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Development of a coupled level set and immersed boundary method for predicting dam break flows

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A B S T R A C T

Dam-break flow over an immersed stationary object is investigated using a coupled level set (LS)/immersed boundary (IB) method developed in Cartesian grids. This approach adopts an improved interface preserving level set method which includes three solution steps and the differential-based interpolation immersed boundary method to treat fluid–fluid and solid–fluid interfaces, respectively. In the first step of this level set method, the level set function ϕ is advected by a pure advection equation. The intermediate step is performed to obtain a new level set value through a new smoothed Heaviside function. In the final solution step, a mass correction term is added to the re-initialization equation to ensure the new level set is a distance function and to conserve the mass bounded by the interface. For accurately calculating the level set value, the four-point upwinding combined compact difference (UCCD) scheme with three-point boundary combined compact difference scheme is applied to approximate the first-order derivative term shown in the level set equation. For the immersed boundary method, application of the artificial momentum forcing term at points in cells consisting of both fluid and solid allows an imposition of velocity condition to account for the presence of solid object. The incompressible Navier–Stokes solutions are calculated using the projection method. Numerical results show that the coupled LS/IB method can not only predict interface accurately but also preserve the mass conservation excellently for the dam-break flow.

1. Introduction

Dam-break flows interacting with solid bodies are commonly observed in hydraulics and civil engineering [1,2]. Computational methods developed for simulating dam-break flows in a complex domain can be categorized into three classes: meshless, moving grid, and fixed grid methods. Meshless or meshfree methods such as the smoothed particle hydrodynamics (SPH) [3], moving particle semi-implicit (MPS) [4,5] methods have featured their remarkable flexibilities in handling interface deformation as well as fragmentation. These methods do not require grid structure, thereby alleviating a time consuming and troublesome mesh generation. However, due to the difficulty of coping with the Laplacian operator, application of a meshless method is limited normally to low Reynolds number flow simulation. In moving grid methods, classical body-fitted grid-based methods, which are used to discretize the governing equations in curvilinear coordinates that conform to physical boundaries, involve re-gridding mesh at each time step. It is well known that grid generation requires considerable manpower and computational time. In fixed grid methods [6–8], treatment of fluid–fluid interfaces and solid boundaries need to be taken into account when predicting an interface flow inside which there is a solid body. Solid boundaries and fluid–fluid interfaces may have unrestricted motions across the underlying fixed grid lines. These methods simplify the gridding requirements and have been applied to fixed curvilinear and unstructured grids. In this study, a coupled level set (LS)/immersed boundary (IB) method, which belongs to the fixed grid method, is chosen to simulate incompressible fluid flow over solid bodies of different shapes.

Level set method [9–15] is one of the popular fluid–fluid interface capturing methods. The level set method is a successful approach developed to model two-phase flows, especially for the case with a marked topological change. Given a level set function for the physical interface, both shape and its curvature of this interface can be easily transported and accurately calculated, respectively. Choice of a proper signed distance function for reshaping level set function and implementation of re-initialization

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procedure for the purpose of enhancing numerical stability are normally required while applying the level set methods. Level set method applied to predict interface suffers the problems of numerical dissipation and non-conserved mass. Many attempts have been made to cope with these two difficulties. The global mass correction equation [16,17] coupled with the first and second distance functions is used to preserve mass in time. In addition, for improving mass conservation using the level set method, one can also apply the hybrid method such as the coupled level set and volume of fluid (CLSVOF) method [18–21]. The other method known as the particle level set (PLS) method [22,23] combines the advantage of Lagrangian tracking methods owing to their simplicity and the efficiency embedded in level set method. It is also numerically possible to improve mass conservation by using the volume preserving level set method [24,25]. Volume preserving level set method uses high-order upwinding combined compact difference (UCCD) and high-order symplectic Runge–Kutta (SRK) scheme for the approximation of the spatial derivative term and the temporal derivative term shown in the level set equation, respectively. The conservative level set method [26,27] solves a conservative form of the LS advection equation with the high resolution scheme. Then, a re-initialization equation with the artificial compression and viscosity terms is applied to sharpen interface and to avoid small interface thickness. The mass conservation is significantly better for the conservative level set method as compared to the conventional level set method introduced in [9].

For modeling solid boundaries in fluid flow, the immersed boundary (IB) method has become increasingly popular since generation of grids can be greatly simplified when simulating flow problems with complex stationary or moving boundaries. Immersed boundary methods include the continuous and discrete forcing methods [28]. The first class of methods involves adding a forcing term into the continuous governing equations prior to the discretization of the differential equations. Since the constitutive equations can be directly incorporated into the formulation, application of continuous forcing methods can give us a sound physical basis to accurately simulate fluid flow problem with elastic boundary. It is therefore applicable to simulate biological flows rather than to predict flows containing rigid bodies. Another advantage of applying continuous forcing methods roots in the fact that these methods can be formulated independent of the employed spatial discretization. This typical continuous forcing method due firstly to the original work of Peskin [29] was subsequently extended by Goldstein et al. [30]. In the discrete forcing methods, the forcing term is either explicitly or implicitly applied to the discretized Navier–Stokes equations [31–33]. In comparison with the first category of the immersed boundary methods, discrete forcing methods allow adopting a sharper representation of the immersed boundary. More application of IB method can be found in Refs. [34–37].

