Computers and Fluids 124 (2016) 86–104

Contents lists available at ScienceDirect

Computers and Fluids

journal homepage: www.elsevier.com/locate/compfluid

A simple and efficient direct forcing immersed boundary method combined with a high order compact scheme for simulating flows with moving rigid boundaries

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ARTICLE INFO

Article history:
Received 12 March 2015
Revised 7 September 2015
Accepted 20 October 2015
Available online 30 October 2015

Keywords:
Immersed boundary method
Moving boundary
Direct numerical simulation
Interpolation scheme

ABSTRACT

A non-boundary conforming formulation for simulating complex flows with moving solid boundaries on fixed Cartesian grids is proposed. The direct forcing immersed boundary method (IBM) is implemented in a direct numerical simulation (DNS) code (called Incompact3d) based on high-order compact schemes for incompressible flows.

To satisfy the boundary conditions on the immersed interface, the velocity field at the grid points near the interface is reconstructed via momentum forcing on a Cartesian grid by means of interpolation at forcing points in the fluid domain. A novel interpolation scheme which is applicable to boundaries of arbitrary shape is introduced and compared to a bi-linear model. A variance of this method utilizes a more compact stencil which allows compatibility with two-dimensional domain decomposition of the DNS code.

Local force distributions and velocity fields were compared to identify which interpolation scheme best represents the solid boundaries by computing flow induced by a transversely oscillating cylinder.

The accuracy and efficiency of the present technique are examined by simulating two-dimensional flow over a traveling wavy foil and comparing against numerical reference data. Finally, we present results from a three-dimensional simulation of a lamprey-like body undulating with prescribed experimental kinematics of anguilliform type, in order to demonstrate the ability of the present implementation in computing flows around moving solid objects with non-trivial geometries.

1. Introduction

Fluid flow around complex stationary or moving geometries appears in a large number of situations of practical interest including biological fluid mechanics (airflow in the vocal folds for instance) or in life-science context as well as in engineering applications (fish-like swimming e.g.). The numerical treatment of these kinds of problems appears to be a challenging task because of time-varying geometries.

In order to take accurately small details of the geometry into account, the most popular method is to generate a sophisticated grid following the body geometry and discretize the governing equations on a non-structured mesh for which the boundaries of the computational domain lie on those of the physical domain. However, this technique shows a lack of ability to handle moving bodies which require the development of specific numerical schemes to deal with the tedious task of the re-meshing.

An alternative method to avoid the drawbacks of the body-fitted approach consists in extending capabilities of codes based on Cartesian grids via the use of non-boundary conforming techniques, which may be classified into two categories. The first category, including for instance sharp interface ([1,2]) or immersed interface methods ([3,4]), mimics the presence of embedded geometries by modifying the numerical scheme in the immediate vicinity of the immersed boundary. Such approaches lead to a sharp representation of the immersed interface but extending it to three-dimensional problems may appear to be a challenging task regarding the coding logistic. In the second category a forcing term is added to the governing equations. Here, we use the term 'immersed boundary' (IB) method introduced by Peskin [5] where this idea was employed to consider the full interaction between elastic solids and the fluid. For situations considered in this paper where the motion of solid surfaces is a known of the

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http://dx.doi.org/10.1016/j.compfluid.2015.10.016
0045-7930/

problem, IB methods are categorized as either feedback-forcing (FF) or direct-forcing (DF) approaches. In [6], Goldstein et al. propose the FF method in which the forcing term can be viewed as a force density that brings the fluid velocity to zero near the immersed boundary through a damping oscillation process. The numerical scheme used in this case requires a spreading of the forcing term over the interface. Moreover, the FF method leads to a severe additional restriction on the time step to maintain very low residual velocities in locations where no-slip conditions are expected. In order to avoid this limitation, the use of the DF technique proposed by Mohd-Yusof [7] and then adapted by Fadlun et al. [8] is very attractive. In this method, which introduces no additional numerical stability restriction, the boundary condition is ensured in a quite straightforward way by prescribing directly the velocity in forcing region, leading to a quasi sharp representation of the interface.

The high implementation capability of the DF technique in existing Navier–Stokes solvers, motivated a number of recent studies where alternative DF formulations have been proposed. The main difference between them concerns the reconstruction of the velocity field close to the immersed boundary and the treatment of grid nodes that present geometric ambiguities with respect to the discretization stencil. In [8,9,48], for example, the solution is reconstructed at the fluid nodes that lie near the immersed boundary (fluid points with at least one neighbor in the solid phase, labeled 'forcing-nodes'). In the former study an one-dimensional interpolation scheme along an arbitrary grid line is considered, while in the last two the reconstruction is performed along the well-defined line normal to the interface. In [10,12,13] on the other hand, the solution is reconstructed at 'ghost-cells', which are points inside the solid phase with at least one neighbor in the fluid phase. Both the above strategies have the velocity boundary conditions implicitly build into the reconstruction stencil, and therefore will potentially result in methodologies of comparable overall accuracy. The former strategy, however, which is the one adopted in the present work has some advantages in cases with moving boundaries as it will be discussed in the following.

