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A new approach for fluid dynamics simulation: The Short-lived Water Cuboid Particle model

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ABSTRACT

There are many researches to simulate the fluid which adopt the traditional particle-based approach and the grid-based approach. However, it needs massive storage in the traditional particle-based approach and it is very complicated to design the grid-based approach with the Navier-Stokes Equations or the Shallow Water Equations (SWEs) because of the difficulty of solving equations. This paper presents a new model called the Short-lived Water Cuboid Particle model. It updates the fluid properties (mass and momentum) recorded in the fixed Cartesian grids by computing the weighted sum of the water cuboid particles with a time step life. Thus it is a two-type-based approach essentially, which not only owns efficient computation and manageable memory like the grid-based approach, but also deals with the discontinuous water surface (wet/dry fronts, boundary conditions, etc.) with high accuracy as well as the particle-based approach. The proposed model has been found capable to simulate the fluid excellently for three laboratory experimental cases and for the field case study of the Malpasset dam-break event occurred in France in 1959. The obtained results show that the model is proved to be an alternative approach to simulate the fluid dynamics with a fair accuracy.

1. Introduction

In the field of fluid simulation two main classes of approaches are typically used: the mesh-based approach and the particle-based approach. The former is essentially an Euler approach and many academic researches have been done including the finite difference methods (FDM), the finite element method (FEM) and the finite volume method (FVM). These methods are usually designed with the Shallow Water Equations (SWEs), and many solution methods can be considered, such as the Godunov-type scheme (Kurganov and Levy, 2002; Kurganov and Petrova, 2007), the approximate Riemann solver (Glaister, 1988; Roe, 1981; Zhao et al., 1996), the Galerkin method (Aizinger and Dawson, 2002; Lai and Khan, 2011, 2012). Among the mesh-based approaches, the grid-based approach is the most widely applied one because it allows to easily store the properties recorded in the grids in image format and to easily build the structure. Generally, in the one-dimensional (1D) case and the two-dimensional (2D) case it is used with the SWEs (1D-SWEs and 2D-SWEs, respectively) (Cea and Blade, 2015; Kurganov and Levy, 2002; Kurganov and Petrova, 2007; Singh et al., 2015). Also, it could be designed with the Navier-Stokes Equations in the three-dimensional (3D) case (Masciopinto and Palmiotta, 2013; Stam, 1999). The particle-based approach is essentially a Lagrange approach. To begin with, the particle systems were introduced as a technique for modeling a class of fuzzy objects by Reeves (1983). Among the particle-based approaches, the Smoothed Particle Hydrodynamics (SPH), developed by Lucy (1977), is the most used one. The original SPH is basically designed to formulate the Navier-Stokes Equations (Crespo et al., 2015; Liu and Liu, 2010; Müller et al., 2003; Wu et al., 2013). Only a few researches have attempted to extend SPH to the SWEs (Chang et al., 2011; De Leffe et al., 2010; Kao and Chang, 2012; Lee and Han, 2010). And the particle-based approach is powerful when it deals with the discontinuous waters such as the interfaces between dry area and wet area and boundaries of simulation area. In addition, there are two main hybrid particle-mesh approaches. One is called Particle-In-Cell (PIC) method which was invented at the Los Alamos National Laboratory in 1955 by Harlow (1955) and became the practical methodology in 1964 (Harlow, 1964). The PIC method uses particles to store the properties and when computing external forces, pressure, etc., the properties are transferred to the grids. The velocities are computed based on the grids, and then they are used to evaluate the velocities of the particles by spatial interpolating (Kelly et al., 2015; Salomonsson, 2011). Many excellent methods are developed based

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the PIC method improving such as the fluid implicit particle (FLIP) method (Brackbill and Ruppel, 1986) and the material point method (MPM) (Mao et al., 2015; Sulsky et al., 1994). The other one is called Arbitrary Lagrangian-Eulerian (ALE) method (Donea et al., 2004; Hirt et al., 1997; Hu et al., 2001; Pin et al., 2007). It involves two kinds of motion: the material mesh motion and the reference mesh motion. When using the ALE method, the nodes of computational mesh are considered as the dynamic objects, which can be moved along with materials or be moved according to the specified rules.

However, the traditional particle-based approach demands massive data storage and controls the memory difficultly because it needs to take some new memories when simulating the new inflows. Also, it takes much more time on the search algorithms to obtain neighbors of particles. And it is difficult to solve the SWEs although many solution methods have been researched. Moreover, the SWEs need to discretize the continuity equations under different conditions (dry area, boundary conditions, consecutiveness restructure, etc.) with accuracy loss. The PIC method needs massive particle to simulate and numerous calculations need to do in order to transfer the properties between the particles and grids. In the ALE method, although moving independently, the nodes need follow the geometry topology relation for the stable of the computational mesh and it needs to rezone the mesh, which requires extensive computational effort. In this context, we develop a new model called 'Short-lived Water Cuboid Particle (SWCP)' for improving the efficient and accuracy numerical simulation while maintaining a proper computational effort. The SWCP model is a two-type-based approach which not only owns manageable memory like the grid-based approach, but also deals with the discontinuous water surface (wet/dry fronts, boundary conditions, etc.) with high accuracy as well as the particle-based approach. Furthermore, the SWCP model is based on the methodology of reducing the dimensionality from 3D to 2D, which could utilize fewer particles than particle-based approach and the PIC method to simulate the fluid; therefore it can simulate more large domains than the traditional particle-based approach and the PIC method. As the grids and particles own the regular shape in the SWCP model, it is easier to compute and store than the ALE method in the program design.

