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Numerical modeling of dam-break flow impacting on flexible structures using an improved SPH–EBG method

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ABSTRACT

An improved coupling method of smoothed particle hydrodynamics (SPH) and element bending group (EBG) is developed for modeling the interaction of viscous flows with free surface and flexible structures with free and fixed ends. SPH and EBG are both particle methods which are appealing in modeling problems with free surfaces, moving interfaces and large deformations. SPH is used to model viscous fluid, while EBG is used to model flexible structure. Structure particles are also used as moving boundary for SPH, and the interaction of flexible structure with fluid is therefore modeled through the interaction of structure particles and fluid particles. A fixed-end treatment is introduced for flexible structures. A free surface treatment and a surface tension model are used for free surface flow. The improved SPH–EBG method is applied to simulate problems of dam break flow on flexible structures. The good agreement of presented numerical results with existing experimental and numerical results clearly demonstrates the effectiveness of the SPH and EBG coupling approach in modeling fluid–flexible structure interactions.

1. Introduction

There are many examples of fluid–structure interactions in nature, coastal and ocean engineering. How to accurately model the interaction of fluids and structures is of great importance both in engineering and scientific research. Numerical methods to model fluid–structure interactions have been developed for decades. If the deformation of a structure is very small, the structure is usually treated as a rigid structure. If the deformation of a structure is large, it should be considered in numerical simulations. Although the modeling of fluid–structure interactions has been studied for several decades, it is still a challenging work to model the interactions of fluids and flexible structures. The numerical difficulty in modeling fluid–flexible structure interaction is the treatment of moving interfaces and deformable boundaries. Due to the complexity of the problem, there are only a limited number of literatures describing the numerical modeling of flexible structures interacting with fluid flows (Hosseini and Feng, 2009; Idelsohn et al., 2008; Walhorn et al., 2005; Yu, 2005; Zhu and Peskin, 2003), and most of those numerical methods are based on mesh or grid. Walhorn et al. (2005) presented a space–time finite element method for fluid–structure interactions with level set method for free surfaces. Idelsohn et al. (2008) solved fluid–structure interactions using the particle finite element method. In order to model Newtonian fluid interacting slender bodies, a coupling method of fictitious domain and mortar element was developed (Baaijens, 2001). This method is suitable for complicated mesh movement in arbitrary Lagrangian–Eulerian (ALE) method. Antoci et al. (2007) simulated both fluid and structure using smoothed particle hydrodynamics (SPH) method.

A numerical method which can well model the interaction of a fluid with free surface and a structure with large deformation would be appealing in modeling fluid–flexible structure interactions. In this paper, an improved coupling method of SPH and element bending group (EBG) is developed for modeling the interaction of viscous fluid with free surface and flexible structure with large deformation.

SPH method is a Lagrangian meshfree particle method. It was first invented to solve astrophysical problems (Gingold and Monaghan, 1977; Lucy, 1977), and later extended to solve many other problems, especially fluid simulations (Breinlinger et al., 2013; Hu and Adams, 2007; Marrone et al., 2013; Morris et al., 1997). In SPH, a fluid is represented by a set of particles which move according to the governing equations of the fluid. Then the motion of the fluid is represented by the motion of the particles, and free surface or interface of multiphase flow moves with particles representing their phase defined at the initial stage. The meshfree nature of SPH method removes the difficulties due to large deformations since SPH uses particles rather than mesh as a computational frame to approximate related governing equations. Therefore, SPH is well suited for modeling fluid flows with free surfaces and moving interfaces.

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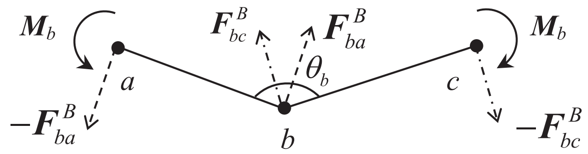

Fig. 1. An EBG is made of two adjacent line segments connecting three neighboring particles.

EBG technique can also be regarded as a particle method, and it was first proposed for modeling membrane structure which can be considered as an elastic shell (Zhou and Wagoner, 1995). Later it was extended to model red blood cell membrane (Hosseini and Feng, 2009; Tsubota et al., 2006). A flexible structure can also be modeled by EBG method. In EBG model, an EBG consists of two adjacent line segments connecting three neighboring particles. Except for the tension force, the bending moment needs to be considered when modeling the movement and deformation of a flexible structure. The bending moment on an EBG can be converted into pairs of forces acting on the neighboring particles. Hence the EBG method can be attractive in modeling the movement and deformation of flexible structures.

