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A semi-implicit coupling technique for fluid–structure interaction problems with strong added-mass effect

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ABSTRACT

This paper is concerned with the numerical simulation of fluid–structure interaction problems involving an incompressible viscous flow and an elastic structure. A semi-implicit coupling technique is presented which strongly couples the added-mass term of the fluid (pressure stress) to the structure, while the remaining terms are only loosely coupled. A thorough numerical analysis is carried out to verify the accuracy of the proposed method by comparing its results to experimental data and other numerical results from the literature. The performance and accuracy of the proposed method are also compared against a fully implicit coupling technique. Numerical tests show that semi-implicit coupling significantly reduces the computational cost of the simulations without undermining either the stability or the accuracy of the results. The question of implicit or explicit coupling of the dynamic mesh step is addressed by evaluating its effect on the overall accuracy and performance of the semi-implicit method. The implicit coupling of the dynamic mesh step is found to slightly improve the accuracy, while significantly increasing the computational cost. Moreover a comparison is made on the performance of the semi-implicit method with different interface solvers.

1. Introduction

Fluid–structure interaction (FSI) refers to problems that deal with mutual interaction of fluid flow and a moving or deforming structure. On the one hand, fluid flow induces surface forces on the structure which make it move or deform. On the other hand, the movement of the solid boundary affects the fluid flow. A very wide range of applications is cited for FSI, ranging from civil engineering to biomechanics. An interesting example of FSI application in biomedical engineering is simulation of blood flow inside deformable vessels in human arterial system. The simulations may help improving the quality of artificial blood vessels and predicting the rupture of aneurysms during specific medical treatments or surgeries (e.g. Barker and Cai, 2010; Borghi et al., 2008). Another interesting application is predicting the flow-induced vibration on the submerged structures in offshore engineering (e.g. Shiels et al., 2001; Bearman, 2011).

Broadly, two different approaches could be used to solve FSI problems, called monolithic and partitioned methods. In monolithic approach one uses a single solver to solve fluid and structural governing equations simultaneously. As the equations are solved together, the interaction between the domains is inherently taken into account. The main advantage of the monolithic approach is the elimination of the need for any further coupling technique at the fluid–structure

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interface, which reduces the complexity of the problem. However, this approach requires using the same numerical methods to discretize and solve the fluid and structural equations, while they are different in nature and have their own considerations. This may cause monolithic methods to be less efficient or reliable in some applications (Degroote, 2013). Another disadvantage of the monolithic approach is its inability to exploit the already-developed fluid and structural solvers. Therefore, it requires a large software development effort and usually results in a less modular solver (Degroote, 2013; Hou et al., 2012).

Partitioned methods, on the other hand, use separate solvers for fluid and structural equations and adopt a coupling scheme to account for the interaction of the domains. The coupling scheme determines the order and frequency in which the fluid and structural equations should be solved. It also determines the manner of communication and information exchange between the two solvers which is essentially restricted to the fluid–structure interface. Partitioned approach alleviates both disadvantages of the monolithic schemes. It allows using the most adapted numerical methods for each sub-problem. These methods are previously tested and verified on diverse cases which greatly increases the reliability of the FSI simulations. It also enables the use of the previously developed solvers for fluid and structural equations which saves a large development effort and increases modularity of the software. However, partitioned approach introduces a new challenge to the problem, i.e. the coupling between the two solvers (Degroote, 2013; Hou et al., 2012).

Partitioned methods are further divided into explicit (or loosely coupled) and implicit (or strongly coupled) schemes. In an explicit coupling method, the fluid and structural equations are solved in sequence and only once at every time step. Consequently, explicit methods do not satisfy the exact coupling condition at the fluid–structure interface. The most basic explicit scheme is the conventional serial staggered method (Lesoinne and Farhat, 1998). Implicit methods, in contrast, enforce the equilibrium condition at the interface by means of coupling iterations between the fluid and structural solvers at each time step. Fixed-point (Gauss–Seidel or Jacobi) iterations (Degroote, 2013; Küttler and Wall, 2008) and Newton-based methods (Michler et al., 2005; Fernández and Moubachir, 2005; Gerbeau and Vidrascu, 2003) are the most commonly used techniques to carry out the FSI coupling iterations. Vector extrapolation methods have also been used for this purpose (Kuttler and Wall, 2009).

