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A sliding mesh technique for the finite element simulation of fluid–solid interaction problems by using variable-node elements

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ABSTRACT

A new sliding mesh technique for finite element simulation of fluid–solid interaction problems with large structural motions is presented in this paper. Fluid meshes surrounding a solid can slide each other to accommodate a rotational motion of the solid, and a fluid mesh outside the sliding interface can translate through a background fluid mesh. Because of relative motions of sliding fluid meshes and independently designed fluid and solid meshes, non-matching meshes occur at their common interfaces. The non-matching meshes are connected by using variable-node elements which guarantee the continuity, the compatibility and the force equilibrium across the interfaces.

1. Introduction

Finite element (FE) analysis of fluid–solid interaction (FSI) with large structural motions is one of challenging problems in computational mechanics. Some computational difficulties have been encountered and investigated for the FE simulation of fluid flows with structural interactions. Among them, fluid mesh motions in FSI analysis based on an Arbitrary Lagrangian–Eulerian (ALE) formulation should follow the movement of solid boundaries, and the choice of appropriate fluid mesh movement is important to preserve acceptable element geometries in the fluid mesh when a solid undergoes large motions. In particular, it is not a simple task to satisfy interface boundary conditions along the FS interface when a solid is moving freely in a fluid domain. Accordingly, an efficient method is needed to prevent fluid mesh distortion near the FS interface because a large motion of the solid can lead to a distorted or tangled fluid mesh following the solid boundary.

Some techniques have been proposed for handling fluid mesh movement [1–3] and a complex motion of the FS interface [4,5]. As an intrinsic approach, sliding mesh techniques have been tackled to solve the moving interface problems by many researchers. Gartling [6] proposed a sliding mesh technique by using the multi-point constraint method; some or all of the dependent variables from the slave mesh are constrained to be the interpolants of the variables in the master mesh. Sieber and Schäfer [7] introduced a sliding mesh technique by way of dynamic mesh scheme which has the overlapped ghost cells on the sliding interface. The values in the ghost cells are found by a linear interpolation between two neighboring elements overlapping the inner cells. Behr and Tezduyer [8] used the shear slip mesh update method to construct the sliding mesh on the interface. This method is accomplished by remeshing the elements in a thin zone of the mesh to undergo shear deformation. To deal with a complex motion of the FS interface, many researchers have used adaptive remeshing techniques. However, adaptive remeshing techniques are not only time-consuming but also require field variables remapping between source and target meshes over the entire computational domain. Peskin [9] proposed the immersed boundary method to study flow patterns around heart valves. The immersed boundary method has been extensively studied and applied to a wide variety of FSI problems [10–12]. This method solves the background fluid equations with a fixed Eulerian mesh, and tracks a moving boundary to impose FSI force and fluid velocity on the immersed boundary. Since the solid domain described as a fiber network cannot occupy volume in the fluid domain, this assumption has a limitation in representing an arbitrary movement of submerged solid in a fluid domain. Glowinski et al. [13] studied the interaction between fluid and rigid solid by fictitious domain method. In their method, the rigid solid is represented by a fictitious fluid with the same density

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and viscosity as the surrounding fluid. Wang and Liu [14] proposed the immersed FE method which extends the immersed boundary method adopting FE formulation for solid and fluid domains. As an extension of the partition of unity method to arbitrary discontinuities, the extended finite element method (XFEM) has been applied to solve FSI problems. Wagner et al. [15] applied the XFEM to Stoke flows with rigid particles by using analytical solutions as the partition of unity enrichment. Gerstenberger and Wall [16] applied the XFEM to solve FSI problems by using Heaviside function as the enrichment. Although the XFEM has a great ability to represent the FS interface without fluid mesh movement, a method for coupling non-matching meshes at the FS interface is still required to impose the interface conditions.

Sliding mesh algorithms require a method to join dissimilar meshes along the sliding interface. Many researches [17–20] have used Lagrange multiplier and projection methods to connect non-matching meshes. Jaiman et al. [21] proposed a projection method for load transfer along the non-conforming interface, and Park et al. [22] introduced the intermediate reference frame by localized Lagrange multipliers, which can be regarded as an independent interface field. The mortar method as an efficient approach using interface Lagrange multipliers has been developed to weakly impose continuity of the velocity field along the non-conforming interface between fluid and solid domains [23,24]. Casadei and Patapov [25] proposed a generalized velocity compatibility condition along the non-matching meshes, which enforces the fluid nodes along the FS interface to follow the motion of a solid. Cavagna et al. [26] proposed a mesh-free moving least square (MLS) method to transfer nodal velocities and forces at the FS interface through a conservation interpolation matrix which preserves the conservation of momentum and energy transfer between dissimilar fluid and solid meshes. The accuracy of load transfer and the compatibility of displacements or velocities are not guaranteed when interpolation or projection methods are used to transfer information along the FS interface with non-matching meshes. Accordingly, an effective method for connecting non-matching meshes is required to ensure the interface conditions of displacement compatibility and traction equilibrium along the FS interface.

