

Computing Fluid-Structure Interaction by the Partitioned Approach with Direct Forcing

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Abstract. In this paper, we propose a new partitioned approach to compute fluid-structure interaction (FSI) by extending the original direct-forcing technique and integrating it with the immersed boundary method. The fluid and structural equations are calculated separately via their respective disciplinary algorithms, with the fluid motion solved by the immersed boundary method on a uniform Cartesian mesh and the structural motion solved by a finite element method, and their solution data only communicate at the fluid-structure interface. This computational framework is capable of handling FSI problems with sophisticated structures described by detailed constitutive laws. The proposed methods are thoroughly tested through numerical simulations involving viscous fluid flow interacting with rigid, elastic solid, and elastic thin-walled structures.

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1 Introduction

The interactions between viscous fluid flows and immersed solid structures are nonlinear multi-physics phenomena with application to a wide range of scientific and engineering disciplines [4, 10]. The study of fluid-structure interaction (FSI) is an emerging field that has been fast growing in recent decades. Owing to the difficulties in analysis and limitations in experiments for these strongly nonlinear problems, FSI research and development largely rely on computational methods.

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Current numerical methods for FSI may be broadly classified in two categories: the *monolithic* approach and the *partitioned* approach. The first approach [13,23] uses a unified system to represent the entire FSI problem and employs a single algorithm to solve the fluid and structure dynamics simultaneously. The monolithic approach can potentially achieve very high accuracy in FSI simulation, but it typically demands large computational effort, and it may require substantial resources and expertise to develop and implement such an algorithm. In contrast, the partitioned approach [26,30] treats the fluid and the structure as two systems which can be computed separately with their respective solvers. Thus, fluid and structural dynamics may be solved with different mesh discretizations and numerical algorithms, and the solution data communicate at the fluid-structure interface. A significant advantage of this approach is the capability to integrate available disciplinary algorithms with respect to the fluid and structural dynamics, thus reducing the effort and time in FSI code development. A challenge, however, is to effectively coordinate the disciplinary solvers to achieve an accurate and efficient FSI solution procedure.

Another way to categorize FSI methods is based on the types of meshes employed, and there are two major classes: the *conforming mesh* methods and the *non-conforming mesh* methods. The Lagrangian methods [4,6] and the Arbitrary Lagrangian-Eulerian methods [25] are typical examples of the conforming mesh approach, where a mesh-updating procedure is generally required at each time step corresponding to the movement/deformation of the immersed structures. On the other hand, non-conforming mesh methods employ fixed (normally Cartesian) grids which eliminate the need of re-meshing and lead to reduced algorithmic complexity and improved computational efficiency, an advantage compared to the conforming mesh methods.

The best known non-conforming mesh method for FSI is probably the immersed boundary method invented by Peskin [20]. This numerical technique solves the fluid equations with an additional forcing term which represents the effects of the immersed structure acting on the fluid motion. Essentially, the fluid equations are solved in the entire domain with a fixed Eulerian mesh, and the immersed structure is represented as a moving boundary tracked on a separate manner. Due to its efficiency, flexibility and robustness, the immersed boundary method has become increasingly popular in FSI study and many progresses, in both the methodology and application, have been made in recent years (see, e.g., [11,15,17,24,31,32]). One major limitation associated with this approach, however, is that it primarily deals with structures that do not occupy volumes; e.g., a fiber in 2D space and a membrane in 3D space. Although immersed bodies with a finite volume can be approximated by a network of connected fibers, each of which can be treated as an immersed boundary, such an approximation may not accurately model the realistic structural response to the fluid motion. Some other variations of the method, such as the immersed finite element method [32], are able to handle bulk solid structures described by material constitutive laws, yet their applications to more sophisticated structural settings are still to be seen. Additionally, in the presence of rigid or nearly rigid structures, methods of the immersed boundary type generally result in highly stiff