Explicit methods work well for aeroelastic simulations and problems involving compressible flows (Farhat et al., 2006; Van Brummelen, 2009). However they are unstable for a wide range of problems, especially ones with incompressible flow and low solid/fluid density ratios (values close to one). The instability is regardless of the time step size or discretization schemes for each domain. It is inherent to the coupling method and is often called "added-mass effect". The instability rises due to the fact that fluid forces in the explicit coupling depend upon a predicted displacement of the structure, rather than the correct one. As the structure moves, it has to accelerate the bulk of the fluid around it as well. Thus, part of the fluid acts as an extra mass in the structural dynamics system—given rise to the name added-mass effect. This effect is particularly strong when densities of the fluid and the structure are similar. For any loosely coupled method there is a density ratio limit that the method would suffer instability beyond it (Causin et al., 2005; Förster et al., 2007). While added-mass effect causes instability in the loosely coupled schemes, it deteriorates convergence of the strongly coupled methods. Thus, a FSI problem with strong added-mass effect is also challenging for implicit methods, as it requires many coupling iterations to converge at each time step (Causin et al., 2005; Förster et al., 2007).

Implicit methods provide stable solution for FSI problems with strong added-mass effect, of which explicit methods are incapable. However, performing several coupling iterations, i.e. solving the complete system of governing equations several times per time step, requires significantly higher computational resources. To alleviate this, Fernández et al. (2007) proposed a semi-implicit coupling technique in which they used a projection method to solve the fluid equations and only implicitly coupled the projection step to the structure. Therefore the pressure stress term of the fluid is strongly coupled to the structure. It is argued that the pressure stress term is the main contributor to the added-mass effect and coupling this term explicitly will cause numerical instability (Causin et al., 2005). By implicit treatment of the added-mass term (pressure stress), the semi-implicit method maintains the favorable stability of the implicit schemes, while explicit treatment of the other terms helps avoiding excessive computational cost (Fernández et al., 2007). A very similar method was also proposed by Breuer and Münsch (2008) and Breuer et al. (2012) to solve FSI problems with turbulent flow. An analogous idea is present in the hybrid monolithic-partitioned method of Grétarsson et al. (2011) for FSI problems with compressible flow. It strongly couples the fluid pressure and solid velocity by solving them implicitly in a monolithic manner, while the remaining terms are loosely coupled in a partitioned manner. Other semi-implicit methods are also reported in the literature which share the same basic idea, e.g. Astorino et al. (2009) and He et al. (2017).

Despite receiving attention from researchers, semi-implicit coupling technique is far from perfect. Many of the reported methods in the literature lack modularity and simplicity. Moreover most of the reported methods are only tested in a specific type of FSI problems and their robustness in dealing with different types of FSI problems is not evaluated. Besides, there are many unaddressed questions concerning different aspects of the semi-implicit coupling methods that require more work and attention. Some semi-implicit methods in the literature implicitly couple the dynamic mesh step of the fluid (Breuer and Münsch, 2008; Breuer et al., 2012), while others only explicitly couple it (Fernández et al., 2007; Astorino et al., 2009; He et al., 2017). However, to the best of our knowledge, there has been no study that evaluates the effect of this modification on the overall performance and accuracy of the semi-implicit coupling method.

In this work, we follow a semi-implicit approach to develop an efficient coupling technique for FSI problems with strong added-mass effect. We also try to address some of the open questions concerning semi-implicit methods. The main improvements and advantages of the proposed method are as following.