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A SIMPLE-based monolithic implicit method for strong-coupled fluid–structure interaction problems with free surfaces☆

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Abstract

A SIMPLE-based implicit method (SBMIM) for the strong coupling of fluid and structure is proposed. The SBMIM solves the Navier–Stokes (NS) equations of fluid by using a modified SIMPLE algorithm, which takes into account the structure governing equation. The free surfaces are reconstructed using the volume of fluid method (VOF), and the structure equation, embedded into the fluid solver, is processed with the widely used finite element method (FEM). We validate SBMIM by performing numerical simulations of a dam-breaking issue, a tank sloshing problem, and the free oscillation of a wash bulkhead in a liquid tank, and making comparisons against experimental measurements, theoretical results as well as other numerical solutions. The SBMIM is proved to be stable and robust under extreme simulation circumstances, and is applied to the strong coupling of wave impact on deck structure.

Keywords: SIMPLE-based monolithic implicit method; Fluid–structure interaction; Hydroelastic slamming; Hydroelastic vibration; Rogue wave impact

1. Introduction

With the rapid development of computer technology and an ever increasing availability of computational resources, the coupled computation of multi-physics has become a reality. Being a subclass of multi-physics [1], the fluid–structure interaction (FSI) has raised much attention during decades, due to its great relevance to many engineering branches. These branches, to name but a few, range from hydroelastic dynamics [2–4], parachute dynamics [5,6], hemodynamics [7–9], and aeroelastic dynamics [10,11].

FSI problems, depending on their inherent mechanisms, could be divided into two categories. For the first category, the fluid and structure exist in separate domains, and the interaction happens on their contact surface. This category

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could be found in many realistic engineering issues, for instance, the coupled wave–ship (or ocean platform) motion and the oil–pipe oscillation. For the second category, the structure (or fluid) is mixed with the fluid (or structure) domain, and no obvious interface could be found. Under this condition, the fluid and structure could not be treated in a separate way, but in a whole coupling system whose constitutive relationship is different from the one of either fluid or structure. Typically, seepage flow belongs to the second category. In this article, we are concerned about FSI issues of the first category.

Zienkiewicz and Bettess [12] divided the first-category FSI issue into 3 types: large relative motion between fluid and structure, impulsive short-time interaction, and long-term interaction. Area elastic flow around wings, vortex-induced vibration and turbine flow are typical cases of the first type; wave slamming and underwater explosion [13–15] belong to the second type; and hydroelastic motion of ships or marine structures under ocean waves belongs to the third type. Since the nature of the three types is inherently different, researchers are interested in different physical qualities. To be specific, the pressure and deformation in the vicinity of the contact surface are of interest for the impulsive short-time interaction, whereas the global response of the coupled system is much concerned about for the long-term interaction. Due to the diversification of FSI problems, various approaches have been proposed.

Generally, a widely used approach is the so-called partitioned scheme [16]. A partitioned approach solves the fluid and structure equations in separate solvers, connecting the existing fluid and structure solvers in a certain manner with minimal changes. The partitioned approach is attractive from the computational point of view, as the researchers can focus their minds on the coupling iteration algorithm, rather than the isolated fluid approach or structure approach. Besides, the partitioned method could make the best use of the existing solvers, which are treated as black-boxes in the coupled system. However, the simulation efficiency could be limited, as the fluid and structure are solved individually. Even if both the fluid variables and the structure variables of the current time step have been obtained, the entire time integral of the coupling system should not advance unless the interaction condition is satisfied. This means the fluid and structure are repeatedly solved in one time step, which is usually very time-consuming.

For unsteady FSI problems, various time advancing algorithms have been developed, i.e., the explicit, implicit and semi-implicit method [2]. During simulation, an explicit algorithm does not meet all the coupling conditions simultaneously. For example, at one time step, the continuity of the fluid velocity holds, but the stress or velocity continuity across the fluid–structure interface is violated. The explicit algorithms are simple, and have been successfully applied to some aeroelastic problems [17]. On the contrary, at each time step of an implicit algorithm, both the fluid/structure equations and the continuity condition of the interface pressure and velocity should be satisfied, often using iterative methods. This can be done using the Newton or quasi-Newton methods [1,18]. The semi-implicit approach is a compromise of the former two algorithms. Though being efficient, the explicit or semi-implicit algorithms are sometimes unstable, especially for FSI problems with strong added mass effects [16]. Even if the implicit algorithms could improve the solution stability to some extent, it is still a challenge to simulate transient FSI issues with extreme added mass effects, without introducing many assumptions and simplifications.

In this paper, we propose a SIMPLE-based monolithic implicit method (SBMIM) for FSI problems of the first category, with complex free surface flows. SBMIM could effectively simulate both transient and long-term FSI problems with extreme added mass effects, without using many simplifications for the mathematical model. In addition, to improve the simulation efficiency, a monolithic strategy is adopted, which assembles the fluid and structure equations into a single system and solves them simultaneously for each iteration step [19,20], rather than a partitioned approach. The finite difference method (FDM) is employed for the discretization of NS model, and the volume-of-fluid (VOF) method is used for the capture of free surface. The structure model, embedded into the fluid solution, is discretized with the finite element method (FEM). The traditional SIMPLE algorithm for NS model is modified, taking into account the structure equation, which is modified considering the added damping effect of the fluid. With good stability, SBMIM could be applied to transient FSI problems under extreme conditions (i.e., the 2nd type problem in paragraph three), for instance problems characterized by impulsive load or velocity. The simulation results are proved to be reliable, by comparisons against experimental records, theoretical solutions and other numerical results.

The content of this paper is organized as follows. In Section 2, the article starts with the governing equations applied to model the FSI system. Section 3 presents an introduction to the fluid and solid solver. Section 4 gives a detailed discussion on the SBMIM, and gives a flowchart of the monolithic approach procedure. In Section 5, we provide validations of SBMIM, by performing simulations of various issues and making comparisons with existing results. Section 6 gives a realistic application of SBMIM, by studying a Japan rogue wave impact on a deck structure. The major conclusions of this work are reported in Section 7.