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Waterjet penetration simulation by hybrid code of SPH and FEA

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Abstract

The creativity of this work is combining finite element analysis (FEA) and smoothed particle hydrodynamics (SPH) methods to simulate the waterjet (WJ) penetration process. In WJ penetration, the waterjet undergoing extremely large deformation will introduce the distortion of mesh in FEA. To overcome this difficulty, the coupled method of SPH and FEA was developed, in which the waterjet was modeled by SPH particles and the target material was modeled by finite elements. The two parts interacted by contact algorithm of "nodes-to-surface". Utilizing this hybrid model, waterjet with high velocity penetrating the target materials was calculated and the mechanism of erosion was depicted. The computation result gives the relationship between the jet velocity and the erosion capacity, including the depth of penetration and mass removal, which was compared with the experimental data.

Keywords: Waterjet penetration; Finite element analysis; Mesh-free method; Smoothed particle hydrodynamics

1. Introduction

WJ (Waterjet) cutting technique had been applied successfully in material machining such as metal cutting and decoating operation. The principium of WJ is making the water pressure increase to a very high extent ($\leqslant$700 Mpa), then shooting from the orifice with a diameter from 0.08 to 1 mm [1] where the potential energy of the high-pressure water was transferred to the kinetic energy of the jet. The waterjet with high velocity striking on the target can produce strong force to cut the materials.

The cutting process usually includes some parameters such as water pressure, nozzle diameter and jet velocity, which have important effect on control and work optimization. Some literatures [2–7] have executed experimental study on the parameters and the cutting quality, including the profile of the impact surface and the physical properties. Momber et al. [2,3] investigated the surface quality features of waterjetted surfaces, involving average surface roughness, Rockwell hardness and surface microstructure. Guo and Ramulu [4] used Moiré interferometry to measure the displacement distribution of the erosion surface. Compared to these experimental investigations on WJ, there are a few literatures [6–9] focused on the numerical simulation of the impact process, which is used often by the means of finite element analysis (FEA) to calculate the motion/deformation of the flow and the target. But this fluid–solid impact problem, often accompanied with the large deformation, may lead to the distortion of the mesh in FEA as depicted in Section 3.3. For instance, Mabrouki et al. [6] employed the FEA method to study the interaction between a pure high-velocity waterjet and targets, though with the arbitrary Eulerian/Lagrangian (ALE) formulation, the authors reported some distortions in the grid mesh relative to the impact center. On the other hand, the ALE formulation introduced the extra computational field and needed to constrain Lagrangian point with Eulerian nodes on the intersurface of fluid and solid; all these reduced the automaticity of the program and made the computation expensive.

To overcome the above difficulty, we developed a coupled method of smoothed particle hydrodynamics (SPH) and FEA, by which all steps were in the frame of Lagrangian description; it made the computation more

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compact and automatic. This coupled method includes two aspects: firstly, it represented the coupled model of SPH particles and finite elements; secondly, the two different discrete parts interact by the contact algorithm of "nodes-to-surface", which was available in the LS-Dyna 970 code [10,11].

SPH is one of the mesh-free particle methods that was developed in the recent two decades [12–14]. By SPH method, the continuous material was expressed by a serious of particles, which carry some physical quantum such as mass and velocity. Because there is no mesh structure among these particles, the distortion of the mesh can be avoided. Johnson and Beisssel [15–17] applied SPH in high velocity impacting problems and got encouraging result.

This paper combined SPH and FEA to study the interaction of high-velocity waterjet impacting the target materials. The waterjet was modeled by SPH particles and the target metal was still modeled by finite elements. The procedure of creating the SPH particle model of waterjet was explained and the jet velocity distribution was supposed as uniform according to [9]. Based on the explicit program LS-Dyna 970, the hybrid-code of SPH and FEA was conducted to simulate the penetration process, and the computational result gave the relationship between the waterjet velocity and the depth of cut and removal mass, also the result was compared with the experimental data of [2].

2. Theory of SPH

FEA is a widely used method in simulation of mechanical behavior of materials, but to materials that undergo extremely large deformation, an element may become so distorted and finally induce the failure of computation. However without mesh structure, the mesh-free method can overcome this difficulty. Fig. 1 shows the different discrete model between FEA and mesh-free particle method.

2.1. Basic theory of SPH

In SPH, the approximation $u^h(x)$ was expressed by its neighbored particles in a domain Ω_y

$$u^h(x) = \int_\Omega w(x-y,h)u(y)\,\mathrm{d}\Omega_y, \tag{1}$$

where h is a measure of the size of support, $w(x-y, h)$ is a kernel weight function that should satisfy the following five conditions:

(1) $w(x-y,h) > 0 \quad \text{in domain } \Omega_y,$ (2)

(2) $w(x-y,h) = 0 \quad \text{outside the domain } \Omega_y,$ (3)

(3) $\int_\Omega w(x-y,h)\,\mathrm{d}\Omega = 1,$ (4)

(4) $w(s,h)$ is a monotonically decreasing function, where $s = ||x-y||$ (5)

and

(5) $w(s,h) \to \delta(s), \quad \text{as } h \to 0.$ (6)

In this computation, the kernel weight function was B-spline type:

$$w(r,h) = \frac{2}{3h^d}\begin{cases} 1-\frac{3}{2}r^2+\frac{3}{4}r^3, & r\leqslant 1, \\ \frac{1}{4}(2-r)^3, & 1\leqslant r\leqslant 2, \\ 0, & r\geqslant 2, \end{cases} \tag{7}$$

where r is the ratio of distance between two particles to the support length h and d is the dimension of the problem.

Eq. (1) can also be written in discrete form:

$$F(x_I) = \sum_{J=1}^{N} w_{IJ}\frac{m_J}{\rho_J}F(x_J) \tag{8}$$

and its derivative function is

$$\nabla F(x_I) = \sum_{J=1}^{N} \frac{m_J}{\rho_J}\nabla w_{IJ}F(x_J). \tag{9}$$

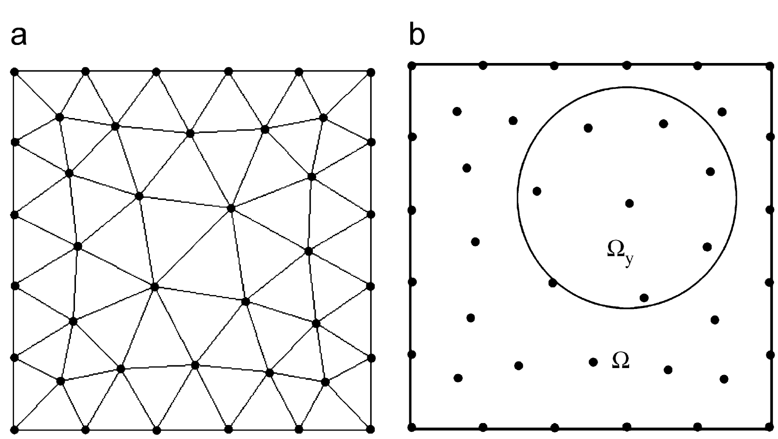

Fig. 1. Discrete model type. (a) Finite element model. (b) Mesh-free model.