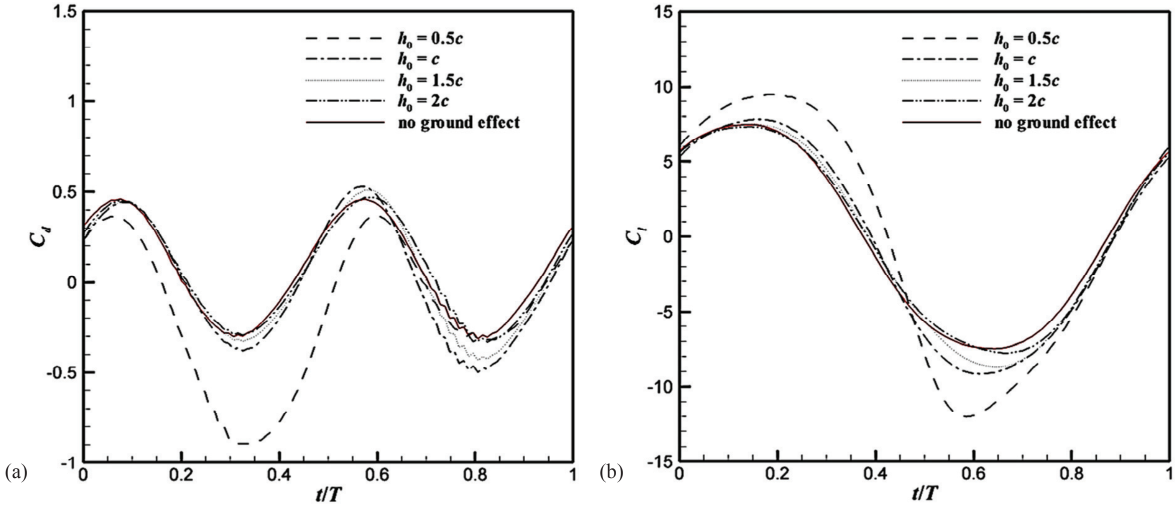

Fig.4 Time histories of drag and lift coefficient at St_h = 0.3 in one cycle. (a) drag coefficient, (b) lift coefficient

Similar to the frequency, the flow patterns can also be altered by mean distance. Figure 5 plot the instantaneous vorticity contours at h_0 = 0.5c and 2c in one cycle. It is shown from the figure that the flow patterns demonstrate great difference at difference h_0. Due to weak ground effect, regular vortex shedding happens at h_0 = 2c. When t = T/4, as plotted in Fig. 5(a), the trailing edge vortex is strengthened due to ground effect at h_0 = 0.5c. As a result, higher thrust force is generated as compared to the case of h_0 = 2c, which can be found in Fig. 4(a). After a T/4 interval (Fig. 5(b)), the distance h reaches the minimum. As pointed out by Molina and Zhang [14], there is a higher-velocity channel between airfoil and ground when h is small. Consequently, the pressure distribution on the lower surface of airfoil is lower at h_0 = 0.5c than that at h_0 = 2c, which corresponds to smaller C_l in Fig. 4(b). When the airfoils returns to the position of h = h_0 at t = 3T/4, the value of C_d is different from that at t = T/4 for h_0 = 0.5c, which is caused by the interaction between vortex and ground. When t = T, the distance h reaches the maximum, as shown in Fig. 5(d). Then, the ground effect on pressure distribution on the lower surface of airfoil becomes weak, which induces the nearly same C_l for different h_0.