In this study, a combined LS/IB method will be implemented in Cartesian grid system. The fluid–fluid interface is captured through the use of the currently adopted high-order level set method, the application of the sixth-order accurate symplectic Runge–Kutta scheme, and the sixth-order accurate upwinding combined compact difference scheme. This upwinding combined compact difference scheme is manifested with the minimized phase error, thereby reducing much of the dispersion error generated from the discrepancy between the effective and actual scaled wave numbers. More importantly, application of this upwinding difference scheme can preserve very well the shape of interface for the advection equation, thus avoiding either mass accumulation or depletion. Another main objective of our study is to modify the level set function before performing the re-initialization step so as to improve the level of mass conservation in arbitrarily shaped interfaces which may be merged or split. Furthermore, the differential-based interpolation immersed boundary formulation is applied to track the solid–fluid interface for the purpose of increasing computational efficiency [37].

This paper is organized as follows: Section 2 presents the smoothing method for the hydrodynamic system which consists of the Navier–Stokes equations and the level set equation. In Section 3, the numerical schemes for solving the Navier–Stokes equations and the level set equation are described. Section 4 describes the immersed boundary method for modeling complex geometry flow in Cartesian grids. Section 5 describes the algorithm of the proposed coupled level set/immersed boundary method. Section 6 presents the predicted results concerning the impact of dam break flow on the solid object. Finally, we will draw some conclusions in Section 7.

2. Mathematical model

2.1. Equation for the free surface modeling

2.1.1. Advection step

In this study an improved interface preserving level set method is developed to predict the time-varying interface (or free surface) in a domain of incompressible fluid flow. At a surface where the value of the level set function is zero, or $\phi(\underline{x}, t) = 0$, both kinematic and dynamic boundary conditions are specified. The kinematic boundary condition is interpreted in Lagrangian sense: for fluid particles sitting on a surface, they will always stay. We can therefore write a mathematically equivalent pure advection equation for the level set function ϕ at an interface that separates the gas and liquid, which is

$$\phi_t + \underline{u} \cdot \nabla\phi = 0, \tag{1}$$

where $\underline{u}$ denotes the flow velocity. Note that the level set function ϕ is initially prescribed to have the following signed distance values in gas and liquid domains

$$\phi = \begin{cases} -d & for \;\; x \in \Omega_{gas} \\ 0 & for \;\; x \in \Gamma_{sf} \\ d & for \;\; x \in \Omega_{liquid}. \end{cases} \tag{2}$$

In Eq. (2), Ω_{gas} and Ω_{liquid} are the gas region and the liquid region, respectively. Γ_{sf} denotes the location of interface and d is the absolute normal distance to the interface.

2.1.2. Intermediate step

Interface motion is represented by the propagation of the zero level set which is embedded in Eq. (1). Although the interface is still represented by the reference value, the other values of ϕ might not be the distances from the interface after calculating Eq. (1), thereby implying that mass is not conserved all the time

$$\int_\Omega \mathbf{H}(\phi, t=0)\, d\Omega - \int_\Omega \mathbf{H}(\phi, t)\, d\Omega = \mathcal{H}_{error} \neq 0. \tag{3}$$

In Eq. (3), Ω is a fixed domain. $\mathbf{H}(\phi, t)$ is the smoothed Heaviside function at any time and can be described below

$$\mathbf{H}(\phi, t) = \begin{cases} 0 & ;\; if \;\; \phi < -\epsilon \\ \dfrac{1}{(1 + e^{-\frac{3\phi}{\epsilon}})} & ;\; if \;\; |\phi| \le \epsilon \\ 1 & ;\; if \;\; \phi > \epsilon. \end{cases} \tag{4}$$

Note that the value of ϵ shown above is chosen to be $2\Delta x$ to conserve the area of a flow bounded by the interface, where Δx denotes the grid spacing. To retain the mass conservation property, the Heaviside function defined in Eq. (4) is modified as

$$\mathbf{H}_{new}(\phi, t) = \begin{cases} \mathbf{H}(\phi, t) + \dfrac{\mathcal{H}_{error}}{\mathbf{N_{in}}} & ;\;\; if \;\; 0 < \mathbf{H}(\phi, t) < 1, \\ \mathbf{H}(\phi, t) & ;\;\; if \;\; \mathbf{H}(\phi, t) = 0 \text{ or } \mathbf{H}(\phi, t) = 1, \end{cases} \tag{5}$$