LARGE SCALE OPTIMAL TRANSPORTATION MESHFREE (OTM) SIMULATIONS OF HYPERVELOCITY IMPACT

Bo Li, Luigi Perotti, Mark Adams, Jonathan Mihaly, Ares J. Rosakis, Michael Ortiz*[a)]
Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, CA 91125, USA

Summary Large scale three-dimensional numerical simulations of hypervelocity impact of Aluminum alloy 6061-T6 plates by Nylon 6/6 projectile have been performed using the Optimal Transportation Meshfree (OTM) method along with the seizing contact algorithm. In support of the conventional validation analysis, in-house experiments are conducted over a range of plate thicknesses, impact velocities and obliquities at Caltech. Excellent agreement between experimental measurements and computational results is found.

Hypervelocity impact of metallic targets involves large unconstrained plastic flows, contact and friction, fracture and fragmentation and complex thermomechanical material behavior. Thus it supplies an exacting validation and verification test that probes the very limits of predictability of any numerical scheme. In this work, we evaluate the performance of the Optimal Transportation Meshfree (OTM) method of Li [1][2] in applications involving hypervelocity impact.

The OTM method combines: i) optimal transportation concepts such as the Wasserstein distance between successive mass densities in order to discretize the action integral in time; ii) Maximum-entropy (max-ent) meshfree interpolation [3] from a nodal-point set in order to avoid mesh entanglement and the need for continuous remeshing in simulations of unconstrained flows; and iii) material-point sampling in order to track the local state of material points, carry out complex constitutive updates and serve as the numerical integration points. The optimal-transportation approach to time discretization leads to geometrically-exact updates of the local volumes and mass densities, thus bypassing the need for solving a costly Poisson equation for the pressure and entirely eliminating the mass conservation errors that afflict Eulerian formulations. In addition, by adopting a discrete Hamilton principle based on a time-discrete action furnished by optimal transportation, the discrete trajectories have exact conservation properties including symplecticity, linear and angular momentum. The total energy can also be exactly conserved, subject to solvability constraints, if time is taken as an independent generalized coordinate and the successive time steps are computed so as to render the action stationary [4]. Max-ent interpolation [3] offers the advantage of being mesh-free and entirely defined–essentially explicitly–by the current nodal-set positions. In particular, max-ent interpolation satisfies a Kronecker-delta property at the boundary, which greatly facilitates the enforcement of essential boundary conditions, and has good accuracy, convergence and monotonicity conditions that render it well-suited to applications involving shocks. A convenient feature of OTM, which is common to other material point methods [5], is that *seizing contact* is accounted for automatically, essentially for free, by simply allowing nodal points from different bodies to belong to the local neighborhoods of material points. The ensuing cancelation of linear momentum then automatically accounts for dynamic contact interactions of the seizing type.

In order to validate the OTM method, we have conducted tests concerned with the hypervelocity impact of Aluminum alloy 6061-T6 plates by Nylon 6/6 cylindrical projectile with diameter and length equal to 1.78mm over a range of plate thicknesses of [0.5, 1.6]mm, a range of impact velocities of [5.0, 7.0]km/s and obliquities of $[0, 30]^o$. The tests were conducted at Caltech's GALCIT Small Particle Hypervelocity Range (SPHIR) Facility, which houses a two-stage powder gun. The validate the OTM model by direct comparison of predicted and measured performance measures: the perforation area, temperature field and characteristics of debris cloud.

In all calculations, the material for the target is described by the variational thermomechanical coupling constitutive model of Yang [6], in which we assume the condition is adiabatic. Specially, we adopt the SESAME equation of state, J_2-viscoplasticity models with power-law hardening, rate-sensitivity and thermal softening at high strain rate [7], Newtonian viscosity model with temperature dependence [8] extended to gas phase in the variational formulation of the finite deformation thermomechanical constitutive equations. A polytropic type of equation of state fit to in-house ReaxFF calculations is employed to model the Nylon 6/6 projectile under extreme conditions.

With shared memory and distributed memory schemes, a dynamic load balancing MPI/PThreads parallel OTM method is developed in order to take advantage of the petascale computing facilities for accurate and detailed description of the hypervelocity impact event. Large scale three-dimensional OTM simulations of hypervelocity impact corresponding to the experimental setups are performed on departmental class systems. We found good agreement between the numerical results and experimental measurements. Based on this validation analysis, we find that the OTM-based model results in robust convergence and high-fidelity predictions of the high-energy density dynamic response of materials. In addition, excellent speedup to $O(10^5)$ threads is achieved in our numerical experiments, which indicates the potential of the parallel OTM algorithm for the next generation exascale computing.

References

[1] Li B., Habbal F. and Ortiz M.: Optimal transportation meshfree approximation schemes for fluid and plastic flows. *Int. J. Numer. Meth. Engng* **83(12)**:1541–1579, 2010.

[a)] Corresponding author. E-mail: ortiz@aero.caltech.edu

[2] Li B., Kidane A., Ravachandra G. and Ortiz M.: Verification and Validation of the Optimal-Transportation Meshfree (OTM) Simulation of Terminal Ballistics, *Int. J. Impact Eng.* **42**:25–36, 2012.

[3] Arroyo M. and M. Ortiz M.: Local maximum-entropy approximation schemes: A seamless bridge between finite elements and meshfree methods, *Int. J. Numer. Meth. Engng* **65**:2167–2202, 2006.

[4] Kane C., Marsden J.E. and Ortiz M.: Variational integrators and the Newmark algorithm for conservative and dissipative mechanical systems, *Int. J. Numer. Meth. Engng* **49(10)**:1295–1325, 2000.

[5] Yang Q., Stainier L. and Ortiz, M.: A variational formulation of the coupled thermo-mechanical boundary-value problem for general dissipative solids, *J. Mech. Phys. Solids* **54(2)**:401–424, 2006.

[6] Sulsky D. and Chen Z. and Schreyer H.L.: A particle method for history-dependent materials, *Comput. Meth. Appl. Mech. Eng.* **118**:179–186,1994.

[7] Yadav S., Chichili D.R. and Ramesh K.T.: The mechanical response of A 6061-T6 Al/Al_2O_3 metal matrix composite at high rates of deformation, *Acta Metall. Mater.* **43(12)**:4453–4464, 1995.

[8] Assael M.J., Kakosimos K., Banish R.M.: Reference Data for the Density and Viscosity of Liquid Aluminum and Liquid Iron, *J. Phys. Chem. Ref. Data* **35**:285–300, 2006.