This paper is organized as follows: in Section 2, the concept of the SWCP model is described. Section 3 introduces the governing equations and how to model fluids with particles. Section 4 introduces the model running conditions including the initial conditions, boundary conditions and stable conditions. Section 5 introduces the flow chart to describe the structure of application design for the SWCP model. Section 6 describes the case studies and the results for the three investigated laboratory experiments and the for the one real field case. Section 7 compares the SWCP model with the traditional approaches to highlight its contributions. Section 8 gives the conclusions.

2. SWCP model

The SWCP model considers that the water body is composed of many square cuboids on the fixed Cartesian grids. It records the properties (mass and momentum) of the fluid in the fixed Cartesian grids and updates them based on the shorted-lived particles which are moving on the grids in a time step. The edge length of the cuboid bottom stands for the resolution of simulation, and the height stands for the water depth (Fig. 1).

The SWCP model consists of two processes in one time step: the motion process and the integration process. During the motion process, the square cuboid is considered as a water cuboid particle, and the new position and momentum of each water cuboid particle are computed based on the governing equations after one time step. During the integration process, the fluid properties recorded in the fixed Cartesian grids are updated by integrating the water cuboid particles which are the result of the motion process. After the two processes, the lives of water cuboid particles are ended and the fixed Cartesian grids with the new fluid properties are generated. That is the reason why we describe particles with a step time life as short-lived and the model as a semi-grid-based and semi-particle-based approach. At the beginning of the next time step, the new square cuboids on the fixed Cartesian grids are considered as the new water cuboid particles to continue these two processes.

Obviously, each water cuboid particle could affect up to four fixed Cartesian grids during its life time. Fig. 2a shows a single water cuboid particle's motion and integration process from top view. Four fixed Cartesian grids are marked with letters A, B, C and D respectively. At the beginning, the square cuboid on the grid A is considered as the water cuboid particle A. The velocity of the water cuboid particle A is marked with the letter V, and the subscripts t and $t+1$ stand for the time step. After a time step, the water cuboid particle A_t moves to the position of A_t' and is then divided into four new grids 1, 2, 3 and 4 by the fixed Cartesian grids. In the integration process, the properties of the water cuboid particle A_t contributes to the grids A, B, C and D could be computed according to how much percent grids 1, 2, 3 and 4 take up of the grid A_t'. $S_{A'\_}$ (_ = A, B, C and D) identifies the area of the grid A' covering the grids A, B, C and D, and S_g is defined as the area of the fixed Cartesian grid. $\mathbf{Q}$ with subscripts A, B, C and D is defined as the properties of the corresponding grid/particle (for example, $\mathbf{Q}_{A'}$ stands for the properties of the grid/particle A'), and $\mathbf{Q}$ with two subscripts is defined as the properties of the first subscript corresponding particle contributing to the second subscript corresponding grid in the integration process (for example, $\mathbf{Q}_{A'B}$ stands for the properties which the particle A' contributes to the grid B). Following shows the Eq. (1):

$$\begin{aligned} \mathbf{Q}_{A'B} &= \mathbf{Q}_{A'}\frac{S_{A'B}}{S_g} \\ \mathbf{Q}_{A'C} &= \mathbf{Q}_{A'}\frac{S_{A'C}}{S_g} \\ \mathbf{Q}_{A'D} &= \mathbf{Q}_{A'}\frac{S_{A'D}}{S_g} \\ \mathbf{Q}_{A'A} &= \mathbf{Q}_{A'}\frac{S_{A'A}}{S_g} \end{aligned} \tag{1}$$

At the end, the water cuboid particle A_t ends its life and integrates its properties into the four fixed Cartesian grids. The grids A, B, C and D update their properties from A_t, B_t, C_t and D_t to A_{t+1}, B_{t+1}, C_{t+1} and D_{t+1}.

To update the properties of a grid, all water cuboid particles that could potentially affect it have to be considered. The effect radius is the maximum displacement of all water cuboid particles under the Courant–Friedrichs–Lewy (CFL) condition. The template size is determined according to the effect radius. In this paper, we take control of the CFL condition in order to limit the effect radius to less than one unit and, hence, the template size is $3 * 3$. Fig. 2b shows the process how the template of size $3 * 3$ updates the properties of a grid. Letter A stands for the target grid of which the properties needs to be updated and numbers 1–9 are marked on the grids which can potentially affect grid A. At the beginning, the square cuboids on the grids 1–9 is considered as water cuboid particles. After a Δt time, the particles 1–9 move to the positions of grids 1′–9′. Then the grid A can be updated from A_t to A_{t+1} by integrating the water cuboid particles 1–9 using the Eq. (2):

$$\mathbf{Q}_{A_{t+1}} = \sum_{i=1}^{n}\mathbf{Q}_{i'A_t} = \sum_{i=1}^{n}\mathbf{Q}_{i'}\frac{S_{i'A}}{S_g} \tag{2}$$