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A LBM–DLM/FD method for 3D fluid–structure interactions

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Abstract

The previously developed LBM–DLM/FD method derived from the lattice Boltzmann method and the distributed Lagrange multiplier/fictitious domain method is extended to deal with 3D fluid–structure interactions. In our current algorithm, the fluid motion is solved by LBM, the deformation of the solid body is solved by the finite element method, and the Lagrange multiplier is solved on the low-order mesh. Three numerical examples are employed to validate the LBM–DLM/FD method and reveal the potential of the method to deal with the fluid/elastic-body interaction problems.

Keywords: Lattice Boltzmann method; Distributed Lagrange multiplier; Fictitious domain method; Fluid–structure interactions; Fluid/elastic-body interactions; High-order finite element method

1. Introduction

Fluid–structure interactions widely exist in various kinds of phenomena in nature and engineering. Particularly in the biomechanics field (e.g. blood flow in elastic vessels [1], aortic or heart valves [2], deformations and aggregations of the red blood cells and white blood cells [3], cell adhesion [4], cell trap and separation), the mechanism of fluid–structure interactions plays a key role. As an alterative method to laboratory experiments, numerical simulation attracts more and more interests of researchers. A variety of numerical methods for the fluid–structure systems have been developed from different backgrounds.

Generally, it is convenient for the flow field to be solved in the Eulerian frame where the mesh is fixed, whereas the Lagrangian description is more suitable for the solid deformation and motion. In the fluid–structure system, a straightforward strategy for the fluid–structure coupling is to directly treat the fluid–structure interface as a moving boundary of fluid mesh, as in the conventional ALE (arbitrary Lagrangian–Eulerian) method [5]. The accuracy of the fluid–structure interface presented on the fluid mesh is guaranteed, but the trade-off is mesh updating due to the moving interface and re-meshing due to the large deformation of the interface or the too distorted mesh. The re-meshing procedure is always time-consuming and difficult in

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complex topology. Moreover, when the solid deformation is large and the geometry is complex, the algorithm cannot keep robust [2].

Another algorithm of coupling the fluid and the structure is accomplished by proposing a pseudo body force like multiplier to constrain the fluid velocity and structure velocity. The fluid mesh is independent of the motion of solid mesh. The algorithms of distribution and interpolation are adopted to impose the fluid–structure coupling on each fluid or solid mesh. The re-meshing is not required. The original immersed boundary (IB) method of Peskin [6] was developed for the volumeless flexible solid body submerged in flow, and its capacity has been enhanced by other variants such as immersed finite element method (IFEM) [7]. The fictitious domain method (FDM) was firstly proposed for particulate flows [8,9], and then extended to fluid/elastic–structure interactions [10,11]. Both IFEM and FDM for flexible structures are more accurate and realistic than original IB because the solid problem is solved by finite element method rather than using fiber network presentation and volumelessness assumption in IB.

The lattice Boltzmann method (LBM) has been widely used in different areas of computational fluid dynamics (CFD) as an alternative choice to its continuum counterpart [12,13]. In the area of fluid–structure interactions, the bounce-back rule was first introduced to impose the fluid–structure coupling [14]. It was proved robust and efficient for particulate flows, especially in the case of large number of particles. The bounce-back rule was also applied to fluid/rigid–structure interactions [15], fluid–membrane interactions [16] and fluid/flexible–elastic-body interactions [17]. Later, the IB method was incorporated successfully into LBM for the 2D and 3D fluid–particle systems [18]. Recently, the LBM–DLM/FD method [19], which combines the ideas of the LBM and FDM, has been proposed for the two-dimensional fluid/elastic–structure interactions.

The aim of the present study is to extend the LBM–DLM/FD method from 2D to 3D. The new idea is the combination of LBM and FD method, which lets the proposed LBM–DLM/FD method inherit the advantages of both methods. Compared with IB based method, the LBM–DLM/FD method has the potential to deal with more general solid sub-problems. In the following sections, we first briefly describe the roots of the LBM–DLM/FD method: DLM/FD and LBM. Subsequently, we present the equations of LBM–DLM/FD for fluid–structure interactions. Finally, the method is applied to three numerical examples, a plate in a channel flow, the flow past two spheres placed side by side and a spherical shell in a duct flow to validate the algorithm and demonstrate the capability of the method.

2. Mathematical formulation

2.1. DLM/FD method

Before the presentation of our method, let us briefly introduce the fictitious domain method for fluid–elastic structure interaction. The FDM was initially designed for fluid/rigid-body system. In recent years, the fictitious domain/mortar element method [10] and the DLM/FD method [11] have been proposed for the fluid/elastic–structure interactions by considering the elastic-solid governing equations. We prefer the DLM/FD formulation for its greater generality. The basic idea of fictitious domain method is to fill the solid domain with fluid, which simplifies the fluid boundary geometry greatly. The distributed Lagrange multiplier (DLM) is introduced to impose the kinematical constraint in the solid domain, or the fictitious fluid domain. Let us use Ω_f and Ω_s to define the extended fluid and structure domain, respectively. The weak-form equations of DLM/FD method for the elastic structure immersed in a Newtonian fluid are expressed as [11]:

$$\int_{\Omega_f} \rho_f \left(\frac{\partial \mathbf{u}_f}{\partial t} + \mathbf{u}_f \cdot \nabla \mathbf{u}_f - \mathbf{f}_f \right) \cdot \boldsymbol{\varphi}_f \, d\Omega_f + \int_{\Omega_f} (-p\mathbf{I} + \eta(\nabla \mathbf{u}_f + (\nabla \mathbf{u}_f)^T)) : \nabla \boldsymbol{\varphi}_f \, d\Omega_f - \int_{\Omega_f} \boldsymbol{\lambda} \cdot \boldsymbol{\varphi}_f \, d\Omega_f = 0, \quad (1)$$

$$\int_{\Omega_f} \psi_f \nabla \cdot \mathbf{u}_f \, d\Omega_f = 0, \quad (2)$$

$$\int_{\Omega_s} \left((\rho_s - \rho_f) \frac{d\mathbf{u}_s}{dt} - (\rho_s \mathbf{f}_s - \rho_f \mathbf{f}_f) \right) : \boldsymbol{\varphi}_s \, d\Omega_s + \int_{\Omega_s} (\boldsymbol{\sigma}_s - \boldsymbol{\sigma}_f) : \nabla \boldsymbol{\varphi}_s \, d\Omega_s + \int_{\Omega_s} \boldsymbol{\lambda} \cdot \boldsymbol{\varphi}_s \, d\Omega_s = 0, \quad (3)$$