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Particle-based numerical simulations of impact events

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Impacts of meteorite are important phenomenon for the planetary geology. Since these processes cannot be experimented in laboratories, numerical hydrodynamical simulations of the impact process play important role. For these processes, particle based numerical hydrodynamical simulations have several advantages over grid-based methods, because these processes often involve large deformation of target and oblique impacts. The Smoothed Particle Hydrodynamics (SPH) is a widely used particle based numerical hydrodynamical scheme. It is first developed in astrophysical field. Recently, it was adopted to the impact cratering. However, it has been pointed out that the standard SPH formulation has difficulties in the treatment of contact discontinuity; an unphysical repulsive force acts between two different materials, such as rock and water. Thus, we have developed new particle based hydrodynamical, Density Independent SPH (DISPH), which overcomes this difficulty. We have developed a new massively parallel particle based numerical hydrodynamical simulations code by means of DISPH. We adapted Framework for Developing Particle Simulator (FDPS), which enables us to perform high-performance parallel particle simulations easily. We will show the results of impacts of the tuff to the water with both DISPH and SSPH.

1 Introduction

The Smoothed Particle Hydrodynamics (SPH) method is a widely accepted hydrodynamical numerical simulation method (Gingold & Monaghan, 1977; Lucy, 1977). Because of its Lagrangian nature, recently, it is adapted to the numerical simulations of impact cratering (e.g., Jutzi et al., 2008, 2009). However, a shortcoming of the standard SPH (SSPH) formulation is reported (e.g., Agertz et al., 2007). They pointed out that SSPH cannot treat the contact discontinuity correctly. This means that SSPH should not treat the multi-material simulations correctly. Recently, an improved SPH, density independent SPH (DISPH) has been developed (e.g., Saitoh & Makino, 2013; Hopkins, 2013; Hosono et al., 2013). DISPH overcomes the shortcoming and can treat the multi-material flows more correctly. In this work, we aimed to carry out the numerical simulations of impact cratering with both SSPH and DISPH and then compare the results.

2 Method

Now let us recap the idea of SPH. SPH is a particle-based numerical hydrodynamical scheme developed in astrophysical field (Gingold & Monaghan, 1977; Lucy, 1977). The governing equations, namely, the equation of continuity, the equation of moment and the equation of energy are converted into the sum of interactions between surrounding particles. The equations for SSPH are

$$\rho_i = \sum_j m_j W_{ij}, \tag{1}$$

$$\frac{\mathrm{d}\vec{v}_i}{\mathrm{d}t} = -\sum_j m_j \left(\frac{p_i}{\rho_i} + \frac{p_j}{\rho_j}\right) \nabla W_{ij}, \tag{2}$$

$$\frac{\mathrm{d}u_i}{\mathrm{d}t} = \sum_j m_j \frac{p_i}{\rho_i} \vec{v}_{ij} \cdot \nabla W_{ij}, \tag{3}$$

where ρ, m, $\vec{v}$, p and u are the density, mass, velocity, pressure and the specific internal energy, respectively. The subscript i means the label of each particle. Note that W_{ij} is the so-called kernel function.

On the other hand, those for DISPH are

$$p_i = \sum_j Y_j W_{ij}, \tag{4}$$

$$\frac{\mathrm{d}\vec{v}_i}{\mathrm{d}t} = -\sum_j \frac{Y_i Y_j}{m_i} \left(\frac{1}{p_i} + \frac{1}{p_j}\right) \nabla W_{ij}, \tag{5}$$

$$\frac{\mathrm{d}u_i}{\mathrm{d}t} = \sum_j \frac{Y_i Y_j}{m_i p_i} \vec{v}_{ij} \cdot \nabla W_{ij}, \tag{6}$$

where $Y = p\Delta V$ and ΔV is the volume of particles.

3 High Performance Computing

The reliability of SPH depends on the number of particles deployed in a run. Basically, the calculation cost increases $O(N^2)$, where N is the number of particles. In order to carry out large scale numerical simulations quickly, we employed the `Framework for Developing Particle Simulator` (`FDPS`, Iwasawa et al., 2015, 2016; Hosono et al., 2016).

