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An adaptive immersed boundary-lattice Boltzmann method for simulating a flapping foil in ground effect

J. Wu [a,*], Y.L. Qiu [a], C. Shu [b], N. Zhao [a], X. Wang [c]

[a] Department of Aerodynamics, Nanjing University of Aeronautics and Astronautics, Yudao Street 29, Nanjing, Jiangsu 210016, China
[b] Department of Mechanical Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, Singapore
[c] National Key Laboratory of Science and Technology on Hydrodynamics, China Ship Scientific Research Center, Wuxi, Jiangsu 214082, China

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ABSTRACT

An adaptive immersed boundary-lattice Boltzmann method (IB-LBM) for simulating two-dimensional moving boundary problems is presented in this work. On one hand, to accurately and efficiently simulate flow field, our recently developed solution-adaptive LBM (Wu and Shu, 2011) is employed. On the other hand, a smoothed discrete delta function (Yang et al., 2009) is utilized to suppress the non-physical force oscillations produced by IBM when dealing with the moving boundary problems. After simulating some validation cases including flows over a transversely oscillating circular cylinder and insect hovering flight in ground effect, the current method is employed to numerically investigate the ground effect on the performance of a flapping foil. In this study, the ground is represented by a flat or wavy plate. Due to the existence of the ground, the performance of the flapping foil is greatly changed. Higher lift force or power extraction efficiency can be achieved.

1. Introduction

Depending on the flapping motions, insects and birds or aquatic animals can produce highly effective propelling and maneuvering [1,2]. Their kinetic mechanism in locomotion is closely related to the generation and control of a reverse Karman vortex street. Based on experimental measurements, Triantafyllou et al. [3] indicated that the mean velocity profile in the reverse Karman vortex street has the form of a jet, which is attributed to the propulsive efficiency of the flapping motions. Owing to such appealing features, the subsequent studies on the flapping motions for propulsion purpose have been widely applied in the engineering including micro aerial vehicle (MAV) and robotic fish [4,5].

As the application of flapping motions for power extraction purpose, on the other hand, biomimic energy harvesting devices based on flapping foils have been developed in recent years. Unlike rotational blade-based power extraction devices, such biomimic energy converters have less noise generation and higher structural robustness due to their relatively low tip speed [6]. Harvesting energy based on the flapping motions originates from the study of Wu [7], who stated that an unsteady wavy flow is essential to power extraction. Later, McKinney and DeLaurier [8] reported that an oscillating wing could also extract energy from a uniform flow. This finding drives the rapid development of flapping foils based biomimic energy generators during the past few years [9–16].

Although various factors have been considered in the flapping motions, the ground effect still receives very limited attention. The ground effect is defined as when a foil is close above a plane surface and a high lift together with a drop in induced drag is produced, which is due to the interactions of vortices from the foil with the ground [17]. Few studies have been conducted in regard to the ground effect on a flapping foil. Moryossef and Levy [18] numerically investigated the flow field around a vertically oscillating airfoil near the ground. Gao and Lu [19] studied the ground effect on the unsteady forces and flow structures of an elliptical foil that executes translation and rotation near the ground. Later, Liu et al. [20] also investigated the ground effect on the aerodynamic performance of two-winged insect hovering flight. Recently, Truong et al. [21] experimentally measured the aerodynamic forces and flow structures of a single flapping wing. To the best of our knowledge, however, the ground effect has never been considered in a flapping foil based biomimic energy generator.

It is known that a flapping foil in ground effect belongs to a moving boundary problem. Generally, to accurately and efficiently simulate flows over moving objects presents challenges to numerical techniques. From the view point of computational mesh adopted, the numerical approaches for handling moving boundary problems can be roughly classified as either boundary conforming

* Corresponding author.
E-mail address: wuj@nuaa.edu.cn (J. Wu).

