A Cartesian Structured AMR Framework for Parallel Fluid-Structure Interaction Simulation

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ABSTRACT

Fluid-structure interaction simulations of strong shock and detonation waves impinging on heavily deforming solid structures require numerical methods that can cope with almost arbitrary topology changes. We present a level-set-based approach that allows the incorporation of time-accurate computational solid dynamics (CSD) solvers with large deformation, fracture and fragmentation capability into a parallel Eulerian Cartesian detonation solver. Structured adaptive mesh refinement (SAMR) is used in the fluid to dynamically capture the near-body interaction and incoming waves at minimal computational costs. Special attention is given to a scalable implementation of the hierarchical mesh refinement method, efficient parallel inter-solver communication routines, and the effective transformation of the evolving solid boundary into a Cartesian level set function. As computational example, the venting of an ethylene-oxygen detonation out of a thin aluminum tube involving large plastic deformations is presented.

The governing equations of detonation wave propagation in gases are the inviscid Euler equations [1]. In here, we consider only the simplified case of a single exothermic chemical reaction that we incorporate numerically with the constant volume burn model suggested by Mader [2]. This model neglects the detailed chemical depletion, and therefore the internal detonation structure, but ensures the right the speed of propagation and the correct state in chemical equilibrium at all resolutions. The model is intended to be applied together with the method of fractional steps that decouples chemical reaction and hydrodynamic transport numerically. As shock-capturing finite volume upwind scheme, we utilize the robust and positivity-preserving second-order upwind scheme by Van Leer. Geometrically complex moving boundaries are considered by using some of the finite volume cells as internal ghost cells to enforce immersed moving wall boundary conditions [3]. The boundary geometry is mapped onto the Cartesian mesh by employing a scalar level set function that stores the unsigned distance to the boundary surface. The level set function is derived on-the-fly from the embedded triangulated surface mesh received from the CSD solver by employing a highly efficient algorithm that is based on geometric characteristic construction and polyhedron scan conversion. The algorithm has linear complexity both in the number of surface triangles and the number of Cartesian finite volume cells [4].

A finite volume cell is considered to be a valid fluid cell within the interior, if the distance ϕ in the cell midpoint satisfies the condition $\phi > d/2$ and as an exterior ghost cell otherwise. In the example discussed later, the embedded surface is derived from a thin-shell finite element solver with optional fracture and fragmentation capability by F. Cirak [5,6] and corresponds to the dimensional mesh of element midplanes. The utilization of condition $\phi > d/2$ is a straightforward, unambiguous solution to achieve the mandatory thickening of this mesh by the shell element thickness. The contour line $\phi = d/2$ used as effective embedded boundary in the fluid solver is depicted as the dotted line around the shaded cells in Fig. 1. The hydrodynamic

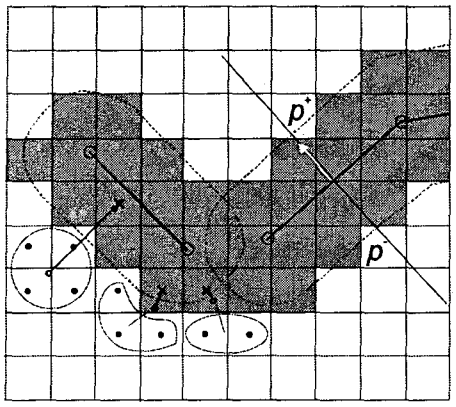

Figure 1. Ghost cells (gray) around the shell elements and construction of three mirrored values.

