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Propulsion velocity of a flapping wing at low Reynolds number

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ABSTRACT

This paper presents a computational fluid–structure interaction analysis for free movements with a flapping wing in a quiescent fluid. We demonstrated the moving velocity of a flapping wing according to the phase difference between the angle of attack and the positional angle in the case of a fruit fly with a Reynolds number of 136. If we considered the moving velocity of the flapping wing, the physics were different from that of hovering flight of previous studies, which did not consider the propulsive velocity and presented the advanced rotation of the angle of attack as the best mechanism for propulsion force, as compared to symmetric rotation and delayed rotation. We found that symmetric rotation produced a better propulsion velocity with less fluctuation in other direction than the advanced rotation. The hairpin vortex generated at the end of a stroke did not clearly contribute to the enhancement of propulsion; the wake capture is considered to be one of the main enhancements of the advanced rotation in a previous studies. We studied the effects of the angle of attack to determine why the fruit fly uses a large angle of attack during a constant angle of attack period. Larger angles of attack produced greater propulsion velocities. Further, larger angles of attack did not generate greater peak force during the rotation of the angle of attack at the reversal of stroke, but they produced less fluctuation at the reversal of the stroke and greater force during the constant angle of attack period.

1. Introduction

We computationally investigated the unsteady flow and resulting movement of a flapping wing used by small insects, specifically fruit flies. Dickinson et al. (1999) introduced the mechanisms of insect flight used to achieve enhanced aerodynamic performance and showed that insect flight uses various angles of attack during the stroke. They proposed three mechanisms to enhance the propulsion force: delayed stall, rotational circulation, and wake capture. Sun and Tang (2002) conducted a numerical analysis of the flow around flapping wing of a hovering fruit fly using a rigid plate in a quiescent fluid. Nakata and Liu (2012) presented a fluid–structure interaction model of the flapping flight of hovering insects with flexible wings, and demonstrated the feasibility of their model by accurately and quantitatively evaluating the flexible-wing aerodynamics of the flapping flight of hovering insects. Medjroubi et al. (2011) used the spectral/hp element method associated with a moving frame of reference to investigate the performance of a two-dimensional NACA0012 airfoil oscillating in heaving movement. Heasthcote and Gursul (2007) carried out experiments with a flexible plate fixed at the end of an airfoil. They found that the effect of chordwise flexibility is beneficial for purely heaving airfoils.

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There are several studies related to a body that freely moved by forces from the interaction of the surrounded fluid. Carling et al. (1998) investigated anguilliform swimming using a numerical model combining two-dimensional fluid flow and the dynamics of the creatures movement. The self-propelled body shows the important property of allowing both acceleration and deceleration. Alben and Shelley (2005) numerically studied the dynamics of a body that flapped vertically and was free to move horizontally. Specifically, they investigated the two-dimensional flow around a flapped elliptic body and demonstrated that unidirectional locomotion emerges at sufficiently large frequency Reynolds number. In addition, they studied the effects of the several parameters such as the periodicity of translation velocity according to frequency Reynolds number, aspect ratio of the ellipse, and the density ratio of the body and fluid. Iima (2007) investigated the effect of the motion of the center of mass of an insect on its flight using two-dimensional numerical simulation around a flapping wing that was freely moved vertically and flapped horizontally. He showed that there were two different flights with an external force such as gravity acting on the model. Specifically, he demonstrated that steady flight was numerically stable if the external force is less than a critical value and wandering flight with randomly distributed vortices was observed if the external force is large. These possible flights are analyzed in terms of bifurcation and suggest the significance of the effect of motion of the body. Zhang et al. (2010) numerically studied the two-dimensional flow around a passively flapping rigid plate with a torsion spring acting about the pivot at the leading edge of the plate to consider the effect of the flexibility of the plate. It was found that the frequency ratio between the flapping frequency and the natural frequency of the spring had an important role in the forward movement and the torsional flexibility can remarkably improve the propulsive performance. Tian et al. (2012) numerically studied a propulsive body with a traveling-wave surface in two-dimensional flow. They showed the effects of propulsive properties including the forward speed, the swimming efficiency, and the flow field, which will be helpful in developing novel propulsion concepts for underwater vehicles. Lee and Lee (2012, 2013) showed by two-dimensional numerical calculations that flexible plates could produce better performance in the generation of propulsion force and velocity during the flapping stroke.