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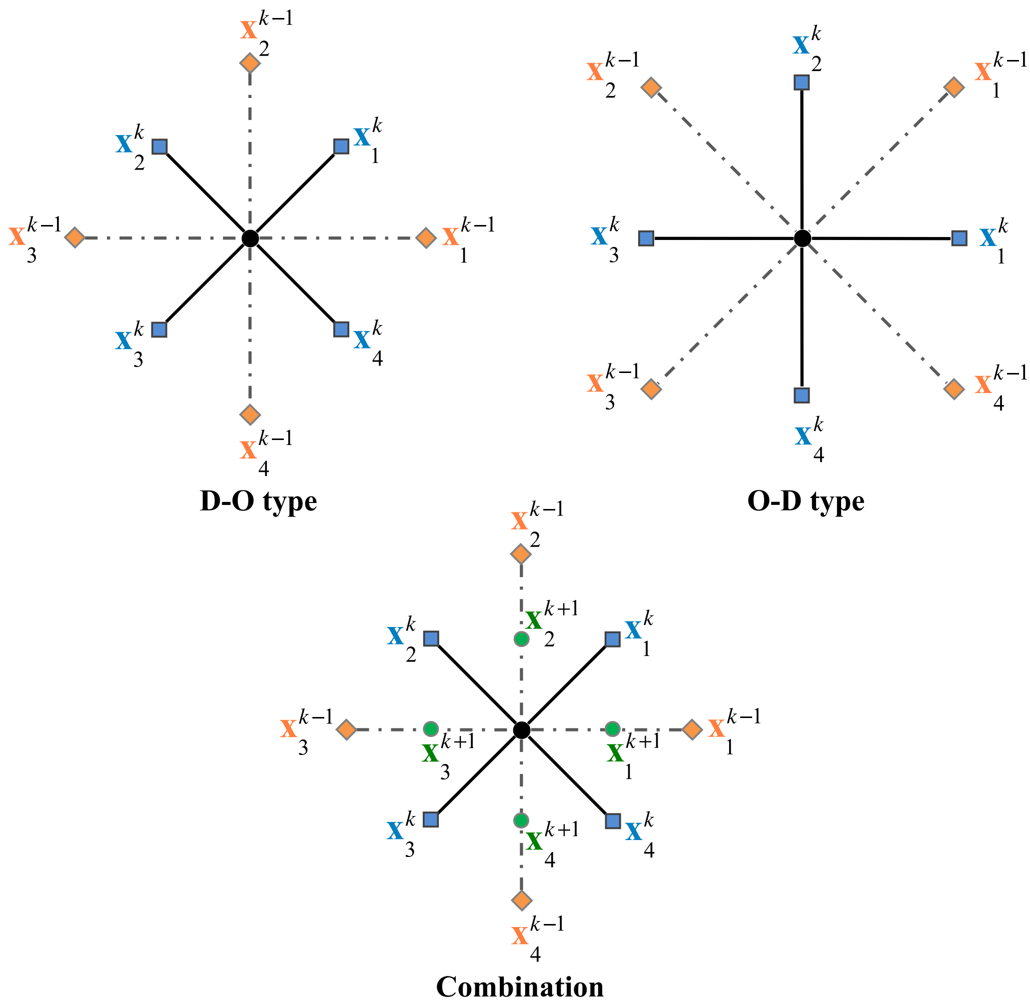

Fig. 1. Sketch of two types of 9-point structures in solution-adaptive LBM.

method or non-boundary conforming method. Compared with the former, no tedious mesh regeneration or reconstruction is required in the latter, which significantly improves the efficiency of simulation for moving boundary problems. Among the non-boundary conforming method, the immersed boundary method (IBM) [22], proposed by Peskin, may be a most famous representative because of its simplicity. In this method, the flow field is resolved on a Cartesian mesh and the boundary is mimicked by a set of Lagrangian points loaded with external forces. Using a discrete delta function, the flow field and the external forces are connected. After the pioneer work of Peskin, the IBM has experienced remarkable developments. Among them, the IBM has been combined with the lattice Boltzmann method (LBM) [23], an elegant flow field solver, to simulate various moving boundary problems [24–30].

There are two important concerns in the simulation of a flapping foil in ground effect. One is to precisely capture the vortex interactions and the other is to accurately compute the aerodynamic forces on the foil. To accomplish the first goal, a direct strategy is to refine the whole computational mesh. From the view point of computational efficiency, however, such implementation is not acceptable. A more feasible way is to employ an adaptive mesh refinement (AMR) technique. Due to the inherent restriction of LBM, in which the time step and the mesh spacing is coupled, the traditional AMR techniques successfully applied to Navier–Stokes solvers do not work well for LBM. To date, very limited efforts are made on the development of solution-adaptive LBM. Using hierarchical tree-type grids, Tölke et al. [31] and Yu and Fan [32] applied the AMR based LBM to simulate multiphase flows. In this method, the relaxation time parameter in LBM and the time step size are changed across the interface of grids with different sizes. Both temporal and spatial interpolations are required at the grid interface. Recently, this technique has also been used to simulate turbulent flows [33]. On the other hand, it has been reported that the simulation of flows over moving objects by using IBM generally suffers the non-physical temporal oscillation of pressure fields, which is the origin of spurious force oscillations produced. To overcome this deficiency, some remedies have been proposed. Yang and Balaras [34] proposed a field-extension scheme to treat the Cartesian grid points around the moving boundary. Liao et al. [35] applied a direct-momentum forcing on the cells near the moving boundary. Seo and Mittal [36] identified that the pressure oscillations are due to the violation of local mass conservation near the moving boundary, and they adopted a cut-cell based approach to enforce geometric conservation. Uhlmann [37] carefully chose a discrete delta function to control the force oscillations.

In this paper, an adaptive IB-LBM for the simulation of two-dimensional moving boundary problems is presented. To perform AMR in LBM, our recently developed solution-adaptive LBM [38] is employed. It uses a unified relaxation time parameter and time step size, and only spatial interpolation is required. Meanwhile, to suppress the non-physical force oscillations on moving