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A particle-element contact algorithm incorporated into the coupling methods of FEM-ISPH and FEM-WCSPH for FSI problems

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ABSTRACT

Numerical simulation of FSI problems is one of the most important topics in computational fluid dynamics. In this paper, a particle-element contact algorithm is incorporated into coupling methods of FEM-ISPH and FEM-WCSPH for solving FSI problems. The objective of contact algorithm is to adjust positions and normal velocities of slave particles and master nodes by conservation of linear momentum and angular momentum. Compared with particle–particle contact algorithm, which is based on contact force of Monaghan boundary condition, the calculation of contact force is not required in the present contact algorithm. Moreover, correction algorithms of Yildiz et al. are used for both WCSPH and ISPH to treat noises in fluid field and improve the accuracy of numerical simulations. Numerical examples investigate the comparison of particle-element contact algorithm and commonly used particle–particle contact algorithm, and it indicates that the present contact algorithm is effective for FSI problems.

1. Introduction

Fluid–Structure Interaction (FSI) is an important problem in computational mechanics. For example, the drive to model nonlinear flutter response has spawned in computational aeroelastics (Bennet and Edwards, 1998). The response of cardiac, arterial and respiratory systems is crucial in the computational biomechanics (R. van Loon and F. N. van de Vosse, 2010; Taylor and Figueroa, 2009). In recent years, many numerical methods have been proposed for these FSI problems with complex geometry (Oxtoby and Malan, 2012). Most of these numerical methods have been proposed for FSI problems by Eulerian approach in fluid medium and Lagrangian approach in solid medium (Morinishi and Fukui, 2012), such as Arbitrary Lagrangian Eulerian (ALE) method (Hirt et al., 1974; Donea et al., 1982). However, ALE method is time consuming to track the moving interface. Because Lagrangian meshless methods can naturally handle moving interface with large deformations of fluid, pure Lagrangian method may be attractive for FSI problems.

Smoothed Particle Hydrodynamics (SPH) is a Lagrangian meshless method, which has been originally developed by Lucy (1977), Monaghan and Gingold (1983), Gingold and Monaghan (1977). It has been successfully employed in engineering problems, such as astrophysics, fluid mechanics, solid mechanics and etc. Lucy (1977), Monaghan and Gingold (1983), Gingold and Monaghan (1977), Messahel and Souli (2013) There are two principal variants of SPH to impose the incompressibility constraint of fluid, namely Incompressible SPH (ISPH) and Weakly Compressible SPH (WCSPH) methods. ISPH is based on velocity-divergence-free projection method (Cummins and Rudman, 1999). In this method, pressure term in the conservation of momentum equation is obtained by solving a pressure Poisson equation. Velocity-divergence-free projection method has been reported to suffer from the accumulation of density error (Pozorski and Wawreńczuk, 2002). Hu and Adams (2007) have proposed a stable algorithm to obtain velocity-divergence-free field and constant density by solving the Poisson equation twice in each time step. Furthermore, Artificial Particle Displacement (APD) technique has been employed to treat the particle clustering and accumulation of density errors (Xu et al., 2009; Lee et al., 2008). The scheme of APD can significantly improve accuracy by modifying the particle distributions without any further computational cost.

Compared with ISPH method, WCSPH is easy to program (Shadloo et al., 2012). In WCSPH, random oscillation of pressure is presented due to numerical noises. Lee et al., (2010) have illustrated that ISPH method produces more accurate pressure fields than the WCSPH method for FSI problems. However, Hughes and Graham (2010) have compared ISPH with WCSPH for free surface water flows, they have concluded that both WCSPH and ISPH can obtain the same accurate results. Shadloo et al. (2012) have applied APD to WCSPH and have compared it with ISPH, they have concluded that WCSPH can provide accurate results of pressure. Recently, Chen et al. (2013) have developed an improved WCSPH using Moving Least Square approach (MLS) for density re-

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initialization, and they have concluded that the improved WCSPH is more accurate and stable than ISPH for incompressible flows. Ozbulut et al. (2013) have combined the density correction algorithm, the APD algorithm and Monaghan's XSPH velocity variant algorithm for SPH method to improve accuracy of violent free surface flows.

For FSI problems, the pressure and viscous stresses of the fluid can cause a considerable deformation on the solid boundary, which in turn affects the pressure, velocity and stress in fluid. Because of the advantage of FEM for solving structural dynamics and SPH for simulating free-surface fluid dynamics, FEM has been coupled with SPH (FEM-SPH) to investigate FSI problems. FEM-SPH model was proposed by Attaway et al. (1994) to study on structure-structure impact problems. Zhang et al. (2011) have presented an alternative FEM-SPH model for the dynamic impact problem. FEM-SPH model has also been applied to fluid–structure impact problems by Vuyst et al. (2005) and to free-surface flow interaction with elastic structures by Groenenboom and Cartwright (2009), Fourey et al. (2010) and Yang et al. (2012). In their works (Attaway et al., 1994; Vuyst et al., 2005; Groenenboom and Cartwright, 2009; Fourey et al., 2010; Yang et al., 2012), the calculation of contact force is required and it is very sensitive to handle the interaction of interface. For particle–particle contact algorithm, Vuyst et al. (2005) and Yang et al. (2012) used contact potential or Monahan boundary condition to treat contact force in SPH.

