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Numerical simulation of 3-D free surface flows by overlapping MPS*

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Abstract: An overlapping moving particle semi-implicit (MPS) method is applied for 3-D free surface flows based on our in-house particle solver MLParticle-SJTU. In this method, the coarse particles are distributed in the whole domain and the fine particles are distributed in the local region of interest at the same time. With the fine particles being generated and removed dynamically, an algorithm of generating particles based on the 3-D overlapping volume is developed. Then, a 3-D dam break flow with an obstacle is simulated to validate the overlapping MPS. The qualitative comparison among experimental data and the results obtained by the VOF and the MPS shows that the shape of the free surface obtained by the overlapping MPS is more accurate than that obtained by the UNI-coarse and close to that obtained by the UNI-fine in the overlapping domain. In addition, the water height and the impact pressure at P_1 are also in an overall agreement with experimental data. Finally, the CPU time required by the overlapping MPS is about half of that required by the UNI-fine.

Key words: overlapping particle, moving particle semi-implicit (MPS), generating particles, free surface flow, dam breaking

Introduction

The meshfree particle method is a flexible tool to deal with largely deformed free surface flows such as the dam breaking[1,2], the wave breaking[3,4], the sloshing[5], and the wave-body interaction[6]. However, when it is applied for the 3-D free surface flows, the number of the corresponding particles with a uniform mass increases sharply, which may lead to a huge computational cost in terms of CPU time and memory requirement. To overcome this problem, some attempts were made to develop local refinement techniques. Feldman and Bonet[7] proposed a particle splitting technique, which was considered as the major step towards Adaptive Particle Refinement (APR) by Barcarolo et al.[8]. Based on Feldman's work[7], Vacondio et al.[9,10] studied a coalescing technique. Similar to Feldman's work[7], Lopez et al.[11] described another particle splitting criterion by minimizing the error of the gradient of a general function. Most of these attempts were implemented based on weakly compressible SPH (WCSPH) with the explicit algorithm to produce the pressure field. Unlike the WCSPH, a semi-implicit algorithm is often adopted to obtain the pressure field in the moving particle semi-implicit (MPS), which makes it much more difficult developing the local refine technique in the MPS than that in the SPH. Recently, Shibata et al.[12] proposed an overlapping particle technique (OPT) in the MPS to reduce the computational cost. Then, Tang et al.[13] applied this overlapping method for 2-D free surface flows based on their in-house code MLParticle-SJTU. However, the capability of the overlapping MPS for 3-D free surface flows is not made evident.

The main purpose of the present work is to apply the overlapping particle technique[12] for a 3-D dam break flow with an obstacle. This paper is organized as follows: firstly, the improved MPS (IMPS) method together with the overlapping technique are introduced briefly. In particular, we employ a different pressure gradient term to be consistent with the conservative model in the IMPS. In view of the fact that the high-resolution particles are generated or removed

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dynamically in the overlapping region, an algorithm of generating particles in our previous work[13] is extended to the 3-D case now. Finally, the validation is made against a 3-D dam breaking flow, with the computational results compared with the experimental data in the literature.

1. Governing equations

In the MPS method, the governing equations are the mass and momentum conservation equations. They are as follows:

$$\frac{1}{\rho}\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\nabla\cdot\boldsymbol{V} = 0 \tag{1}$$

$$\frac{\mathrm{D}\boldsymbol{V}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\cdot\boldsymbol{V} + \boldsymbol{g} \tag{2}$$

where ρ is the fluid density, $\boldsymbol{V}$ is the velocity vector, p is the pressure, ν is the kinematic viscosity, $\boldsymbol{g}$ is the gravitational acceleration vector, and t is the flow time.

2. Particle interaction models

2.1 *Kernel function*

In the MPS method, the differential operators are modeled based on a kernel function. In the present work, we adopt the following modified kernel function suggested by Zhang and Wan[14], which can be expressed as follows:

$$W(r) = \frac{r_e}{0.85r + 0.15r_e} - 1, \quad 0 \le r < r_e \tag{3a}$$

$$W(r) = 0, \quad r_e \le r \tag{3b}$$

where r is the distance between particles and r_e is the supported radius of the particle interaction domain.

2.2 *Gradient model*

In the traditional MPS, the gradient operator is expressed as a weighted average of the gradient vector between particle i and its neighboring particles j, and it can be expressed as

$$\langle\nabla p\rangle_i = \frac{d}{n^0}\sum_{j\ne i}\frac{p_j - p_i}{\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|^2}(\boldsymbol{r}_j - \boldsymbol{r}_i)\cdot W(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|) \tag{4}$$

where n^0 is the initial particle number density, d is the space dimensions, and $\boldsymbol{r}$ is the coordinate vector of the fluid particle.

Equation (4) suffers from a drawback that it cannot conserve the linear and angular momentums of the system. To overcome this problem, we employ a conservative form as follows[15]

$$\langle\nabla p\rangle_i = \frac{d}{n^0}\sum_{j\ne i}\frac{p_j + p_i}{\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|^2}(\boldsymbol{r}_j - \boldsymbol{r}_i)\cdot W(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|) \tag{5}$$

2.3 *Divergence model*

The divergence model for the vector $\boldsymbol{V}$ can be formulated as[15]

$$\langle\nabla\cdot\boldsymbol{V}\rangle_i = \frac{d}{n^0}\sum_{j\ne i}\frac{(\boldsymbol{V}_j - \boldsymbol{V}_i)\cdot(\boldsymbol{r}_j - \boldsymbol{r}_i)}{|\,\boldsymbol{r}_j - \boldsymbol{r}_i\,|^2}W(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|) \tag{6}$$

2.4 *Laplacian model*

The Laplacian operator is modeled by a weighted average of the distribution of a quantity ϕ from particle i to its neighboring particles j, which can be expressed as follows:

$$\langle\nabla^2\phi\rangle_i = \frac{2d}{n^0\lambda}\sum_{j\ne i}(\phi_j - \phi_i)\cdot W(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|) \tag{7}$$

$$\lambda = \frac{\sum_{j\ne i}W(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|)\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|^2}{\sum_{j\ne i}W(\left|\boldsymbol{r}_j - \boldsymbol{r}_i\right|)} \tag{8}$$

where the parameter λ is introduced to keep the variance increase equal to the analytical solution.

2.5 *Model of incompressibility*

In the MPS method, the semi-implicit algorithm is adopted and the pressure fields are obtained implicitly through solving the Poisson pressure equation (PPE). In the present work, we employ a mixed source term method combined with the velocity divergence-free condition and constant particle number density condition, which is proposed by Tanaka and Masunaga[15] and rewritten by Lee et al.[16] as

$$\langle\nabla^2 p^{k+1}\rangle_i = (1-\gamma)\frac{\rho}{\Delta t}\nabla\cdot V_i^* - \gamma\frac{\rho}{\Delta t^2}\frac{\langle n^k\rangle_i - n^0}{n^0} \tag{9}$$

where Δt is the calculation time step, the superscripts k and $k+1$ indicate the physical quantity in the kth and $(k+1)$th time steps, γ is the weight of the particle number density term in the right hand side of Eq.(9) and is assigned a value between 0 and 1. In this paper, $\gamma = 0.01$ is selected for all numerical experiments.