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Fluid–structure partitioned procedures based on Robin transmission conditions

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Abstract

In this article we design new partitioned procedures for fluid–structure interaction problems, based on Robin-type transmission conditions. The choice of the coefficient in the Robin conditions is justified via simplified models. The strategy is effective whenever an incompressible fluid interacts with a relatively thin membrane, as in hemodynamics applications. We analyze theoretically the new iterative procedures on a model problem, which represents a simplified blood-vessel system. In particular, the Robin–Neumann scheme exhibits enhanced convergence properties with respect to the existing partitioned procedures. The theoretical results are checked using numerical experimentation.
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1. Introduction

In the last three decades, there has been an increasing interest in the simulation of fluid–structure interaction (FSI) problems that appear in several engineering and life science applications. We consider in this work the situation of an incompressible Newtonian fluid interacting with a relatively thin structure. Such situation appears for instance in hemodynamics applications when studying the interaction between blood and arterial wall. The numerical approximation of this type of heterogeneous systems is challenging. They are coupled and highly nonlinear problems with the following peculiarities:

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(1) The position of the fluid–structure interface is an unknown of the coupled problem. It introduces a geometrical nonlinearity.
(2) The convective term of the fluid problem is nonlinear and, in case of using an ALE formulation (introduced in Section 2), also depends on the velocity of the fluid domain.
(3) The fluid and structure subproblems are coupled through transmission conditions which state the continuity of velocity and normal stresses on the fluid–structure interface.

In this paper, we focus on algorithms based on subsequent solutions of fluid and structure sub-problems (*partitioned procedures*). Every sub-problem is solved separately, allowing the reuse of existing codes/methods (modularity). This is the main reason why partitioned procedures are so popular, see, e.g, [17,2,15,11,13].

In order to enforce continuity of velocity and normal stresses at the interface (condition (3)) one could consider loosely coupled strategies, which solve the fluid and the structure only once (or just few times) per time step and do not satisfy exactly the coupling transmission conditions. As a consequence, the work exchanged between the two sub-problems is not perfectly balanced and this may induce instabilities in the numerical scheme. For example, it was shown in [3] (see also [10]) that an explicit coupling is unstable in those applications where the added mass effect is important, as in hemodynamics. Alternatively, one can treat implicitly (strongly) the coupling conditions at each time step, obtaining the solution of the fully coupled, monolithic system of nonlinear equations. Several strategies have been proposed for the treatment of the nonlinearity. In particular, one could consider Picard or Newton iterations over the nonlinear FSI system, to handle both nonlinearities (1) and (2) (*implicit* strategy, see, e.g. [15,8]), or treat the interface position and the convective term in an explicit way by extrapolation from previous time steps (*semi-implicit* algorithm, see, e.g. [7,16,1]). In this way, no iterations are needed within each time step.

Whatever strategy is adopted, a sequence of linearized FSI problems (implicitly coupled through condition (3)) has to be solved. Each of these problems can then be solved in a partitioned way via sub-iterations between the fluid and structure sub-problems until convergence. Several iterative procedures have been investigated so far, see e.g. [20,5,13]. In all these approaches, the work exchanged between the two sub-problems is perfectly balanced in each time step and the numerical scheme is stable. The price to pay is a relatively large number of sub-iterations, particularly in those cases where the added mass is important. Up to now, the computational cost remains extremely high.

The need to reduce the computational cost for those fluid–structure simulations where it is necessary to treat implicitly the transmission conditions has motivated this work. In particular, we start from the Dirichlet–Neumann (DN) partitioned procedure, in which the fluid problem is solved with a Dirichlet boundary condition at the interface (the structure velocity at the previous sub-iteration) and the structure with a Neumann boundary condition at the interface (the fluid normal stress just computed). This is the standard nomenclature for partitioned procedures: the first kind of transmission conditions refers to the fluid sub-problem while the second one refers to the structure sub-problem. This scheme is very easy to implement, yet, as shown in [3], it often needs a large relaxation to converge and a quite high number of iterations when fluid and structure densities are comparable.

This paper proposes new partitioned procedures based on Robin transmission conditions (linear combinations of the Dirichlet and Neumann transmission conditions), applicable to those FSI problems where the fluid and the structure have the same spatial dimension (say $d = 2, 3$). We introduce the general Robin–Robin algorithm, which generates a whole family of partitioned procedures that includes the classical DN and other new algorithms, such as the Robin–Dirichlet (RD), the Robin–Neumann (RN), the Dirichlet–Robin (DR) and the Neumann–Robin (NR) schemes. At the algebraic level, all these algorithms can be interpreted as suitable block Gauss–Seidel iterations on the monolythic FSI system.

The use of Robin transmission conditions is motivated by introducing simplified models for the fluid and the structure (see [3,16]). In particular, in [16] a simple membrane model for a thin $(d-1)$-dimensional structure has been derived, under the assumption of normal displacements. It was shown that this model can be embedded into the fluid problem leading to a Robin boundary condition. Hence, the original FSI problem is reduced to a single fluid problem. A similar approach was previously proposed in [9] for a fixed fluid geometry. For FSI problems in which the structure is d-dimensional, the previous considerations motivate the construction of iterative procedures based on Robin transmission conditions applied to the fluid sub-problem.

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