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Fluid–structure interaction for the propulsive velocity of a flapping flexible plate at low Reynolds number

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ABSTRACT

This paper presents computational analysis of a fluid–structure interaction for a flapping flexible plate moved with propulsive velocity in quiescent fluid to investigate the effect of flexibility on propulsive velocity, which is critical for fish, birds, insects, and micro air vehicles with flapping wings. This study found that the mechanism of the flapping plate moved with propulsive velocity differs from that of the plate fixed in the propulsive direction, and the flexibility of the plate improves the propulsive velocity to create an optimal propulsion. The lattice Boltzmann method with an immersed boundary technique using a direct forcing scheme is used to simulate the fluid, while the finite element method with Euler beam elements is used to model structural deformation of the flexible plate. We developed the moving domain scheme to reversely move the domain at the velocity of the plate to simulate the moving plate.

1. Introduction

We computationally analyzed the unsteady flow and resulting propulsive velocity of a flapping flexible plate used to represent the mechanism of real locomotion of fish and flight of birds. Dickinson et al. [6] showed that the three mechanisms of insect flight used to enhance propulsion are delayed stall, rotational circulation, and wake capture. They found that rotational circulation and wake capture at the end of the translational stroke are important to enhance propulsion for forward movement, and the phase sequences between the translational stroke reversals and rotations are important to generate propulsion. Sun and Tang [11] conducted numerical analysis of flow around the flapping wing of a fruit fly using a rigid plate. Their results agreed well with those of Dickinson et al. [6]. Medjroubi et al. [39] for the first time used the spectral/hp element method associated with the moving frame of reference to investigate viscous flow over a two-dimensional NACA0012 airfoil oscillating in heave. However, the real wing of an insect has flexibility. Heathcote and Gursul [21] carried out experiments with a flexible plate at the end of an airfoil and found that the effect of chordwise flexibility is beneficial for purely heaving airfoils. Toomey and Eldredge [30] investigated the role of flexibility in flapping wing flight using the viscous vortex particle method and two-component wing structure connected by a single hinge with a damped torsion spring. Unger et al. [40] considered the flexibility of the airfoil to investigate the fluid flow around a handfoil of a seagull using the finite element method. They found that flexibility improved thrust efficiency by introducing a time dependent airfoil stiffness. Lee et al. [41] conducted fluid–structure interaction analysis to investigate the influence of flexibility on the generation of propulsion and to improve propulsion efficiency by optimizing flexibility of the plate.

Among recent studies, there has been little investigation of propulsive velocity by flapping movement. Increased and stable propulsive velocity without severe fluctuation is the final goal for fish and birds. In the present study, we investigated the propulsive velocity of a flapping plate, and demonstrated that flexibility can improve propulsive velocity.

Many issues must be resolved for accurate and efficient simulation of a fluid–structure interaction. The treatment of a moving fluid–solid interface is critical for the fluid solver, noise reduction induced by the flow of the solid solver, and the coupling of both solvers in the time domain. Fluid solvers based on the Navier–Stokes equation are commonly used. There are a variety of methods to solve the Navier–Stokes equation in the fluid domain with moving boundaries. These methods can be classified into two categories depending on whether a moving mesh or fixed mesh is used. The arbitrary Lagrange–Eulerian method (ALE) [8,17,20] is used as a moving mesh type solver that reconstructs the mesh with the motion of a structure. It is highly accurate because of boundary adaptability. However, if the structure had large deformations or movements, the re-meshing procedure would be complicated. The fictitious-domain method [7,15,32] is a solver that uses a fixed

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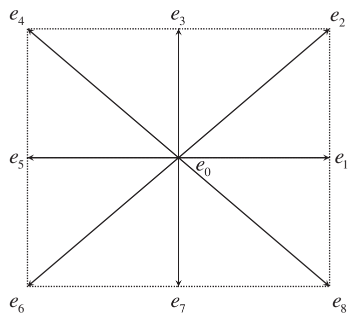

Fig. 1. D2Q9 lattice.

