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A PARALLEL ALGORITHM FOR THE SOLUTION OF LARGE-SCALE NONCONFORMING FLUID-STRUCTURE INTERACTION PROBLEMS IN HEMODYNAMICS *

Davide Forti, Alfio Quarteroni and Simone Deparis
MATH-CMCS, École Polytechnique Fédérale de Lausanne,
Station 8, CH-1015 Lausanne, Switzerland
Email: davide.forti@epfl.ch, alfio.quarteroni@epfl.ch, simone.deparis@epfl.ch

Abstract

In this work we address the numerical solution of large scale fluid-structure interaction problems when nonconforming grids and/or nonconforming finite elements discretizations are used at the interface separating the fluid and structure physical domains. To deal with nonconforming fluid-structure discretizations we use the INTERNODES method (INTERpolation for NOnconforming DEcompositionS) formerly introduced in [6] for the solution of elliptic PDEs on nonconforming domain decomposition. To cope with the high computational complexity of the three dimensional FSI problem obtained after spatial and temporal discretization, we use the block parallel preconditioner FaCSI [7]. A numerical investigation of the accuracy properties of INTERNODES applied to the nonconforming FSI problem is carried out for the simulation of the pressure wave propagation in a straight elastic cylinder. Finally, we study the scalability performance of the FaCSI preconditioner in the nonconforming case by solving a large-scale nonconforming FSI problem in a patient-specific arterial bypass.

Mathematics subject classification: 74F10, 65M55.
Key words: Fluid-Structure Interaction, Domain Decomposition, Nonconforming discretizations, INTERNODES, Biomechanics, Parallel Preconditioners, High Performance Computing.

1. Introduction

Fluid-Structure Interaction (FSI) problems are systems of partial differential equations that couple together flow models (typically described by Navier-Stokes equations) and structural models (typically expressed by the nonlinear elastodynamics equations) through an interface where both dynamics and kinematics coupling conditions are fulfilled [4,5]. In this work we are interested in the numerical solution by finite elements of FSI problems when nonconforming discretizations are used for the fluid and the structure computational domains. Typically, solution algorithms for fluid-structure interaction problems are derived assuming that conforming fluid-structure discretizations are used at the fluid-structure interface. In such cases, the enforcement of the coupling conditions is straightforward. However, due to the different resolution requirements in the fluid and structure physical domains, as well as the presence of complex interface geometries that do not match exactly make the use of matching fluid and structure meshes problematic. In these situations, it is more natural to deal with discretizations that

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are nonconforming, provided however that the coupling conditions at the interface are properly enforced.

In this work, to deal with nonconforming discretizations at the discrete fluid-structure interface we use INTERNODES (INTERpolation for NOnconforming DEcompositionS), an interpolation based method that has been proposed in [6] for the numerical solution of elliptic partial differential equations on nonconforming domain decompositions. INTERNODES is in fact an alternative to the mortar element method, introduced in the context of nonoverlapping domain decomposition [11, 12]. The mortar element method has already been used in the context of nonconforming fluid-structure interaction problems, see e.g. [13–17]. In [18] a dual mortar method was used with discrete Lagrange multipliers that are constructed on a biorthogonality relation with the primal shape functions at the fluid-structure interface. Besides the mortar element method, other coupling strategies have been proposed in the framework of partitioned solution schemes for fluid-structure interaction problems, see [19–21] and references therein.

In our spatial simulation settings we allow the fluid computational grid and/or the fluid finite element discretization to be nonconforming with the structural one at the interface. Even worse, the two interfaces could be geometrically nonconforming, a situation that arises when the two subdomains are triangulated independently. In such nonconforming cases, the kinematic and dynamic coupling conditions between the fluid and structure domains are imposed at the interface by the INTERNODES method. One distinguishing feature of INTERNODES is that it makes use of two interpolants to carry out the transfer of information across the interface: one from master to slave and another one from slave to master. In our algorithm the structural domain is the master while the fluid domain is the slave. Then, we build up two Radial Basis Function (RBF) inter-grid operators, one Π_{sf} from master to slave, and another Π_{fs} from slave to master. We enforce the kinematic condition by equating the fluid velocity at the interface as the image through Π_{fs} of the temporal derivative of the structural displacement. The dynamic interface condition is instead enforced via a variational method wherein the strong form of the structural normal component of the Cauchy stresses is obtained as the image through Π_{sf} of the strong form of the normal component of the fluid stresses (the traction).

We solve the resulting nonlinear FSI problem using a monolithic scheme in which all the nonlinearities are treated implicitly. To cope with the high computational complexity of the three dimensional FSI problem, we use FaCSI, a block parallel preconditioner proposed in [7] for the coupled linearized FSI system obtained after space and time discretization. FaCSI exploits the factorized form of the FSI Jacobian matrix, a static condensation procedure to formally eliminate the interface degrees of freedom of the fluid equations, and the SIMPLE preconditioner for the matrix block generated by the space-time discretization of the unsteady Navier-Stokes equations.

As a first numerical example, we solve the fluid-structure interaction problem on a cylindrical geometry. We assess the accuracy of the INTERNODES method by performing a mesh convergence study using both nonconforming meshes and polynomial interpolation at the fluid-structure interface. Furthermore, we investigate the strong and weak scalability properties of FaCSI using nonconforming discretizations. We compare the results obtained with those of the fully conforming case. We show that FaCSI yields almost the same scalability performance regardless the use of conforming or nonconforming discretizations between the fluid and the structure at their interface. As a second example, we address a large-scale simulation of blood flow in a patient-specific arterial bypass: we show that the results obtained using nonconforming discretizations (fluid velocity, wall shear stress and solid displacement) are in good