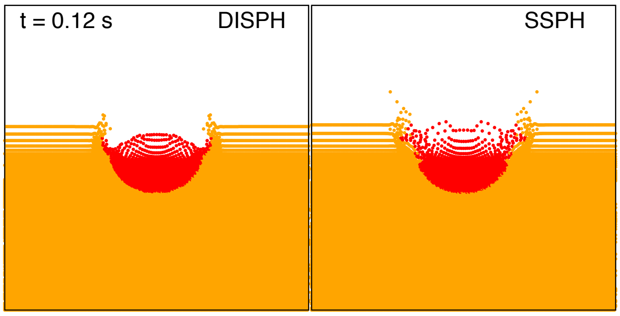

Fig. 1. Snapshots of aluminium-to-aluminium test with DISPH (the left column) and SSPH (the right column) at $t = 0.11$ seconds. The orange particles indicate the target particles while the red particles indicate those of impactor particles.

FDPS is a general-purpose library to perform massively parallelized particle-based numerical simulations. FDPS uses the Tree method (Barnes & Hut, 1986), which allows us to reduce the calculation cost to $O(N \log_8 N)$. FDPS automatically parallelize particle-based numerical simulations using Message Passing Interface.

4 Results

In this work, we performed two test runs, which are carried out by Pierazzo et al. (2008) for the purpose of the scheme comparison.

Figure 1 shows the results of the collision of Aluminium sphere to the Aluminium plate. Both methods produce roughly similar results; the jetting and excavation of the target is produced around the impact site. The crater size and depth are almost indistinguishable between SSPH and DISPH. Note that there are several differences between two results, e.g., the height and expansion of impact jetting.

Figure 2 shows the results of the glass-on-water test with both methods. Unlike the aluminium-to-aluminium test, this test contains the contact discontinuity between water (target) and wet tuff (projectile). Similar to the aluminium-to-aluminium test, the height and expansion of the ejecta curtain is different between two methods, which could be due to the unphysical surface tension between two different materials arising in SSPH calculations. The target particles are pushed up by the projectile particles at the early step of the impact ($t = 0.6\mu$s - 2.0μs). This results in the higher crater rim and greater amounts of "ejected" mass with SSPH than DISPH. At $t = 13.9\mu$s, SSPH produces oblate projectile, while with DISPH, the projectile and target are mixed.

5 Summary

We performed 2D impact simulations by Lagrangian numerical numerical hydrodynamical scheme SPH. We also compared two different implementations of SPH, namely, SSPH and DISPH. The difference between two results is rather large; SSPH seems to generate greater amounts of ejected mass.

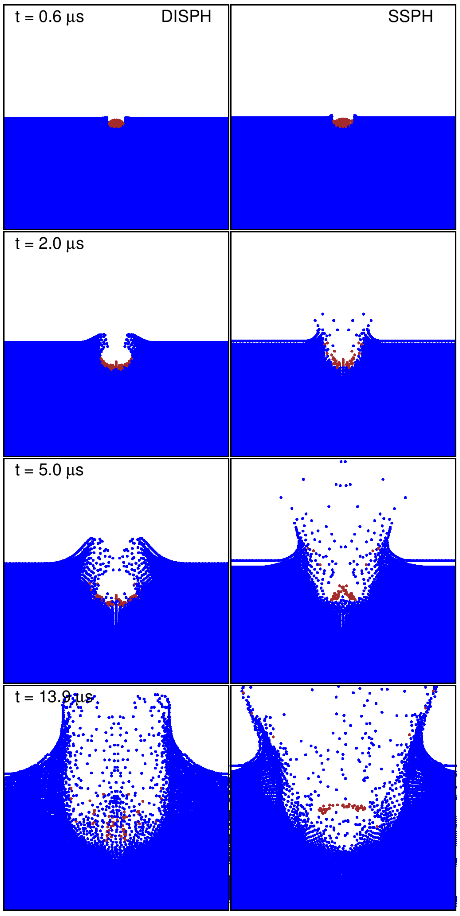

Fig. 2. Snapshots of the glass sphere on water test with DISPH (the left column) and SSPH (the right column). The brown particles indicate the projectile particles (wet tuff) while the blue particles indicate those of target particles (water).

Note that there are some experimental results for these test simulations. In order to determine which result is more plausible, we need to compare the results of numerical simulations with experiments. Also, we need to perform 3D calculations. 3D simulations are not so easy, however, thanks to FDPS, we can run our simulations on any supercomputers like K. We are planning to perform 3D numerical simulations of these situations.

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