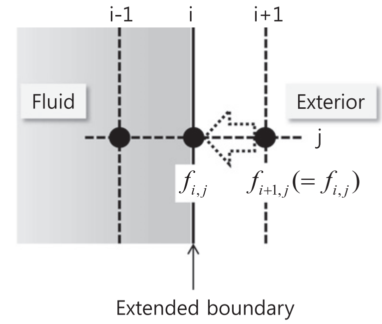

Fig. 3. The extended boundary of the moved domain.

mesh. 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 and is used to solve 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 solver. Numerous schemes are being published and have been developed for moving complex boundaries with accuracy. Bouzidi et al. [9] used 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 [12] developed an 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, schemes that use interpolation or extrapolation may not contain the needed computational information. Lee and Lee [37] used the adaptive relaxation time method to improve accuracy without additional information on neighboring lattices. In order to overcome the limits of interpolation or extrapolation schemes in moving or complex boundaries, Feng and Michaelides [14,16] adopted an immersed boundary method with a direct forcing method to the LBM to simulate particulate flows including collisions. Sui et al. [23] reported on the LBM using a direct forcing scheme with an immersed boundary method to simulate a deformable body in a flow. Xing and Nhan [18] applied a distributed-Lagrange-multiplier/fictitious-domain (DLM/FD) method to the LBM to simulate fluid–structure interaction such as a flexible filament in the wake of a cylinder. The DLM/FD method is a fixed mesh-based method that introduces a distributed Lagrange multiplier to enforce the fictitious fluids in the solid region to satisfy the boundary condition in accordance with the solid motion. Wang et al. [24–27] used the LBM to solve the energy transport equation

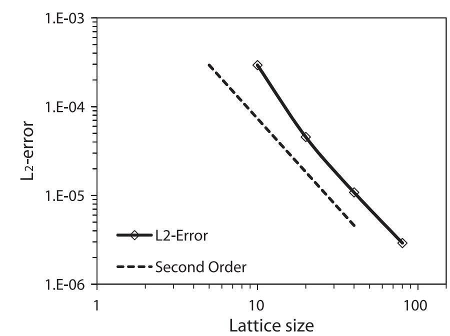

Fig. 4. Overall accuracy of present scheme for the Taylor–Green vortex estimated by L_2-norm error.

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 [29] combined the LBM with the finite difference method to simulate incompressible, resistive magnetohydrodynamic flows. It is well-established that the LBM is superior to conventional Navier–Stokes equation solvers in special areas.

Until now, there have been impressive developments in fluid–structure interaction solvers. Recently among these fluid–structure interaction schemes, there have been progressive developments in the finite element method for structure and the LBM for fluid [31,33,35,36,38]. We combined these two solvers for fluid–structure interaction problems. Among the many different boundary schemes of the LBM, we used immersed boundary treatment with a direct forcing scheme for a moving fluid–structure interface and validated our solver [41]. We developed a moving-domain method to investigate the locally flapping plate with propulsive velocity.

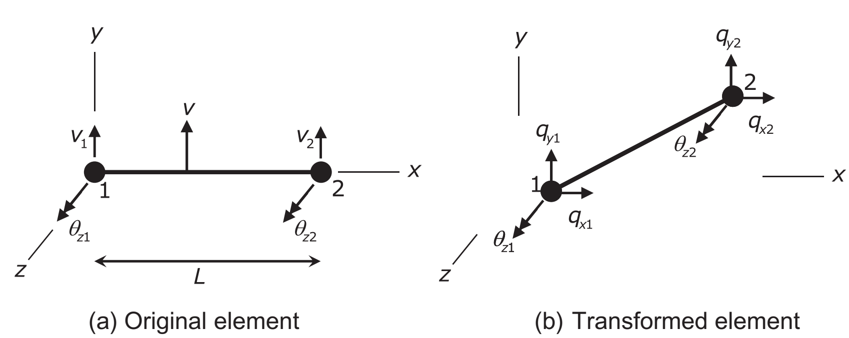

Fig. 2. 1D bending element.