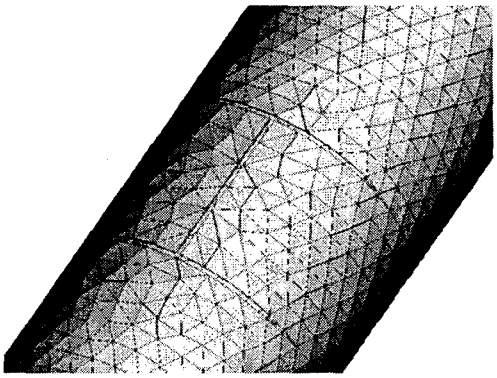

Figure 2. Triangular shell mesh with H-slit.

load on each element is evaluated as the difference between the approximated pressure values at $\phi=d/2$ in the positive and negative direction of each element normal, i.e. $p^F=p^+ - p^-$.

Figure 1 also visualizes the construction of mirrored values across the embedded boundary into internal ghost cells. We employ a dimension-wise linear interpolation for this operation, but it has to be emphasized that directly near the boundary the number of interpolants needs to be decreased to ensure the monotonicity preservation of the numerical solution, which is essential for hyperbolic problems involving discontinuities. The interpolation locations are indicated by the origins of the arrows normal to the contour line that defines the embedded boundary. After the application of the numerical scheme, cells that have been used to impose internal boundary conditions are set to the entire state vector of the nearest cell in the fluid interior. This operation ensures proper values in case such a cell becomes a regular interior cell in the next step due to boundary movement.

Fluid-structure interaction is assumed to take place only at the evolving interface between fluid and solid and is implemented numerically by exchanging boundary data between the SAMR detonation solver and the CSD solver after consecutive time steps in a fractional step splitting approach. In order to facilitate an efficient exchange of the necessary boundary information (element mesh and velocities to the fluid, pressure loadings to the solid) we have implemented a non-blocking communication library that determines the evolving point-to-point communication patterns efficiently by gathering and exchanging Cartesian bounding boxes around the domain decompositions for fluid and solid processes.

In order to provide the required temporal and spatial resolution effectively, we employ the SAMR method of Berger and Colella [7] that uses a patch-based refinement. The SAMR algorithm has been extended appropriately to accommodate the communication operations for fluid-structure coupling, see [8] for details. We parallelize the SAMR method by following a rigorous domain decomposition approach that partitions the SAMR hierarchy from the root level on. A careful analysis of the SAMR algorithm uncovers that the only parallel operations under this paradigm are ghost cell synchronization, redistribution of the data hierarchy and the application of correction terms at coarse-fine boundaries [9]. Currently, we employ a generalization of Hilbert's space-filling curve [10] to derive load-balanced root level distributions at runtime. The entire SAMR hierarchy is considered by projecting the accumulated work from higher levels onto the root level cells. The approach achieves acceptable speed-up on several hundred CPUs, cf. [8].

We present one exemplary simulation that was motivated by the experimental configurations studied by Chao [11]. The setup consists of a detonation tube of 1.52m, filled with C_2H_4+3 O_2 at 100kPa and room temperature, to which a tubular test specimen made of aluminum is attached. The test specimen has a length of 0.896 m, an inner radius of 1.975cm and a wall thickness of d=0.89mm. Thin perpendicular slits of 22mm length are cut in an H-shape into the middle of the tube to ensure a fully reproducible solid deformation and hydrodynamic venting, cf. Fig. 2. The simulations validate the adaptive fluid-structure methodology for later simulations involving complete solid material rupture. A J2 plasticity law with hardening and thermal softening is used as material model.

In order to fully simulate the venting process and the Taylor wave following the detonation wave in the detonation tube we use a computational domain of the dimensions [-0.39m, 0.39m]x [-0.0375m,0.5625m]x[-0.92m,0.896m] with a specimen middle axis at $x_{1,2}$=0m and the specimen extending from x_3=0m to x_3=0.896m. In order to model a sufficiently fine wall thickness we use an SAMR base mesh of 104x80x242 cells and three additional levels with refinement factors 2, 2, and 4. A corresponding unigrid simulation would require 7,930M cells, but the application of adaptive mesh refinement reduces the number of cells throughout the simulation to an average of 40M. The calculation was run on 16 nodes 2.2-GHz-AMD-Opteron quad-processor boards connected with PCI-X 4x Infiniband network and required 4320h CPU to simulate a physical time of 450μs. 8 processes where dedicated explicitly to the CSD solver and 64 to the SAMR fluid code. The upper graphics of Fig. 3 show the opening of the flaps and the hydrodynamic venting. The lower graphics display the levels of refinement in the fluid (indicated by colors of gray) and the enormous benefit in applying dynamic mesh adaptation to this type of simulations is apparent. Aside of the efficient level set evaluation algorithm, the utilization of SAMR for fluid-structure interaction simulation is the key enabling component of our approach.

