Journal of Computational Physics 366 (2018) 226–251

Contents lists available at ScienceDirect

Journal of Computational Physics

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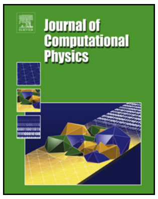

A diffuse interface immersed boundary method for complex moving boundary problems

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ARTICLE INFO

Article history:
Received 8 November 2017
Received in revised form 1 March 2018
Accepted 4 April 2018
Available online xxxx

Keywords:
Immersed boundary
Diffuse interface
Volume fraction
FSI
SFO
3D simulation

ABSTRACT

A diffuse interface immersed boundary method is proposed for problems with arbitrarily moving complex rigid bodies. The solid-fluid interface is replaced by fluid–fluid Lagrangian boundary. A universal equation that combines the momentum conservation and rigid body velocity through the volume fraction is solved in the entire domain. The ever changing volume fraction field is accurately computed locating the object boundary. As the desired boundary conditions are only enforced directly in a volume average sense scope of it spreads over a computing cell. Thus, by reducing size of the computing cell the proposed method approaches the conventional sharp interface methods though it eliminates the spurious force oscillations. Owing to the single universal equation on a fixed Eulerian Cartesian mesh the proposed method retains the simplicity, robustness and versatility of the original Cartesian grid simulation. Convergence study of the transverse oscillation of a cylinder shows second-order convergence with refinement of numerical parameters and significantly diminished force oscillation. The proposed method is parallelized on a mixed shared and distributed memory notions in order to facilitate large scale 2D and 3D simulations. A range of test cases have been carefully chosen to check the quality of prediction of the proposed technique for forced and induced motions of multiple objects. They include in-line, transverse and rotational forced motion of a circular cylinder, motion of a hovering thin wing, vortex induced vibration (VIB) of multiple circular and square cylinder, angular VIB of multiple objects, particle sedimentation, instability driven fluttering of a freely falling plate, settling of a sphere in a quiescent medium, 3D VIB of two cylinders, wake transition due to pitching of a large aspect ratio thin plate and turbulent wake behind a wavy cylinder.

1. Introduction

Immersed boundary method (IBM) was introduced by Peskin [1] to simulate blood flow in arteries using purely Cartesian grids which did not coincide with the boundaries. Since then a number of variants have appeared which mainly rely on simulation on Cartesian meshes enforcing the much needed and perhaps what became the central theme of this method over the years, boundary conditions on a non-conformal mesh, accurately. The evolution of this method has been significant

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https://doi.org/10.1016/j.jcp.2018.04.008

as it offers the simplicity, robustness of the Cartesian grid method and versatility of a method that promises to handle complex geometries without any further modifications. The surge of developments has seen its application for stationary objects and moving objects [2–8], on unstructured meshes [9,10], Lattice–Boltzmann method [11], prediction of complex 2D-3D transition [12], turbulent flows [13], to name a few.

Immersed boundary method was broadly classified [14] into the continuous and discrete forcing approaches. In the former, the immersed boundary (IB) is replaced by a set of elastic Lagrangian markers which are traced as they move with fluid velocity. Deformation of these fibers are modeled by the constitutive relationship and their effects on the immersed boundary is achieved by using a localized momentum forcing. Though it is well suited for elastic boundaries, its direct application in the rigid limit has been debated. On the other hand, a number of methods have been devised where boundary condition(s) is(are) imposed on the immersed surface either in an indirect manner [15] or directly [8]. In direct forcing approach solution of the Navier–Stokes equation is sought at points lying in the fluid domain which are then used to locally reconstruct conditions on the IB through specially designed extrapolation method. This approach has shown remarkable promise as it has been successfully applied to a range of fluid dynamics problem which were once considered unmanageable. However, unlike stationary objects, problems involving complex moving boundary have thwarted its progress owing to its inability to predict smooth aerodynamic force coefficients known as “spurious force oscillation” (SFO) [3,7,2,6] in IBM parlance.