In general, it is not straightforward to satisfy interface conditions such as compatibility, continuity and completeness conditions between non-matching meshes in FE simulations of FSI problems. Kim [27] introduced the interface element method (IEM) to couple the non-matching meshes without any additional process such as Lagrange multiplier technique and projection of information between dissimilar meshes. Cho et al. [28] and Lim et al. [29–32] extended the IEM to variable-node elements (VNEs) by adding nodes on arbitrary sides of FEs with no harm to the reproducing property and the interface conditions. Recently, Kim [33] used this approach to connect the FS interface with non-matching meshes between fluid and solid domains. While this method with fluid nodes attached to solid surfaces leads to a severe fluid mesh distortion or an element entanglement in FE simulations of FSI problems with large structural motions, here we propose an efficient technique of sliding interfaces to provide a good quality mesh in a fluid domain.

In this study, we develop a novel method to simulate FSI problems with a freely moving solid in a fluid domain. A motion of an immersed solid is decomposed into rotational and translational motions, and the fluid domain is discretized into three independent meshes defined as "rotational fluid mesh", "translational fluid mesh" and "background fluid mesh". The solid domain is included in the rotational fluid mesh, which is again contained in the translational fluid mesh that moves through the background fluid mesh. Rotational and translational motions of a solid are imposed on the rotational fluid mesh and the translational fluid mesh, respectively. A relative motion of fluid meshes at the boundary of the rotational fluid mesh requires a special technique to connect non-matching meshes at the sliding interface. In addition, independently designed fluid and solid meshes due to different resolution requirements should be coupled properly at the FS interaction. We use VNEs to accommodate the change of nodal arrangements and positions in elements bordering on the sliding interface. Since VNEs satisfy the compatibility, continuity and completeness conditions along the non-conforming interfaces, a seamless connection of non-matching fluid meshes sliding each other can be achieved. Moreover, the FS interface between independently designed meshes in fluid and solid domains can also be connected by using VNEs. The field variables can be transferred correctly through VNEs, and the connection by using VNEs guarantees the force equilibrium at nodes along the non-conforming interfaces. Consequently, the present method can be very effective to solve FSI problems with moving or rotating solids in a fluid.

2. Governing equations and discretizations

2.1. Governing equations

Since the fluid domain Ω_F deforms substantially during the FSI simulation with respect to the deformed solid domain, ALE formulation is used to describe the fluid flow with deformable domain. The ALE forms of the momentum conservation law and the continuity equation for incompressible flows can be written as

$$\rho_F\left(\frac{\partial \boldsymbol{v}_F}{\partial t} + (\boldsymbol{v}_F \otimes \nabla)\cdot(\boldsymbol{v}_F - \boldsymbol{v}_F^m)\right) = \rho_F \boldsymbol{g} + \nabla\cdot\boldsymbol{\sigma}_F \text{ in } \Omega_F \quad (1)$$

$$\nabla\cdot\boldsymbol{v}_F = 0 \text{ in } \Omega_F \quad (2)$$

where ρ_F, $\boldsymbol{g}$, $\boldsymbol{v}_F$, $\boldsymbol{v}_F^m$ and $\boldsymbol{\sigma}_F$ denote the fluid density, the volume force, the velocity of fluid particles, the velocity of fluid mesh and the fluid stress tensor, respectively. The constitutive equation for Newtonian fluids is written as

$$\boldsymbol{\sigma}_F = -p\mathbf{I} + \mu(\nabla\otimes\mathbf{v}_F + \mathbf{v}_F\otimes\nabla) \text{ in } \Omega_F \quad (3)$$

where μ and p indicate the fluid viscosity and the pressure, respectively. The conservation of momentum in the solid domain Ω_S can be expressed as

$$\rho_S\frac{\partial^2 \boldsymbol{u}_S}{\partial t^2} = \rho_S\boldsymbol{b} + \nabla\cdot\boldsymbol{\sigma}_S \text{ in } \Omega_S \quad (4)$$

where ρ_S, $\boldsymbol{b}$, $\boldsymbol{u}_S$ and $\boldsymbol{\sigma}_S$ denote the solid density, the body force, the displacement of solid particles, and the solid stress tensor, respectively. A rate-type constitutive equation is considered for the solid domain as follows:

$$\dot{\boldsymbol{\tau}}^J = \boldsymbol{C} : \dot{\boldsymbol{\varepsilon}} \quad (5)$$

where $\dot{\boldsymbol{\varepsilon}}$ and $\boldsymbol{C}$ are the rate of strain tensor and the instantaneous stiffness tensor, respectively. Furthermore, $\dot{\tau}^J$ means the Jaumann objective rate of the Kirchhoff stress. This equation is known to depict an isotropic constitutive behavior of linear elastic bodies undergoing finite rotations with small elastic strains when $\boldsymbol{C}$ is chosen to be the constant linear stiffness tensor for isotropic elastic materials.

2.2. Weak formulations and interface conditions

The computation of the incompressible fluid requires the stabilized FE formulation to overcome the numerical instability caused by advection-dominated condition and inappropriate combination of interpolation functions for the velocity and the pressure. The stabilization for the fluid flow is achieved by the streamline-upwind Petrov–Galerkin (SUPG), the pressure stabilized Petrov–Galerkin