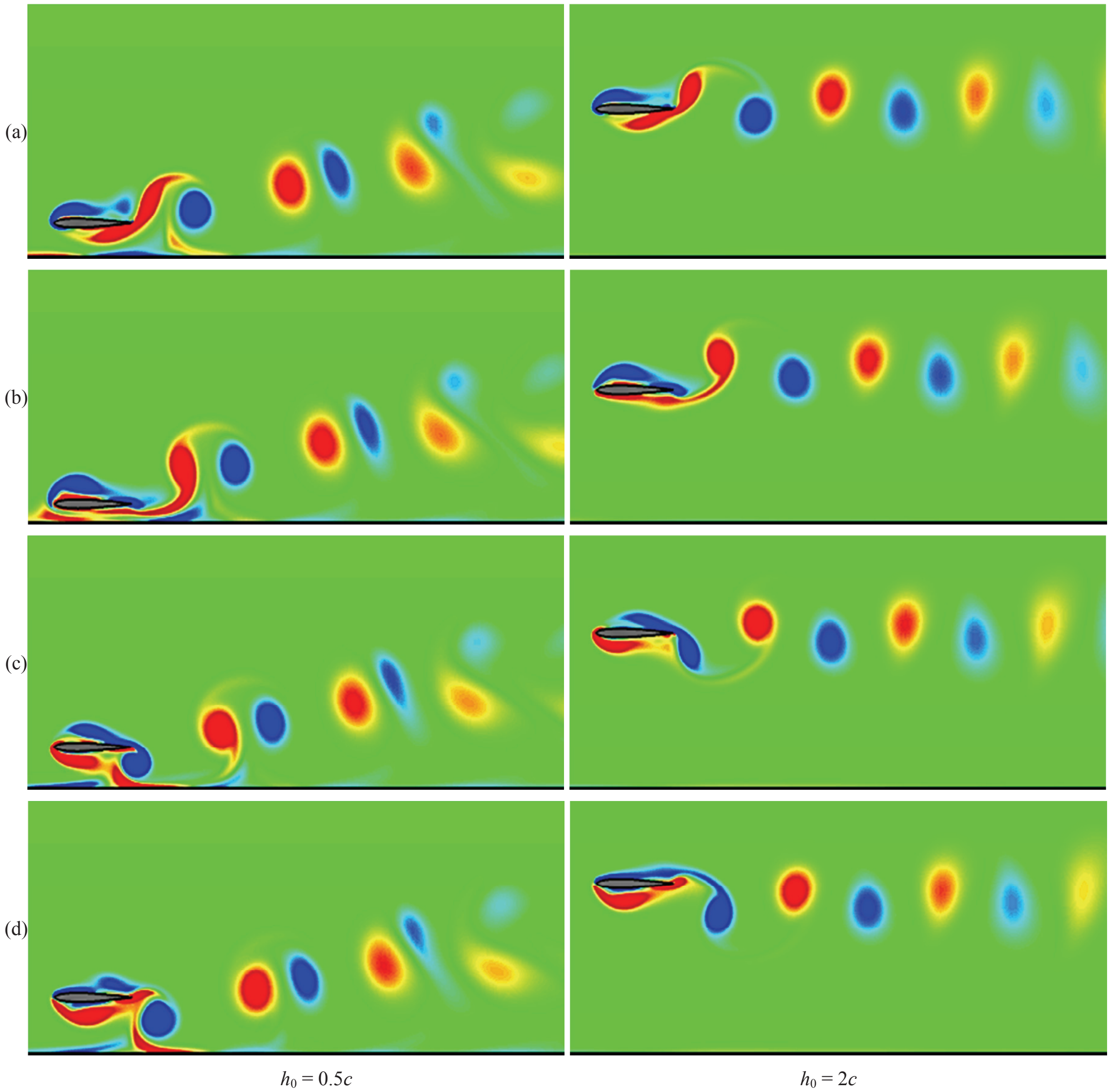

Fig.5 Instantaneous vorticity contours at $St_h = 0.3$ in one cycle. (a) $t = T/4$, (b) $t = T/2$, (c) $t = 3T/4$, (d) $t = T$

Based on the results above, it can be concluded that mean distance is of importance for ground effect on flapping wing. When h_0 is smaller than a critical value, the flow characteristics would be evidently changed due to the existence of ground. Meanwhile, larger instantaneous thrust and lift forces could be generated.

4. Conclusion

By using the immersed boundary-lattice Boltzmann method, the ground effect on flapping wing is studied in this work. To model the wing, a NACA0012 airfoil is employed, which can carry out heaving motion. To perform the numerical investigation, the parameters including the distance between the foil and the ground as well as oscillating frequency are considered. Based on the results established, it is indicated that high frequency and small distance are helpful for generation of thrust force and large lift force. It is expected that current study can shed physical insight into the understanding of aerodynamics and flow structures for air vehicle flying near the ground or water surface.

Acknowledgements

This research work was supported by “the Fundamental Research Funds for the Central Universities”, NO.100156XAA12113.

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