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A stabilised immersed boundary method on hierarchical b-spline grids for fluid–rigid body interaction with solid–solid contact

C. Kadapa*, W.G. Dettmer, D. Perić

Zienkiewicz Centre for Computational Engineering, College of Engineering, Swansea University, Fabian Way, Swansea, SA1 8EN, Wales, UK

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Highlights

- Stabilised immersed framework for fluid–structure interaction.
- A second-order accurate staggered solution scheme.
- SUPG/PSPG stabilisation and ghost-penalty stabilisation.
- Penalty-free unsymmetric Nitsche method for imposing interface and boundary conditions.
- Applied to galloping, particulate flows, ball check-valve and a model turbine.

Abstract

An accurate, efficient and robust numerical scheme is presented for the simulation of the interaction between flexibly-supported rigid bodies and incompressible fluid flow with topology changes and solid–solid contact. The solution of the incompressible Navier–Stokes equations is approximated by employing a stabilised formulation on Cartesian grids discretised with hierarchical b-splines. The solid is modelled as a rigid body and represented by linear segments along its boundary. Kinematic conditions along the fluid–rigid body interface are enforced weakly using Nitsche's method, while ghost penalty operators are employed to avoid excessive ill-conditioning of the system matrix arising from small cut cells. A staggered scheme is used for resolving the coupled fluid–rigid body interaction. The contact between moving or moving and fixed solid bodies is modelled with Lagrange multipliers. The excellent performance and wide range of applicability of the proposed scheme are demonstrated in a number of benchmark tests as well as industrially relevant model problems. The examples cover the galloping phenomena, particulate flow, hydraulic check valves and a model turbine.

Keywords: Fluid–rigid body interaction; Hierarchical b-splines; Immersed boundary methods; Staggered scheme; Particulate flows; Check valve

1. Introduction

Fluid–structure interaction (FSI) is frequently encountered in science and engineering. Developing robust and accurate numerical schemes for the simulation of FSI phenomena has been in the focus of research in computational

* Corresponding author.
E-mail address: c.kadapa@swansea.ac.uk (C. Kadapa).

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engineering for several decades. Despite some considerable developments in this field, see [1–3], a substantial amount of research is still required in order to extend the methodology to the range and scale of problems encountered in industrial practice. This is due to the numerous challenges that the developers of FSI solvers face, including: (a) large structural deformations, (b) topological changes of the fluid domain, (c) added-mass effects and (d) computational efficiency. Therefore the range of applicability of existing numerical schemes and commercial software tools is generally limited. In fact, many important real world engineering problems, for instance, various types of valves, pumps, turbines and blood flow through heart and arteries, require that all these challenges are addressed successfully.

A number of researchers have developed numerical schemes for FSI based on the now well established arbitrary Lagrangian–Eulerian (ALE) formulation using body-fitted meshes, see [4–11] and references therein. Despite the significant research effort invested, such schemes have certain inherent disadvantages that limit their applicability to complex FSI problems. Namely, FSI schemes based on ALE require sophisticated mesh-moving and/or remeshing algorithms in order to capture large structural deformations. These algorithms are not only complex to implement but also introduce additional numerical errors during the data transfer from one mesh to the other, when remeshing is needed during the solution process. In situations involving complex geometries and frequent topological changes, typically encountered in valves, pumps, mixers etc., the use of body-fitted ALE based FSI schemes, although possible in some cases using complex mesh generation strategies (see [12–14]), becomes impractical for the majority of such problems.

In order to overcome the difficulties encountered by ALE formulations in problems with large structural deformations and topological changes, numerical methods based on immersed or unfitted strategies have been explored. Immersed methods offer important advantages over body-fitted ALE schemes, namely, (a) the fluid grid does not have to align with the boundary of the solid and (b) the formulation naturally allows for large structural deformations and topological changes. Several different immersed boundary methods have been proposed, based on different strategies for the imposition of the interface conditions between the fluid and solid phases, such as: immersed boundary method (IBM) of Peskin [15], immersed interface method by LeVeque et al. [16,17], immersed structural potential method (ISPM) by Gil et al. [18], immersed finite element method by Zhang et al. [19,20], immersed b-spline methods by Rüberg and Cirak [21,22] and immersogeometric methods [23–27]. The latter relate to the innovative field of isogeometric modelling which originates from the work by Hughes and co-workers [28]. However, many of these schemes lack local refinement capabilities, a feature that is essential in order to reduce the computational cost of the simulation. In addition, in the original IBM and many of its variants, the interface conditions are enforced weakly using virtual springs which limits the time steps to very small values in order to maintain stability.

With the aim of addressing the above concerns, our recent research effort has been directed at the development of a computational framework based on an immersed method, which is robust and efficient, and suitable for the simulation of complex industrial FSI problems. Kadapa et al. [29] present a fully-coupled numerical scheme for the interaction of thin flexible structures with viscous incompressible fluid flow based on hierarchical b-splines and a fictitious domain method (FDM) employing Lagrange multipliers. The present work presents a new numerical framework motivated by the recent developments in unfitted methods, also known as CutFEM, by Burman et al. [30–33]. A preliminary study of this framework is presented in Dettmer et al. [34], which focuses on the accuracy and robustness of the scheme in the context of the Laplace equation and the steady incompressible Navier–Stokes equations on fixed domains immersed in Cartesian b-spline grids. The methodology is essentially based on the deactivation of the degrees of freedom which do not possess any support in the physical domain. The integration of the cut cells is restricted to the active part of the cells and the immersed boundary conditions are imposed by applying Nitsche's method. It is known and demonstrated clearly in [34] that the presence of small cut cells leads to excessive system matrix condition numbers. So-called ghost penalty terms, originally developed by Hansbo and Burman in [30–32] and references therein, are employed to alleviate this effect. The present article presents the extension of the methodology proposed in [34] to the simulation of fluid–rigid body interaction.

For the temporal discretisation, we employ the generalised-α method for first and for second order problems as proposed by Jansen et al. in [35] and Chung and Hulbert in [36], respectively. The staggered scheme presented by Dettmer and Perić in [9] is used to resolve the interaction between the fluid flow and the flexibly-supported rigid bodies. Thus, the methodology including the weakly coupled FSI solution scheme is based throughout on the second order accurate time integration procedures. Normal contact between moving rigid bodies or moving bodies and the fixed fluid boundary is accounted for by employing Lagrange multipliers in the solid solver. This technique is standard in implicit computational contact mechanics and is described, for instance, in [37].