Based on these studies, we numerically investigated a flapping wing propelled with two directions of freedom, and we further investigated how the wakes interacted with the wing using three-dimensional simulation of flow. The two degrees of freedom can provide efficiency of movement, which discerns the effective forward movement while reducing loss associated with unintended movement. The effect of different phases between the angle of attack and the positional angle is demonstrated, and the benefits of large angles of attack are shown.

Fluid solvers based on the Navier–Stokes equation are commonly used. A variety of methods for solving the Navier–Stokes equation in a fluid domain with moving boundaries can be classified into two categories, depending on whether a moving mesh or fixed mesh is used. The arbitrary Lagrangian–Eulerian (ALE) method (Liu and Kawachi, 1999; Namkoong et al., 2005; Bathe and Ledezma, 2007) is a moving-mesh-type solver that reconstructs the mesh with the motion of a structure. It has the advantage of accurately describing the boundary because of its boundary adaptability. However, if the structure has large deformations or movements, the re-meshing procedure would have limitations due to time-consuming process of frequent mesh generation in case of moving complex geometries. The fictitious-domain (FD) method (Glowinski et al., 1999; Stijnen et al., 2004; Wang et al., 2008a) and the immersed boundary (IB) method (Kim et al., 2001; Mittal and Iaccarino, 2005; Peskin, 2002; Uhlmann, 2005; Wang et al., 2008b) are fixed-mesh-type solvers. Fixed mesh methods are simple and efficient because the solver does not require re-meshing, but they are limited in accurately describing the boundaries because the grid is non-adaptive.

The lattice Boltzmann method (LBM) is a computational method based on the dynamics of particles that is used for solving engineering problems governed by partial differential equations. Since the 1990s, the LBM has been widely used as a fluid solver instead of solving the Navier–Stokes equation. The LBM is basically a fixed-mesh-type solver. Numerous schemes are being published and have been developed for moving complex boundaries with accuracy. Bouzidi et al. (2001) used the well-organized interpolation for the unknown distribution of a curved boundary with precise second-order accuracy and proposed a scheme for a general moving boundary. Lallemand and Luo (2003) developed the interpolated bounce back scheme with second order accuracy and applied it to a moving cylinder in a channel. However, if the boundaries are complex and moving, the schemes using interpolation or extrapolation may lack the information needed for the interpolation or extrapolation. Lee and Lee (2010) improved the accuracy without additional neighbor lattice information by using an adaptive relaxation time. In order to overcome the limits of interpolation or extrapolation schemes in moving or complex boundaries, Feng and Michaelides (2004, 2005) applied an immersed boundary method (IBM) with a direct forcing method to the LBM to simulate particulate flows including collisions. Sui et al. (2007) reported an LBM using the direct forcing scheme with the IBM to simulate a deformable body in flow. Shi and Phan-Thien (2005) applied a distributed-Lagrange-multiplier/fictitious-domain (DLM/FD) method to the LBM to simulate the fluid–structure interactions such as a flexible filament in the wake of a cylinder. The DLM/FD method introduces a distributed Lagrange multiplier to enforce the fictitious fluids in the solid region in order to satisfy the boundary condition in accordance with the solid motion. Beyond the fluid dynamics solver, Wang et al. (2007a,b,c) and Wang and Chen (2007) used the LBM to solve the energy transport equation with complex multiphase porous geometries, and established a method to predict material properties such as the effective thermal conductivities of porous media. Li and Ki (2008) combined the LBM with the finite difference method to simulate incompressible, resistive magnetohydrodynamic flows. It is clear from the above body of work that the LBM can be an alternative to the traditional Navier–Stokes equation solvers.

In order to validate the present scheme, we applied it to a flapping wing in a quiescent fluid, and compared the resultant force with the experimental results of Dickinson et al. (1999). Drag force of a rectangular plate in a free-stream was also

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