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Numerical Study of Two-Winged Insect Hovering Flight

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Abstract. The two-winged insect hovering flight is investigated numerically using the lattice Boltzmann method (LBM). A virtual model of two elliptic foils with flapping motion is used to study the aerodynamic performance of the insect hovering flight with and without the effect of ground surface. Systematic studies have been carried out by changing some parameters of the wing kinematics, including the stroke amplitude, attack angle, and the Reynolds number for the insect hovering flight without ground effect, as well as the distance between the flapping foils and the ground surface when the ground effect is considered. The influence of the wing kinematic parameters and the effect of the ground surface on the unsteady forces and vortical structures are analyzed. The unsteady forces acting on the flapping foils are verified to be closely associated with the time evolution of the vortex structures, foil translational and rotational accelerations, and interaction between the flapping foils and the existed vortical flow. Typical unsteady mechanisms of lift production are identified by examining the vortical structures around the flapping foils. The results obtained in this study provide some physical insight into the understanding of the aerodynamics and flow structures for the insect hovering flight.

AMS subject classifications: 74F10, 74L15, 92C10, 76P05, 76D0, 76D17

Key words: Insect hovering flight, lattice Boltzmann method, ground effect, unsteady force, vortical structure.

1 Introduction

Insects flying through the air display superior maneuverability in their active flight in the complex environments, such as taking off backwards, flying sideways, and landing upside down [1, 2]. Such complex aerial feats are benefited from the unsteady and vortical flow induced by the wing flapping motion [3–6], which gives rise to the

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high aerodynamic force needed for the insect flight. Typically, the wing stroke of an insect can be divided into four kinematic portions: two translational phases (upstroke and downstroke) when the wings sweep through the air with a high angle of attack, and two rotational phases (pronation and supination) when the wings rapidly rotate and reverse direction. How the flapping wings generate high aerodynamic lift for the insect hovering flight still is an important problem and is highly desired to be studied.

Several mechanisms about the enhanced production of the unsteady aerodynamic lift have been identified in the experimental studies, which are related to different stages of the wing flapping motion. A novel rotational mechanism, termed 'rotational lift', was found for the unsteady flow induced by the 'clap and fling' motion in the small insect flight [8–13]. During the fling phase of the 'clap and fling' motion, large attached leading edge vortices (LEVs) arise as the wings open up to form a V-shape by rotating around the trailing edges. The formation of LEVs is verified to result in a high lift production without the delay of Wagner effect [14, 15]. In the translational phases, LEVs are also found attached to the leading edges when the wings move apart or towards each other at high attack angles. The stabilized LEVs are responsible for the large circulatory forces generated transiently in the upstroke and downstroke phases. This translational mechanism for high lift generation is called 'delayed stall' (or dynamic stall) [4, 16]. Therefore, the existence of LEVs has been confirmed to be the most important aspect of the insect aerodynamics to generate significant lift on the flapping wings [17–22]. Another rotational mechanism is termed 'wake capture', which accounts for the large lift peak observed at the beginning of the stroke in case of advanced rotation, i.e., wing rotation preceding the stroke reversal [19]. It is suggested that the enhanced lift production in the insect hovering flight is due to the interaction of these three mechanisms occurring during the cyclic process of the two-winged flapping motion [16].

The unsteady mechanisms of the lift production in the insect hovering flight have also been investigated by numerical simulations [23–32]. Different wing kinematic modes have been employed to study the aerodynamic features in the insect hovering flight [25–37]. It is found that the wing kinematic parameters, such as the translational and rotational speeds, stroke amplitude, attack angle during the translational phases, are of appreciable effects on the lift production and the unsteady vortical flow [38–41]. Recently, Gao and Lu [42] first carried out the numerical simulations to study the ground effect on the unsteady forces and vortical structures around a flapping wing, and found that the ground effect plays an important role on the flight performance in the insect hovering flight. According to their study, three typical regimes of force behavior, i.e., force enhancement, force reduction, and force recovery regimes, are identified, depending on the distance between the flapping wing to the ground surface. To our knowledge, the aerodynamic forces and vortical flow evolution induced by the two-winged flapping motion are still not fully understood for the insect hovering flight, and the relevant studies are highly desired. We will thus investigate systematically the effects of the wing kinematic parameters and the ground effect on the unsteady aerodynamic mechanisms of the lift production in the two-winged insect