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An enhanced smoothing algorithm for MPM to stabilize hydrodynamic impact problems with embedded solids

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Abstract

The impact of debris carried by floods or tsunamis can cause severe damage to structures, but the complex phenomena involved are difficult to model. The Material Point Method (MPM) provides one framework for modeling such systems, with the capability of incorporating combined fluid/solid behavior with complex interaction. Conventional MPM uses regular grids with tri-linear interpolation. However, linear functions introduce volumetric locking for (nearly) incompressible materials, posing problems when modeling liquids. To eliminate locking, hybrid formulations similar to those used with finite elements were adapted by Mast et al. [1]. This approach introduced two classes of anti-locking algorithms for nearly incompressible materials: a cell-based and a node-based variant. Both variants filter incompatible strains and stresses, but also affect the stability of the time integration. For hydrodynamic problems the cell-based algorithm is prone to checker-board stress fields, while the node-based algorithm can introduce excessive dissipation. This paper presents a new numerical flux smoothing algorithm to produce smooth stress fields in complex hydrodynamic problems while enhancing numerical stability. The goal is to combine the stability of the node-based anti-locking approach with the cell-based variant's capability to effectively solve hydrostatic problems. The improved algorithm is validated using a hydrostatic problem to isolate and minimize the effect of integration errors. A complex hydrodynamic problem involving an embedded solid block is then used as an example to display the new algorithm's modeling capabilities.

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1. Introduction

Throughout history, tsunamis have caused severe damage in coastal areas. As coastal populations and the associated infrastructures continue to increase around the world, understanding and managing tsunami effects on structures becomes increasingly important. In the literature, tsunami induced hydrodynamic loads on structures have been widely studied. However, tsunamis can also carry large debris, e.g. shipping containers and boats. Many researchers have experimentally demonstrated that debris carried by water flow (such as in the case of tsunamis) can cause large impact forces on structural components (e.g., [2–4]). These problems have not yet been well-studied numerically, largely be-

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cause the complex interactions between multiple solids and fluids are not easily modeled using typical fluid-oriented or solid-oriented numerical frameworks. The material point method (MPM)[5] provides a unified fluid/solid interaction platform based on updated Lagrangian computational grids, and this enables the modeling of these complex fluid-solid (moving and stationary) interactions.

The standard MPM implementation uses a regular orthogonal grid with tri-linear shape functions. While this is not the only variant in use (see, e.g., [6]), it remains popular for its simplicity. However, the linear shape functions also introduce not only volumetric locking for (nearly) incompressible materials (hence causing problems when modeling liquids), but also integration errors, which arise from the MPM particle discretization. Each of these issues is problematic, and must be addressed to generate useful solutions.

Figure 1(a) illustrates the issue of volumetric locking through filling of a stationary tank using standard MPM [5] and tri-linear shape functions. To eliminate this kind of non-physical behavior, hybrid formulations are generally used in (mixed) finite element methods. This approach was adapted to MPM by Mast et al.[1] as a filter-step between the particle strain update and particle stress update. Two of the three investigated anti-locking algorithms from that study are specifically relevant for fluid modeling: (i) the cell-based formulation; and (ii) the node-based formulation. The characteristics of these algorithms can be demonstrated with simulations modeling water injected into a rigid rectangular box as illustrated in Figure 1. Detailed analysis reveals that these algorithms are able to not only cure the locking problem, but also implicitly stabilize the analysis by smoothing state variable fields and hence dissipating strain energy. In this article, we define *anti-locking* as an energy conserving procedure, while *smoothing* refers to a diffusive, thus, dissipative procedure.

The objective of this paper is to provide an improved smoothing strategy to enable: (i) stable simulation of fluids and fluid-structure interaction; and (ii) realistic analysis when no integration errors are involved. The key target for the proposed smoothing strategy are MPM implementations using multi-linear interpolation functions and single-point-quadrature elements. In the following, the anti-locking strategy applied in this study is first described, and the newly developed numerical flux smoothing algorithms are presented. Validation and application examples are used to demonstrate the effectiveness of the approach, which is further discussed in Section 6.

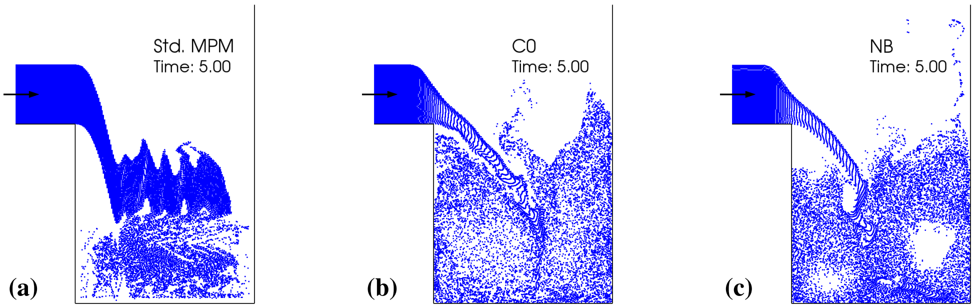

Fig. 1. Comparison of hydro-dynamical simulation snapshots between (a) standard MPM, (b) the cell-based algorithm (C0) and (c) the node-based (NB) algorithm after Mast et al.[1]. The fluid has bulk modulus $K = 2.2\,\mathrm{GPa}$, mass density $\rho = 1000\,\mathrm{kg/m^3}$ and viscosity $\mu = 0.001$ Pa·s; the box has a width of 3 m; the injection velocity is 1 m/s; and the cell size is 0.1 m by 0.1 m.

2. Anti-locking strategy

The anti-locking strategy employed is based on the Hu-Washizu principle[7,8]. It is expressed as a set of weak form equations:

$$\int_\Omega \rho\delta\tilde{\bar{\boldsymbol{\sigma}}} : \left(\boldsymbol{d} - \tilde{\boldsymbol{d}}\right)\, dV = 0 \quad , \qquad \int_\Omega \delta\tilde{\boldsymbol{d}} : \rho\left(\bar{\boldsymbol{\sigma}} - \tilde{\bar{\boldsymbol{\sigma}}}\right)\, dV = 0 \tag{1}$$

and

$$\int_\Omega \delta\boldsymbol{v}\cdot\rho\boldsymbol{a}\, dV = -\int_\Omega \operatorname{grad}\delta\boldsymbol{v} : \rho\tilde{\bar{\boldsymbol{\sigma}}}\, dV + \int_\Omega \delta\boldsymbol{v}\cdot\rho\bar{\boldsymbol{b}}\, dV + \int_{\partial\Omega^\tau} \boldsymbol{\tau}^*\cdot\delta\boldsymbol{v}\, dS \tag{2}$$

where ρ is mass density, $\boldsymbol{v}$ is the velocity field, $\boldsymbol{a}$ is the acceleration field, $\boldsymbol{\tau}^*$ a prescribed surface traction, $\boldsymbol{d} = \frac{1}{2}(\operatorname{grad}\boldsymbol{v} + \operatorname{grad}^T\boldsymbol{v})$ is the rate of deformation tensor, $\bar{\boldsymbol{\sigma}} = \boldsymbol{\sigma}/\rho$ is the mass-specific stress, all defined in the physical