In the case of 'ghost-cell' methods, as the body moves through the fixed grid some of the 'ghost-cells' will emerge into the fluid and will became fluid nodes. Since they were previously in the solid they have no history in the fluid phase and no physically value for the velocity and pressure at the previous timestep. In 'forcing-nodes' methods, the points that emerge from the solid become the boundary points that are central to the reconstruction procedure (labeled as 'forcing points'), and therefore their history in the fluid phase is irrelevant. The points that require special treatment in this case are the forcing points that move further into the fluid. In order to handle such 'phase-change' points, Yang and Balaras [16] introduced a field extension strategy that, at the end of each time step, the flow field is extended into the grid points with non-physical values in the solid surface through extrapolations. By this way, the continuity of the derivatives in forcing points is maintained.

The present work focuses on combination of direct forcing approach with centered finite difference schemes of high accuracy. Such a combination is a priori problematic due to the discontinuities of the velocity derivatives created by the forcing. This problem is related to the quasi-spectral behavior of compact schemes that leads to spurious oscillations near the body surface (Gibbs phenomenon). In order to reduce the discontinuity near the immersed boundary, Parnaudeau et al. [14] proposed an analytical formula for defining a smooth target velocity field in the full solid domain. This definition uses a mirror flow of the fluid domain, where a modulation function is adjusted to ensure the regularity of inner velocities and to avoid a singularity point. However, for moving complex geometries such a specification would not be adequate because of the time-dependent character of the modulation function, for which a proper definition would be difficult to make. Another concern with the target velocity calibration in [14,15] is the internal treatment of the solid body. Because the target velocity is not divergence-free, the incompressibility condition must be modified inside the body in order to allow a mass source/sink.

Fang et al. [47] use a Gaussian radial basis function (RBF) to interpolate the velocity value at any point inside the body by using the known velocity values at the points near the body surface and satisfying the no-slip constraint at the body surface. Unlike analytical smoothing formula in [14], the RBF-based smoothing procedure can be applied for bodies of general surface geometry. Nevertheless, Gibbs oscillation has proven to be significantly alleviated by their method in which only a zero velocity on the immersed boundary is applied, while moving boundary problems has not been considered. In order to deal with this problem, the field extension strategy proposed by Yang and Balaras [16] is implemented in the present study.

In general, the approach proposed in [16] to reconstruct the velocity at forcing points is quite straightforward and efficient. One issue with the bi-linear interpolation scheme used in [16] to compute the velocity at the virtual point (labeled as 'image point' in our study) is that its application deteriorates the spatial structure of the wake flow when using a grid resolution not high enough, as it is shown in the Results section. Furthermore, at marginal spatial resolution, the order of the interpolation scheme is decisive for an accurate prediction of statistical flow quantities. Accordingly, accuracy of such estimations can logically be expected to improve by increasing the order of the interpolation polynomials associated to the immersed boundary reconstruction procedure.

On the other hand, in [16], the fluid force on the immersed boundary was evaluated through a surface force integration procedure. Basically, the immersed boundary is first discretized into elements of size similar to the grid spacing; then the velocity derivatives at the surface are obtained through one-sided differencing; with the stress tensor and the geometric information available for each boundary element, the surface force distribution can be evaluated directly. The procedure is generalized and applicable to different types of IB methods. However, the results from this approach depend on the resolution of the surface discretization and the position of the elements. Also, it is a post-processing step that can only be conducted after the whole flow field has been solved. Actually, Lai and Peskin [26] gave several approaches for evaluating fluid force on an immersed body; the most straightforward approach is to integrate the momentum forcing function over the whole domain, which represents the total effect of the immersed boundary on the fluid. Since the forcing function is available before the final solution of the momentum equations, the fluid force can be evaluated before the whole field is solved [17].

In this paper, we present a strategy that can address both issues discussed above in a simple and efficient manner. First, we propose a local reconstruction of the solution near the immersed boundary based on a high-order formulation which enables a high degree of flexibility with respect to the interpolation stencil [18] in the framework of a compact scheme [19] while allowing the use of a marginal grid resolution to describe accurately the wake flow. Two alternative interpolation strategies, successive 1D high-order polynomial and bilinear interpolation, respectively, are discussed. Then, we describe the formulation consistent with our immersed boundary reconstruction operation for estimating the momentum forcing term explicitly. Therefore, we can use the straightforward point integration of the momentum forcing term to evaluate the fluid force exerted on the immersed body instead of the surface integration approach in [16]. Moreover, as explained in the following, the three-step fractional step method in [19] is modified to impose the Dirichlet boundary conditions on the velocity when forcing is taken into account, allowing a consistent and efficient solution of the pressure equation on the whole domain. Also, as it is shown hereafter, this approach solves the problem of fixing appropriate physically meaningful conditions for the grid points everywhere in the solid region.