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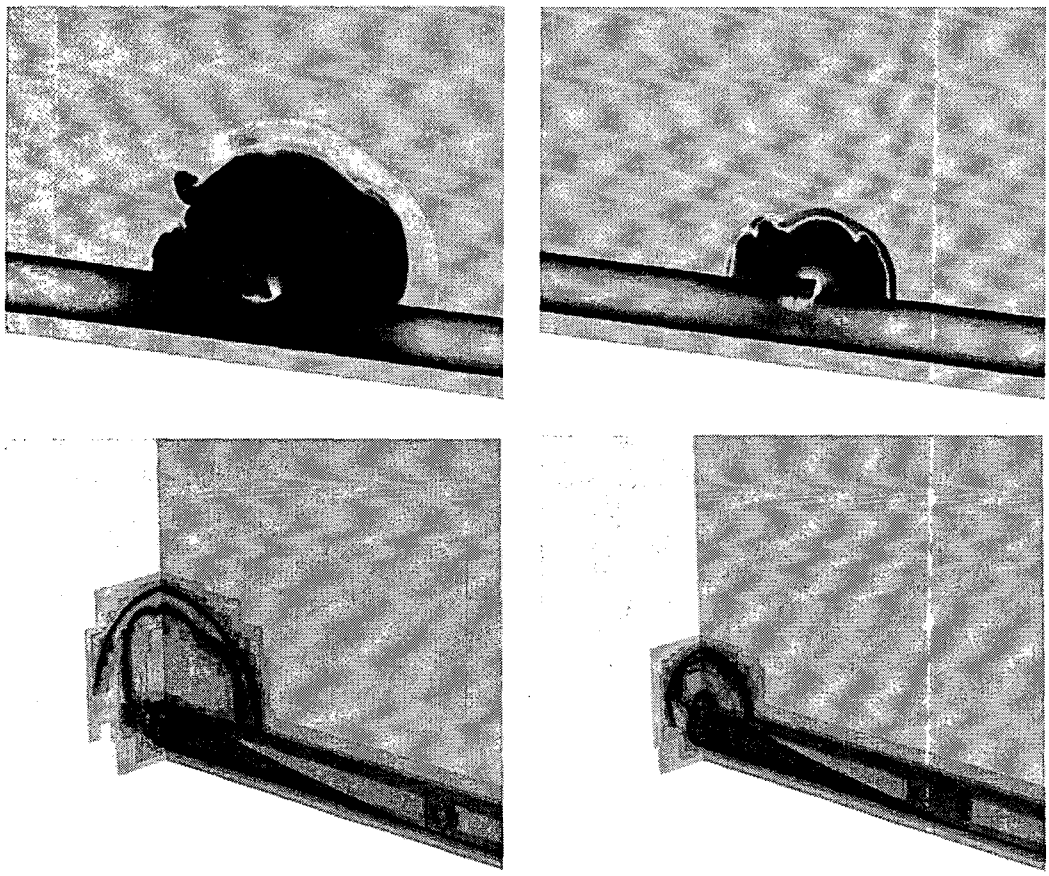

Figure 3. Fluid density and displacement in y-direction in solid (upper row) 90μs (left) and 210μs after the start of the flap opening; corresponding schlieren plot of fluid density on refinement levels (lower row).