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An Efficient Parallel/Unstructured-Multigrid Implicit Method for Simulating 3D Fluid-Structure Interaction

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Abstract. A finite volume (FV) method for simulating 3D Fluid-Structure Interaction (FSI) is presented in this paper. The fluid flow is simulated using a parallel unstructured multigrid preconditioned implicit compressible solver, whist a 3D matrix-free implicit unstructured multigrid finite volume solver is employed for the structural dynamics. The two modules are then coupled using a so-called immersed membrane method (IMM). Large-Eddy Simulation (LES) is employed to predict turbulence. Results from several moving boundary and FSI problems are presented to validate proposed methods and demonstrate their efficiency.

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Key words: Finite volume method, moving boundary, fluid-structure interaction, unstructured multigrid, computational structural mechanics, immersed membrane method, large-Eddy simulation.

1 Introduction

The simulation of fluid flows with arbitrarily moving solid/elastic bodies is one of the challenges in computational fluid dynamics (CFD). The development of accurate, robust and efficient methods that can tackle this problem would provide a powerful tool to solve many practical engineering problems. In recent years significant research efforts have been devoted to the development of numerical models for studying moving boundary problems based on the finite volume and finite element methods. Luo and Pedley [1–3] performed a time-dependent simulation of a coupled flow-membrane problem, using

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the Arbitrary Lagrangian Eulerian (ALE) method together with a spine scheme to treat a compliant wall moving in its wall normal direction in a channel. Zhao *et al.* [4, 5] have also proposed a new dynamic mesh scheme to simulate an arbitrarily moving elastic wall in a similar channel based on the ALE. Gaitonde [6,7] developed a moving mesh method for the computation of compressible viscous flow past moving aerofoils. A sequence of body conforming grids and the corresponding grid speeds were required, where the inner and outer boundaries of the grids moved independently. The required grids and their velocities were found by using a transfinite interpolation technique. Heil [8] studied a three-dimensional steady Stokes flow in an elastic tube using the ALE, which was described by non-linear shell equations. Only the final equilibrium state was presented because the flow was steady. Lefrancois *et al.* [9] developed a finite element model for studying fluid-structure interaction and an ALE formulation was used to model the compressible inviscid flow with moving boundaries with large deformation. It is observed that all the works reported have mostly relied on the costly grid regeneration method to capture large movements of the boundary in the flow field, whist the less costly dynamic grid method is believed to be unable to handle large boundary and mesh deformations.

An alternative to the ALE is the Eulerian method, where the computational mesh is fixed without deformation or movement. The group of Eulerian methods includes Immersed Boundary (IB) method and Fictitious Domain (FD) method *etc*. Peskin *et al.* [10] proposed the IB method to simulate the motion of human hearts and heart valves. At its early stage, the IB method could not consider the inertial effect of the structure because the dynamic equation of the structure was not used to calculate its movement. In their recent work [11], Zhu and Peskin did consider the inertial effect by taking the structure's (a soap film) mass into account. The IB method has been applied to a wide range of problems, mostly in bio-fluid dynamics, including blood flow in the human heart [12], platelet aggregation during blood clotting [13, 14] and the motion of flexible pulp fibers [15]. Generally speaking, Eulerian methods are relatively less-complicated techniques by using fixed fluid meshes, which reduce the computational costs for mesh treatment. However, the above Eulerian methods do not allow for 'jump' conditions between two sides of immersed thin structures, because the flow conditions on structural boundaries are smoothed over several mesh cells across or near the immersed structures due to the fact that the structures are considered as internal conditions in the flow field and source terms are distributed to nearby fluid nodes for constraining the flow field. Recently Zhao *et al.* [16] has also developed a so-called Immersed Object Method (IOM) with overlapping unstructured grids for general Fluid-Structure-Interaction (FSI) simulation. The main idea of the method is that the fluid covered by immersed objects is assumed to be frozen and moves like a solid, whose kinematics is enforced by adding source terms to the momentum equations. Overlapping grids are wrapped around the objects and the boundary conditions for the overlapping grids are transferred from the Eulerian grid to the overlapping grids for further computation on the overlapping grids, in order to capture the fine details of boundary lays over the moving objects.

Tai and Zhao [17] parallelized an incompressible Navier-Stokes solver based on the