In this paper, particle-element contact algorithm based on master–slave scheme is incorporated into the coupling methods of FEM-ISPH and FEM-WCSPH for solving FSI problems, which is originally proposed by Johnson and Stryk (2001) for explosion and impact problems. The advantage of this contact algorithm is that the contact force is not required in calculation. Moreover, in order to treat the noises in fluid field and to improve the computational accuracy of SPH, the correction algorithms proposed by Ozbulut et al. (2013) are used, i.e., the treatments of density correction, Monaghan's XSPH velocity variant and APD algorithms are used for WCSPH, the treatments of Monaghan's XSPH velocity variant and APD algorithms are used for ISPH. Finally, the present contact algorithm is verified and compared with commonly used particle–particle contact algorithm for FSI problems.

2. FEM formulations

In this work, the FEM model is based on updated Lagrangian formulations for large-deformation structure (Johnson et al., 1997). The principle of virtual power of FEM can be written as

$$\int_{\Omega} \frac{\partial(\delta v_i)}{\partial x_j}\sigma_{ji}\mathrm{d}\Omega - \int_{\Omega} \delta v_i \rho b_i \mathrm{d}\Omega - \int_{\Gamma_t} \delta v_i \bar{t}_i \mathrm{d}\Gamma + \int_{\Omega} \delta v_i \rho \ddot{u}_i \mathrm{d}\Omega = 0 \tag{1}$$

where δv_i is virtual velocity, x_j is the coordinate, σ_{ji} is Cauchy Stress tensor, b_i and $\bar{t}_i$ is body force and surface force, respectively. Furthermore Γ_t is the boundary of traction, and $\mathrm{d}\Omega$ is the area of element. The governing equation of Eq. (1) is constructed in the current configuration.

Using the shape function of polynomial interpolation, Eq. (1) becomes

$$\int_{\Omega} \frac{\partial N_I}{\partial x_j}\sigma_{ji}\mathrm{d}\Omega - \int_{\Omega} N_I \rho b_i \mathrm{d}\Omega - \int_{\Gamma_t} N_I \bar{t}_i \mathrm{d}\Gamma + \int_{\Omega} N_I \rho N_J \ddot{u}_{iJ} \mathrm{d}\Omega = 0 \quad \forall\, I \notin \Gamma_v \tag{2}$$

where Γ_v is the boundary of velocity in the current configuration, and N_I is the shape function of node I. Then, FEM formulation is given as

$$M_{IJ}\ddot{u}_{iJ} + f_{iI}^{\text{int}} = f_{iI}^{\text{ext}} \qquad \forall\, I \notin \Gamma_v \tag{3}$$

$$f_{iI}^{\text{int}} = \int_{\Omega} \frac{\partial N_I}{\partial x_j}\sigma_{ji}\mathrm{d}\Omega \tag{4}$$

$$f_{iI}^{\text{ext}} = \int_{\Omega} N_I \rho b_i \mathrm{d}\Omega + \int_{\Gamma_t} N_I \bar{t}_i \mathrm{d}\Gamma \tag{5}$$

$$M_{IJ} = \int_{\Omega} \rho N_I N_J \mathrm{d}\Omega \tag{6}$$

where M_{IJ} is the mass matrix, f_{iI}^{ext} and f_{iI}^{int} is the vector of equivalent external force and internal force for the node I, respectively.

3. SPH formulations

In this paper, governing equations of incompressible fluid are the conservation of mass and linear momentum, which are expressed in Lagrangian form and given as following

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla\cdot\vec{v} = 0 \tag{7}$$

$$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\nabla p + \vec{g} + \upsilon_o \nabla^2 \vec{v} \tag{8}$$

Applying particle approximation of SPH, discretization of governing Equations can be written as

$$\frac{D\rho_i}{Dt} = \rho_i \sum_j \frac{m_j}{\rho_j}(\vec{v}_i - \vec{v}_j)\nabla_i W_{ij} \tag{9}$$

$$\frac{D\vec{v}_i}{Dt} = -\sum_j m_j\left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \prod_{ij}\right)\nabla_i W_{ij} + \vec{g} \tag{10}$$

where $\vec{v}$ is the velocity, p is the pressure, $\vec{g}$ is the acceleration of gravity, ρ is the density, m is the mass, and υ_o is the viscosity of fluid. W is smoothing kernel function with a smooth length h, and cubic Spline kernel function (Monaghan and Lattanzio, 1985) is used in this paper. $\prod$ is the Monaghan artificial viscosity (Monaghan, 1994), which is used to approximate the viscous stresses of fluid, and

$$\Pi_{ij} = \begin{cases} \dfrac{-\alpha_\pi \bar{c}_{ij}}{\bar{\rho}_{ij}} \dfrac{h\vec{v}_{ij}\cdot\vec{r}_{ij}}{\vec{r}^{\,2}_{ij}} & \vec{v}_{ij}\cdot\vec{r}_{ij} < 0, \\ 0 & \vec{v}_{ij}\cdot\vec{r}_{ij} \ge 0 \end{cases} \tag{11}$$

where α_π is the free parameter depending on problems, $\vec{r}$ is position vector, $\bar{c}_{ij} = (c_i + c_j)/2$ is the average speed of sound, $\bar{\rho}_{ij} = (\rho_i + \rho_j)/2$ is the average density, $\vec{v}_{ij} = \vec{v}_i - \vec{v}_j$ and $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ is the relative velocity and position of particles, respectively. The expression of viscous term is proposed by Morris et al. (1997)

$$(\upsilon_o \nabla^2 \vec{v})_i = \sum_{j=1}^{N} \frac{m_j(\upsilon_{oi} + \upsilon_{oj})\vec{r}_{ij}\cdot\nabla_i W_{ij}}{\rho_j(\vec{r}^{\,2}_{ij} + \eta^2)}\vec{v}_{ij} \tag{12}$$

where $\eta = 0.1h$ is a parameter to avoid zero denominator.