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A non-iterative direct forcing immersed boundary method for strongly-coupled fluid–solid interactions

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ABSTRACT

A non-iterative direct forcing immersed boundary method is presented for the strongly-coupled simulations of fluid–solid interactions. While it retains many advantages of the immersed boundary framework by Yang and Stern (2012) [30], especially the simplified field extension strategy for moving boundary treatment and the pointwise integration of hydrodynamic force using the momentum forcing term, the present approach improves upon the previous method in several aspects including optimized computational cost for a strong coupling scheme, reduced algorithm complexity for a straightforward implementation, and enhanced numerical stability for low density ratio problems. Central to these improvements is a simple intermediate step in which the velocity fields around solid bodies are predicted on temporary non-inertial reference frames attached to moving solid bodies in a one-to-one manner. This step enables the explicit inverse of the implicit equations for rigid body dynamics, thus rendering unnecessary the previous predictor–corrector scheme for iteratively adjusting the displacements and velocities of the immersed bodies until reaching a convergence. In addition, a simple, generalized procedure is developed to obtain the interpolation coefficients in a local reconstruction stencil explicitly from the geometric relationship. For verification and validation, the vortex-induced vibration of a circular cylinder and the rotational galloping of a rectangular body are considered first; then several particulate flow problems, including settling and buoyant particles of low density ratios, a settling particle in a small container, and the kissing–drafting–tumbling problem of two settling particles, are studied. The agreement between the present results and the reference data in the literature is excellent. An overall second-order accuracy of the algorithm is verified in two systematic grid convergence tests. The present idea can be easily applied to similar methods for achieving a strong coupling scheme on top of a weak one with a nominal increase in the computational cost. Details of the algorithm are provided to facilitate its implementation in other solvers using non-boundary-conforming grids.

1. Introduction

The immersed boundary method has long been established as a versatile and cost-effective approach for fluid–structure interaction (FSI) problems since its introduction by Peskin in the 1970s [17,18]. It is very attractive in that a simple forc-

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ing term is added to the momentum equation to represent the effect of a complex immersed boundary on the fluid flow, without modifying the regular finite difference schemes on a fixed Cartesian grid. In the conventional immersed boundary method [19], a constitutive relation for the material elasticity is required to determine the forcing term according to the structure deformations. Structures with no/prescribed deformations can be modeled using very stiff springs; but large stiffness values, which are usually determined *ad hoc*, have some numerical stability implications. In the so-called direct forcing approach [15], instead of making use of a constitutive relation, the momentum forcing function was derived by directly injecting the velocity boundary condition at the immersed boundary into the discrete-time momentum equation. Essentially it can be viewed as a local solution reconstruction procedure with which the desired boundary conditions is imposed on the immersed boundary, and the explicit appearance of a forcing term in the momentum equation was not even required [6]. This opened up great opportunities for developing algorithms of various features targeted for specific improvements as well as diversified applications (see, for example, [12,23,1] among others), since the velocity boundary conditions are ubiquitous in numerical simulations of fluid flows regardless of the boundary properties (rigid, deforming, or elastic) and the motion characteristics (stationary, prescribed, or predicted).

It should be noted that, in Peskin's method, the momentum forcing from an immersed boundary represented by a Lagrangian mesh is formulated as a Dirac delta function, which is usually replaced by a smooth approximation in the actual discretization on the underlying Eulerian grid. For a moving boundary problem, ideally, a discrete delta function can smoothly spread out the boundary force onto the surrounding Eulerian grid points without incurring spurious jumps in the flow field, although the smoothing process results in a blurring fluid–solid interface. On the contrary, in a direct forcing approach [6], the velocity boundary conditions are imposed on grid points adjoining the immersed boundary and satisfied "exactly" as for a boundary-conforming method if the grid points coincide with the immersed boundary. This sharp interface treatment produces temporal and spatial jumps in the momentum forcing when the immersed boundary moves across the fixed grid points. Without an appropriate handling, these jumps can result in spurious oscillations of hydrodynamic forces on the immersed boundary, which could be disastrous for FSI problems sensitive to the variations in the hydrodynamic forces. Actually, this issue was a main motivation in [24] to resort to discrete delta functions for the smooth transfer of velocity and forcing information between the Eulerian and Lagrangian locations. Similar Eulerian–Lagrangian coupling ideas in the direct forcing framework were also presented in [8,34]. Uhlmann's method has been widely used in particulate flow simulations and inspired quite some follow-up work for improvements or extensions to general FSI problems, such as [25,33,20,10] among others. In particular, a major limitation of [24] restricting the applicable range of density ratios ($\rho_s/\rho_f \geqslant 1.2$ for spherical particles with ρ_s and ρ_f the solid and fluid densities, respectively) was mitigated to cover cases with $\rho_s/\rho_f \geqslant 0.3$ in [10]. Unfortunately, most if not all of these improvements or extensions came at the price of additional algorithm complexity and increased computational cost, and hardly addressed several inherent drawbacks of the discrete delta function formulations. For instance, depending on the width of the support of the delta function on the Eulerian grid, the sharpness of the fluid–solid interface is weakened and the computational cost of the Eulerian–Lagrangian coupling process is augmented correspondingly; also, some *ad hoc* treatments may be necessary if the Eulerian stencils from two different structures overlap [10]. Furthermore, the Lagrangian markers on the immersed boundary are usually required to be distributed *evenly* with a resolution close to that of the local Eulerian grid (a finer surface mesh will increase the cost, instead of the accuracy) [24], even for stationary geometries or structures with prescribed motions. This could be very difficult, if not impossible, for cases with complex geometries or thousands/millions of particles of arbitrary shapes.

Due to the abovementioned drawbacks, it is still preferred to avoid the dependence on a discrete delta function as the kernel of fluid–structure (i.e., Eulerian–Lagrangian) coupling in many applications by retaining the sharp interface property of the original direct forcing approach [6]. It should be pointed out that the validation in [6] was mainly concerned with stationary immersed boundaries, although a moving boundary problem was demonstrated without force information. Thus, the implications of an immersed boundary moving on a fixed grid in the framework of a fractional-step method were not addressed in [6]. Actually, a close observation in [26] on the role switching of the grid points around the immersed boundary revealed that, when a grid point with a reconstructed solution at the previous time step becomes a normal fluid point at which the governing equations are solved, the non-physical field information from the solid phase may enter the system via the derivatives evaluated at this point. Depending on the deviation from the physical values, these contaminated derivatives may produce spurious force oscillations of various amplitudes when the original method in [6] is applied to moving boundary problems. Therefore, an intuitive remedy of this problem is to exclude the involvement of those points from the solid phase in evaluating the derivatives at such a point. But the penalty will be the loss of the regularity of the discretization stencils for individualizing the treatments in a case-by-case manner. On the contrary, a field extension strategy was proposed in [26] to recover the physical values of the contaminated derivatives by extending the flow field into the solid phase through an extrapolation procedure. The field extension can be performed at the end (or equally, the beginning) of each time step by directly modifying the solution field without tangling with the discretization stencils. Several moving boundary problems ranging from laminar to turbulent flows were carried out to demonstrate the accuracy of this simple approach in [26]. The extension to FSI problems with multiple rigid bodies using a strong coupling predictor–corrector scheme in [27] further verified the effectiveness of the field extension strategy in tackling the issue of spurious force oscillations.

An important feature in [26,27] is that the hydrodynamic force was calculated through a surface integration on all Lagrangian elements; thus there was still a resolution requirement of the surface mesh, e.g., close to that of the local Eulerian grid, in order to obtain an accurate force evaluation. Recently, Yang and Stern [30] substantially simplified the field extension