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Numerical Simulations for Aerodynamic Performance of a Butterfly-Like Flapping Wing-Body Model with Various Wing Planforms

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Abstract. Wing planform is one of important factors for lift and thrust generation and enhancement in flapping flight. In this study, we numerically investigate the effect of wing planform on aerodynamic performance of a butterfly-like flapping wing-body model by using the immersed boundary-lattice Boltzmann method. The model flaps downward for generating the lift force and backward for generating the thrust force like an actual butterfly. We calculate the aerodynamic performance such as the lift force, the thrust force, the power expenditure, and the power loading for (i) trapezoidal wing planforms with various taper ratios (ratio of the wing-tip length to the wing-root length), (ii) rectangular wing planforms with various aspect ratios (ratio of the square of the wing length to the wing area), and (iii) an actual butterfly's wing planform at the Reynolds number of 500. As a result for the trapezoidal and rectangular wing planforms, we find that the lift and thrust forces increase at the cost of the power expenditure as the taper ratio increases and as the aspect ratio increases. In addition, it is found that the actual butterfly's wing planform is more efficient than any of the trapezoidal and rectangular wing planforms.

AMS subject classifications: 76M28, 76Z10

Key words: Lattice Boltzmann method, immersed boundary method, flapping flight, aerodynamic performance, wing planform.

1 Introduction

Insects freely fly by flapping their wings in the air. The outstanding stability and maneuverability of the flapping flight by insects are so attractive that researchers have been trying to develop insect-inspired micro air vehicles. In order to incorporate the outstanding

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features of insects into artificial aircrafts, we have to know how insects obtain aerodynamic forces, save power expenditure, and control their attitude while flying.

From the viewpoint of fluid dynamics, the flapping flight by insects is a typical example of moving boundary flows, in which the movement of the wings and the body of an insect not only induces flows around it but also changes its motion due to the induced flows. Because of recent advances in computer performance and in computational fluid dynamics (CFD), the flapping flight by insects has been numerically modeled and investigated by many researchers. One of pioneering works of the numerical investigation on the flapping flight was conducted by Liu et al. [1, 2]. In their study, a three-dimensional wing model of an insect was constructed by mimicking the shape and movement of wings of a hovering hawkmoth, and unsteady viscous fluid flows around the wing model were simulated by solving the incompressible Navier-Stokes equations with the pseudo-compressibility technique and the finite volume discretization. On the basis of their work, the numerical method has been improved and extended [3], the wing models have become more realistic [4], and other insects such as a fruit fly, a honeybee, and a thrips have been modeled and simulated [5]. Various numerical approaches have been applied to studies concerning the flapping flight, e.g., Refs. [6–12] even in the early 2000s. Recently, Dong and co-workers have conducted a sequential research from developing a numerical method to investigating insects' flapping flight by using their developed method. In their method, the incompressible Navier-Stokes equations are solved using a finite difference discretization on a Cartesian grid, and the no-slip boundary condition on the moving boundary is imposed by using a ghost-cell procedure [13]. This method has been successfully applied to two- and three-dimensional flapping wings with a dynamic trailing-edge flap in hovering flight [14] and to cicada's forward flight [15,16].

Among the numerical approaches used in the above studies, the immersed boundary method (IBM), which was proposed by Peskin [17,18] in 1970s in order to simulate blood flows in the heart, has recently been reconsidered as an efficient method for simulating moving boundary flows. The IBM is a simple approach for moving boundary flows, although some techniques are required to satisfy the no-slip boundary condition at the moving boundary. Various approaches and applications using the IBM were reviewed by Mittal and Iaccarino [19]. On the other hand, the lattice Boltzmann method (LBM) has been developed into an alternative and promising numerical scheme for simulating viscous fluid flows in the Cartesian grid without solving the Poisson equation for pressure fields [20]. Since both of the above methods are based on the Cartesian grid, the LBM combined with the IBM (so-called IB-LBM) is well suited to simulations of moving boundary flows such as the flapping flight by insects. Although the LBM with the interpolated bounce-back scheme [21] has also been developed into an attractive method for moving boundary flows and applied to the flapping flight (e.g., Refs. [22,23]), the IB-LBM has been considered to be more preferable in terms of stability and computational effort [24,25]. Several approaches of the IB-LBM have been proposed and widely applied to the flapping flight by insects. Gao and Lu [26] investigated the ground effect on insect normal hovering through simulations of a two-dimensional wing model of an elliptic foil