By coupling SPH with EBG, it is possible to model fluid–flexible structure interactions. The SPH method can be used to model viscous fluid flows, and the EBG method can be used to model the dynamic movement and deformation of flexible structures. Then the interaction of fluid and flexible structure can be modeled by the interaction of the neighboring fluid (SPH) and structure (EBG) particles. The idea of SPH–EBG coupling method was originally proposed by Hosseini and Feng (2009) to model red blood cell deformations in shear flows, and the reported numerical results demonstrate good consistence with the experimental observations. However, a red blood cell is a closed structure with no free end and no fixed end, and there is no free surface flow around it. Yang et al. (2014) extended SPH–EBG method to model a flexible fiber with two free ends immersed in a viscous flow. They studied the drag scaling law and bending modes of a flexible fiber centrally fixed in a viscous flow.

In the present work, the SPH–EBG method is extended to model the interaction of fluid with free surface and flexible structure with free and fixed ends. Some numerical techniques will be introduced for the SPH–EBG method, and these make the coupling method more powerful.

2. Numerical methodology

In SPH–EBG method, SPH is used to model fluid flow, and EBG is used to model flexible structure. In this section, the SPH and EBG methods will be introduced, respectively. Then the coupling of SPH and EBG will be described.

2.1. SPH method

The Navier–Stokes (N–S) equations are used for viscous fluid. The Lagrangian form of the N–S equations is written as follows

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\mathbf{u} \tag{1}$$

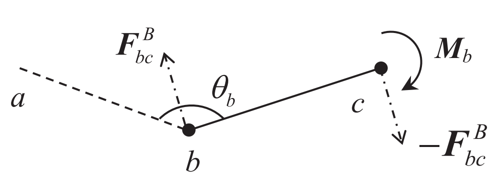

Fig. 2. Fixed end treatment. Assuming that there is a fixed line, *ab*, outside the fixed end *b*.

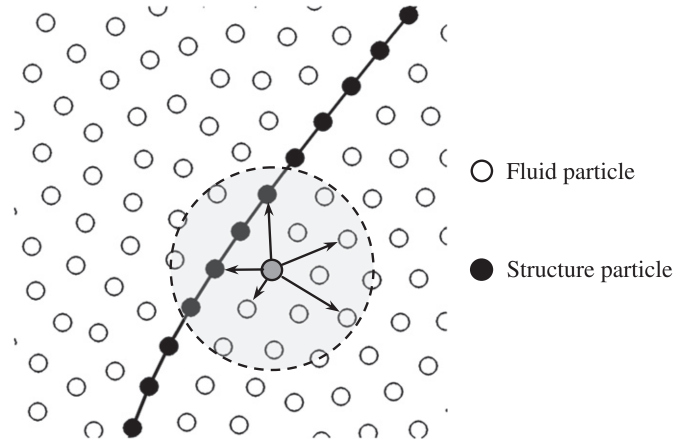

Fig. 3. Interaction of fluid and structure particles.

$$\frac{d\mathbf{u}}{dt} = \mathbf{g} - \frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2\mathbf{u} \tag{2}$$

where ρ is the fluid density, $\boldsymbol{u}$ is the fluid velocity, p is the fluid pressure, μ is the dynamic viscosity of the fluid, and $\mathbf{g}$ denotes the body force acting on the fluid.

In SPH method, a fluid is represented by a set of particles, which can move according to corresponding governing equations. Specifically, for any field variable, $A(\mathbf{r})$, which is a function of the spatial position $\boldsymbol{r}$, the value of function A at a certain point a whose position vector is $\boldsymbol{r}_a$ can be approximated by the following integral interpolation:

$$A(\mathbf{r}_a) = \int_{\Omega} A(\mathbf{r})W(\mathbf{r}_a - \mathbf{r}, h)dV \tag{3}$$

where $W(\mathbf{r}_a - \mathbf{r}, h)$ is a smoothing or kernel function, h is a smoothing length, dV is a differential volume element, and Ω is an integral domain. When representing a fluid domain with discrete SPH particles while the volume of each particle can be represented by m/ρ, the interpolation is approximated by a summation interpolation over particles:

$$A_a = \sum_b A_b W_{ab} \frac{m_b}{\rho_b} \tag{4}$$

where $W_{ab} = W(\mathbf{r}_a - \mathbf{r}_b, h)$, the indexes a and b denote labels of particles. The summation is taken over all particles, but in practice it is only

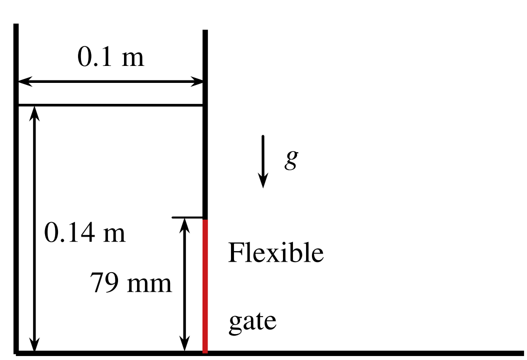

Fig. 4. Sketch of dam break with a top-fixed flexible gate.