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A simple and efficient direct forcing immersed boundary framework for fluid–structure interactions

Jianming Yang *, Frederick Stern

IIHR – Hydroscience and Engineering, University of Iowa, Iowa City, IA 52242, USA

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ABSTRACT

A direct forcing immersed boundary framework is presented for the simple and efficient simulation of strongly coupled fluid–structure interactions. The immersed boundary method developed by Yang and Balaras [J. Yang, E. Balaras, An embedded-boundary formulation for large-eddy simulation of turbulent flows interacting with moving boundaries, J. Comput. Phys. 215 (1) (2006) 12–40] is greatly simplified by eliminating several complicated geometric procedures without sacrificing the overall accuracy. The fluid–structure coupling scheme of Yang et al. [J. Yang, S. Preidikman, E. Balaras, A strongly-coupled, embedded-boundary method for fluid–structure interactions of elastically mounted rigid bodies, J. Fluids Struct. 24 (2008) 167–182] is also significantly expedited by moving the fluid solver out of the predictor–corrector iterative loop without altering the strong coupling property. Central to these improvements are the reformulation of the field extension strategy and the evaluation of fluid force and moment exerted on the immersed bodies, by taking advantage of the direct forcing idea in a fractional-step method. Several cases with prescribed motions are examined first to validate the simplified field extension approach. Then, a variety of strongly coupled fluid–structure interaction problems, including vortex-induced vibrations of a circular cylinder, transverse and rotational galloping of rectangular bodies, and fluttering and tumbling of rectangular plates, are computed. The excellent agreement between the present results and the reference data from experiments and other simulations demonstrates the accuracy, simplicity, and efficiency of the new method and its applicability in a wide range of complicated fluid–structure interaction problems.

1. Introduction

The immersed boundary method was originated by Peskin in the last seventies [20,21] for the computational studies of fluid–structure interaction (FSI) problems in a human heart. This method and its subsequent developments/extensions have substantially expanded the applicability of the traditional finite difference methods relying upon simple Cartesian grids. In Peskin's method [20,21], the effect of flexible structures, such as heart valves and muscular wall, on the blood flow was represented by an external, singular force field in the Navier–Stokes equations to be solved in a regular domain including both the flow field and the structures; and these structures were modeled by sets of spring-linked elements using a Lagrangian representation. Discrete delta functions were used to connect the fluid flow and the immersed boundaries, i.e., to interpolate the fluid velocity from the Eulerian grid points to the Lagrangian elements and to spread out the boundary forces from the latter to the former. For flexible structures, the boundary forces were readily available using a generalized Hooke's law from the relative positions of the boundary elements depending on the boundary material properties. However, for a solid bound-

* Corresponding author. Tel.: +1 319 335 5749; fax: +1 319 335 5238.
E-mail address: jianming-yang@uiowa.edu (J. Yang).

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ary, there is no relative displacement between neighboring boundary elements and the above method could not be applied in a straightforward manner. Goldstein et al. [11] developed a feedback forcing strategy in a pseudo-spectral method using ideas from control systems theory, in which the local forcing function would adapt itself through a feedback controller to satisfy the desired velocity boundary conditions. Saiki and Biringen [23] implemented this feedback forcing scheme in a fourth-order finite difference method to study low Reynolds number flows past stationary and moving circular cylinders. They used a discrete hat function (area-weighted averaging) to transfer velocity/force information between the background grid and the immersed boundary. A major disadvantage of the feedback forcing method is the overly restrictive time step constraint resulting from the feedback mechanism, which contains two large-magnitude tuneable constants that make the equations very stiff. This limitation was removed by Mohd-Yusof [18], who derived a direct forcing formulation by imposing the velocity boundary condition at the immersed boundary "exactly" in the discrete-time equations without any feedback adjustment. The resulting forcing term is no longer defined in the continuous space and associated with the boundary force density function; hence there is no need to transfer force information from boundary elements to Eulerian grid points and the immersed boundary discretization is no longer required. This approach was implemented in a pseudo-spectral method in [18] and then applied in a finite difference method by Fadlun et al. [8]. With Mohd-Yusof's derivation, it is essentially a local solution reconstruction procedure to satisfy the desired boundary conditions at the immersed boundary and an explicit forcing term was not required in the momentum equations at all, as detailed in [8]. On the other hand, the direct forcing idea was also combined into some approaches [26,37,27,36] immediately related to Peskin's method, to which a discrete delta function is central for the information transfer between the Eulerian grid points and the Lagrangian elements. In these approaches, the velocities at surrounding grid points are first interpolated using the discrete delta function to an immersed boundary node; then, instead of using a constitutive law or feedback adjustment, the local forcing is determined by directly requiring the velocity boundary condition at the boundary node to be satisfied after the forcing is applied; finally the local forcing at each boundary node is distributed using the discrete delta function to surrounding grid points. In the present study, we shall focus on a direct forcing approach making no use of the discrete delta functions. Nonetheless, the extension of our FSI algorithm to those with discrete delta functions is straightforward and requires almost no modifications to either the original immersed boundary solver or our algorithm, as will be clear later.