In order to reduce the undesired force oscillations, Uhlmann [16] combined the direct forcing approach with delta function distribution used in continuous forcing approach. However, detailed analyses on SFOs have resulted in a number of possible explanation of the cause and thereby remedies. Since in a moving boundary simulation the object boundary is constantly changing its location, fluid cells which are outside the object at one time, find themselves inside the next instant. This abrupt change in the status of the cells lead to spatial pressure discontinuity and temporal velocity discontinuity. A number of works [17,8], grouped as “field extension” technique, have focussed on creating a consistent extrapolation scheme that correctly considers the fluid cell at an instant to reconstruct solution for the IB points. Liu and Hu [5] dynamically modified the weighting factors in the interpolation scheme. Lack of conservation of mass leading to accumulation near an IB has also been cited as one of the source for SFOs. Seo and Mittal [7] addressed this issue by incorporating a cut-cell method which ensures a strict geometric conservation. Luo [18] argued the cause of SFOs as the instantaneous change in reconstruction stencil while following a moving object and they proposed a smooth transition of such a stencil with time that reduces the temporal velocity discontinuity. In the same note Martins [6] enforced the continuity constraint in the least square sense in order to reduce the temporal discontinuity of adjacent interpolation stencil.

In recent past mixed methods that combine two or more classical approaches have been attempted with mixed Lagrangian–Eulerian approaches can be considered as a significant step forward from methods based on ALE technique [19]. Huang et al. [20] advanced the penalty IBM by assuming an elastic surface by a combination of massive elastic material points undergoing deformation and massless Lagrangian markers following the fluid. The fluid and solid equations were solved in different meshes with surface forces linked to the fluid motion. However, a modified version [21] was proposed earlier where two sets of Lagrangian IB were used to tackle inextensible vesicle problems. Another significant yet less popular method has been techniques largely motivated by the front tracking algorithm [22] where the solid-fluid interface is considered as fluid–fluid interface. These methods rely on the volume fraction of a solid which is used to either blend the velocities [23] or the approximate versions of the solid and fluid equations [24]. Majority of these methods advance such a fraction using the advection equation, an accepted practice in multi phase flows known as the VOF method. On the other hand, in order to reduce numerical diffusion, front tracking algorithms that rely on implicit description of a fluid–fluid interface and predicts its dynamics by hyperbolic conservation laws is popularly known as the level-set method. For solid-fluid interfaces the coupling between them is achieved by either a momentum exchange term [23] or by linear interpolation of volume averaged quantities [25,24]. It should be noted that accurate and efficient prediction of the volume fraction is at the heart of success of this class of methods when applied to arbitrarily moving rigid bodies. Moreover, since most of these works were focussed on a specific class of problems it has not been ascertained whether use of volume averaging at some stage eliminates the SFOs which have been spotted distinctively in sharp interface method.

The present technique is closest in nature to methods that have become popular for multi phase flows. An object is considered part of the fluid domain thereby removing the sharp interface between them that allows solution of a single equation. Thus, in absence of different category of computing cells, the method becomes self-reliant and mass conserving at the microscopic (read computing cell) level, i.e., same for each cell, which makes it favorable to Cartesian grid computing with ease of scalability. The connection between the non-conforming boundary and the fluid is achieved through a volume fraction which, unlike in multi phase flows, is computed accurately using the dynamics of the surface for better flow prediction. This aspect distributes the effect of a complex moving boundary over an entire grid cell alleviating the possibility of emergence of spurious oscillations. The paper is organized as follows. In section 2 governing equations for fluid flow and moving arbitrary objects are mentioned. Numerical details of the proposed method is described in section 3. This includes discrete form of the conservation laws and incremental motion of rigid bodies, solution algorithm, parallelization strategy and linear solver, surface force and moment calculation procedure and convergence tests. Extensive comparative results of a range of complex moving boundary problems both in 2D and 3D are reported in section 4. Finally in section 5, principal observations and closing remarks are listed.