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Development of Compressible and Non-Expanding Fluid Solver for Simulation of Impact and Penetration Dynamics

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An impact probe called penetrator is expected to play an important role in the exploration of the interior of an object in the solar system, especially at a low-cost small mission. To realize the penetrator mission, the analysis model of the penetration dynamics must be established. The fact that the force model based on the Newtonian theory for the aerodynamic prediction of hypersonic flying objects is still effective not only for a penetrator into the regolith (Suzuki, et al., 20th ISTS, 96-i-02V, 1996) but also for that into ice (Suzuki, et al., 30th ISTS, 2015, to be presented) implies that the motion of soil particles or fragmented ice pieces can be macroscopically described in a framework of fluid dynamics. Unlike well-known compressible gas, expansion does not occur at unloaded state or exposure to the vacuum. In the present study, for the purpose of the numerical simulation of impact and penetration dynamics, we consider the compressible but non-expanding fluid (hereinafter referred to as CNEF) model, and the Riemann solver is developed for it.

For the numerical analysis of impact problems, the SPH (Smoothed Particle Hydrodynamics) method is often used with some appropriate fluid dynamics model. Though numerical instability of the SPH method can be overcome by applying Godunov scheme (Namba, et al., CFD symposium, D02-2, 2014), particle-based methods still have problems in computational efficiency and description of rigid surfaces. Consequently, we use the finite volume method with the Godunov scheme for numerical simulation of CNEF flows.

To avoid the appearance of expansion waves in a CNEF flow, we assume that the pressure increases with the density only at loading and it instantaneously becomes zero without changing the density at unloading. By using such pressure model, the CNEF only allows the formation of shock waves. Expansion waves are not formed at all. Instead, it allows for the void (or vacuum) to be formed in a flow. Neglecting the effects of viscosity and diffusivity for simplicity of analysis, the dynamics of a CNEF flow is described by the inviscid Euler equations combined with the above pressure model. It should be noted that the pressure is not a quantity of state any more, because it depends on the path of the process. To consider the presence of a void in a flow, the VOF method (Hirt, C. W. and Nichols, B. D., J. Comp. Phys., 39, 1981) is used.

For the numerical simulation of a CNEF flow with the finite volume method and the Godunov scheme, the Riemann solver is necessary. At present, we have found four types of the fundamental solutions: a) translational motion of the fluid in vacuum, b) a pair of running shock waves formed at the collision between two lumps of fluid, c) formation of unloaded zone at a rear-end collision, and d) separation between a quicker front runner and a slower second runner. We have analytically obtained the fundamental solutions assuming that the pressure linearly increases with the density at loading. The numerical results for the test problems on the one-dimensional collision show that after the collision, two lumps of fluid are combined into a single lump without formation of expansion waves as expected for the CNEF model. For the future works, all the fundamental solutions for the Riemann problem of CNEF should be mathematically confirmed, and the CNEF model should be improved to be suitable for actual impact dynamics problems.

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Keywords: impact, numerical simulation, fluid dynamics, Riemann solver