Sliding interfaces in a 2D Free-Lagrange Godunov scheme on a Voronoi mesh

G.J. Ball
Atomic Weapons Establishment, Aldermaston, Reading, RG7 4PR, UK

High-velocity sliding contact between dissimilar strong materials plays a significant role in the dynamics of some explosively-driven systems, such as shaped charge devices, and in hypervelocity impact scenarios. The numerical simulation of sliding contact, or 'slide', is typically performed using Lagrangian or ALE finite-element hydrocodes. The sliding interfaces must be pre-defined on the initial mesh by specifying 'slide lines', at which appropriate boundary conditions are applied. The most popular slide algorithms use a 'master and slave' scheme in which one of the materials at the interface is designated as the master – the motion of the master controls the geometry of the slide line. In the case of ALE codes, the mesh is constrained to Lagrangian motion in the vicinity of slide lines – at least in the direction normal to the interface. Slide treatments are not generally available in Eulerian hydrocodes. Although slide algorithms are widely and successfully employed, they are cumbersome to code, while in use they are relatively inflexible because of the need to identify all slide lines at the start of a simulation. Also, because the treatment is essentially Lagrangian, they are limited to applications in which the degree of deformation of the slide line is modest, otherwise calculations fail due to mesh tangling.

Free-Lagrange (FL) codes such as *VUCALM*(Ball 1996) are immune to mesh tangling, and therefore offer fully Lagrangian simulations of dynamic systems with unlimited material deformation. However, as far as this author is aware, sliding contact has not been previously addressed using the Free-Lagrange approach. The purpose of this paper is to describe a novel slide treatment that has been developed for *VUCALM*.

VUCALM is a 2D finite volume FL hydrocode that uses a Godunov-type scheme which is 1st order in time and 2nd order in space, and includes a modified MUSCL slope limiter. An elastic-plastic material strength treatment is incorporated via an operator-split timestep (Howell and Ball 2002). The working fluid is divided into particles between which mass exchange is forbidden. A Voronoi mesh is then constructed such that each mesh cell encloses one particle plus the region of the domain which is closer to that particle than to any other. Each particle comprises a single material type, so material interfaces always lie along cell boundaries and are sharply resolved. The Voronoi mesh is treated as ephemeral, and may be reconstructed on every time step, so that the mesh connectivity changes freely in response to flow deformation. The user may opt to reconstruct the mesh less frequently in order to reduce CPU time, in which case the mesh nodes are convected at the local flow velocity between reconstructions.

In the present work, slide is enabled by setting the deviatoric stesses to zero between selected materials. The free connectivity of the FL mesh readily accomodates to the resulting relative motion without tangling. There is no requirement to define slide lines – sliding occurs automatically whenever the relevant materials come into contact. Hence this approach offers the potential for a very simple and flexible slide treatment. However, a difficulty remains in that spurious momentum diffusion, or 'numerical friction', occurs at the sliding interface. In fact numerical friction is endemic to Godunov schemes whenever a discontinuous shear flow is present, unless the flow is aligned with the mesh; on an unstructured mesh, alignment is not generally possible. In the case of a Voronoi mesh at a sliding interface, the cell boundary orientations change constantly relative to the interface. Consider the local Riemann problem to be solved on a cell boundary which is inclined to a shear discontinuity in a region of uniform static pressure. The normal components of the velocity field at the boundary will not be equal on either side, so that the pressure obtained from the Riemann solution, p^* will differ from the local static pressure. The sign of this difference is always in the sense that tends to diffuse momentum, i.e. a friction-like force results.

A novel limiter has been developed to minimise errors due to numerical friction. For each cell, the principal shear axes are determined based on the instantaneous strain rate. When solving the local Riemann problem, the orientation of these axes is compared to the alignment of the *relative* velocity vector between the materials on either side of the cell boundary. When alignment is perfect, pure shear flow exists, and p^* is limited to the mean of the static pressures in the two materials. When a misalignment of $\pi/4$ occurs the flow is shear-free, and no limiting is applied. A smooth but non-linear profile is followed between these extremes. The limiter yields near-zero numerical friction, but does not compromise shock behaviour. Results are presented for two test problems: a set of three concentric steel cylinders in which the middle cylinder rotates relative to the others, and a sandwich of steel and aluminium plates driven parallel to their interfaces by a high-pressure gas resevoir.

References

Ball GJ (1996) A Free-Lagrange method for unsteady compressible flow: simulation of a confined cylindrical blast wave. Shock Waves 5:311–325

Howell BP, Ball GJ (2002) A Free-Lagrange augmented Godunov method for the simulation of elastic-plastic solids. J. Comp. Phys. 175:128-167