The direct forcing immersed boundary approaches have been well received among the developers and practitioners of non-boundary conforming methods in the computational fluid dynamics (CFD) field, mainly because of the simplicity of the concept and the ease of the implementation of the formulations. Initially, the developments were focused on stationary immersed boundaries [8,15,25,2]; and very few were applied to problems with moving boundaries, due to the fact that the implications of boundary movement on a fixed grid in a time-splitting scheme, such as the fractional-step method, were not systematically addressed. (Note that this problem is not prominent in approaches using discrete delta functions as the forcing is spread out over a few grid points across the immersed boundary.) Then Yang and Balaras [31] demonstrated that, non-physical historical information may enter the flow field in a time step, when some grid points with reconstructed solutions at the previous time step become normal fluid points, if no treatment is applied to recover the correct historical information at these points. They proposed 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 near the immersed boundary through extrapolations. A variety of examples ranging from laminar to turbulent flows were given to show the accuracy and effectiveness of this approach. They further extended it in [32] and then [33] to FSI problems with multiple rigid bodies using a strong coupling scheme in which the structural dynamics was solved via Hamming's fourth-order predictor–corrector algorithm. In their strong coupling scheme, the fluid and the structure are treated as elements of a single dynamic system, and both sets of governing equations are integrated simultaneously and interactively in the time domain. It is a very efficient iterative scheme as the number of iterations does not change much with increased number of DOFs (degrees of freedom) of the structural part and the convergence of the whole coupled system usually is reached within ten iterations. In addition, it is not limited to FSI problems with solid bodies, for example, in [28], it was used to study the aerodynamic performance of a flexible hovering wing.

In general, the approaches discussed above for FSI problems (prescribed motion in [31] and predicted motion in [33], respectively) are quite straightforward and efficient. One issue with the field extension strategy is that the definition of pressure points requiring the extension operation is not as simple as that for velocity points. Instead of a simple geometric relationship, for instance, the closest grid points to the immersed boundary along grid lines (for velocity components, closest grid points in the fluid phase and solid phase are defined as forcing points and pseudo forcing points, respectively, in [31]), the status of all surrounding velocity points (four points in two-dimensional (2D) and six points in three-dimensional (3D) cases, respectively) has to be used to find a pressure point that needs the extension operation. And such a point may be in either the fluid or the solid phase, depending on the configuration of the immersed boundary and the grid layout. This is not particularly convenient in terms of algorithm design and implementation. Furthermore, for grid points in the solid requiring field extension operation, ambiguities may sometimes exist near sharp corners or under-resolved regions with regard to the normal directions to the immersed boundary. To remove these ambiguities, significant amount of coding work is needed and the clarity and efficiency of the algorithm may be affected.

On the other hand, in [31,33], the fluid force on an immersed boundary was evaluated through a surface force integration procedure. Basically, the immersed boundary is first discretized into elements of size similar to the local grid spacing; then the pressure value and velocity derivatives at the surface are obtained through extrapolation and one-sided differencing, respectively; with the stress tensor and the geometric information (normal and area) available for each boundary element, the surface force distribution and total force and moment can be evaluated directly. The overall procedure is very generalized