Verification and Validation of the AMROC Fluid Solver Framework Coupling with DYNA3D within the Virtual Test Facility Fluid Structure Interaction Suite

Hydrodynamic equations

Euler equations
\[ \frac{\partial}{\partial t} \begin{pmatrix} \rho \varepsilon \cr \rho \varepsilon u \cr \rho \varepsilon v \cr \rho \varepsilon w \cr \rho \varepsilon E \cr \rho \varepsilon \end{pmatrix} + \nabla \cdot \begin{pmatrix} \rho \varepsilon u \varepsilon u + p & \rho \varepsilon u \varepsilon v & \rho \varepsilon u \varepsilon w & \rho \varepsilon u \varepsilon E \\ \rho \varepsilon v \varepsilon u & \rho \varepsilon v \varepsilon v + p & \rho \varepsilon v \varepsilon w & \rho \varepsilon v \varepsilon E \\ \rho \varepsilon w \varepsilon u & \rho \varepsilon w \varepsilon v & \rho \varepsilon w \varepsilon w + p & \rho \varepsilon w \varepsilon E \\ \rho \varepsilon E \varepsilon u & \rho \varepsilon E \varepsilon v & \rho \varepsilon E \varepsilon w & \rho \varepsilon E \varepsilon E + p \end{pmatrix} = 0 \]

Solid mechanics equations

Finite element scheme

- AMROC is based on a finite element discretization of the three spatial dimensions and finite difference discretization of time.
- DYNA3D is a lumped mass formulation for efficiency. This produces a diagonal mass matrix which renders the solution of the momentum equation

\[ M_{\text{mass}} \frac{\partial^2 \text{u}}{\partial t^2} + \mathbf{K} \text{u} = \mathbf{f} \]

Finite element formulation

- Inviscid at each step in this linear system of equations must be satisfied.

Fluid-structure coupling

- Compatibility conditions between inviscid fluid and solid at a slip interface:
  - Continuity of normal velocity: \(u_n^f = u_n^s\)
  - Continuity of normal stresses: \(\sigma_{nn}^f = \sigma_{nn}^s\)
  - No shear along interface: \(u_{ij}^f = u_{ij}^s\)

- Time-splitting approach for coupling

Structural AMR for hyperbolic problems

- Refined subgrid overlay coarse core
- Computational decoupling of subdomains by using ghost cells
- Redefinition in space and time
- Block-based data structures
- Cells without mesh are refined
- Explicit finite volume scheme

Routines to facilitate AMROC-DYNA

- Geometry
  - Pre-processor routine
  - Reads output from CUBIT 11.0 Mesh Generator and dynamically creates a DYNA3D input file
  - Supports hexahedral, tetrahedral, brick, and thin shell elements

- Cohesive elements
  - Numerical simulation cohesion or inter-element forces between "parallel" hex elements
  - Empties traction-displacement relationships to generate nodal forces based upon the projected displacements of the hex element corners in opening stage (node 1) and in plane shear (node 6) directions

- DYNA3D Post-processor routine
  - Extracts data from DYNA3D data structures
  - Supports hexahedral and thin shell elements
  - Outputs displacements, velocities, and stresses in XYZ format

Verification Test Case: Shock-induced panel motion

- Elastic motion of a thin steel plate (thickness \(h = 1\)mm, length \(50\)mm)
- Steel plate modeled with finer difference solver using the beam equation

\[ \frac{\partial^2 \text{y}}{\partial t^2} = \frac{E \text{I}}{\rho h^3} \frac{\partial^2 \text{y}}{\partial x^2} - \frac{p(x,t)}{E \text{I}} \]

Panel motion – FSI verification

- Overall structure geometry, reflective boundaries everywhere except trifur at left side, panel 1.5m behind start of step.
- Simulation run: 1.2s (100000 steps), 1 additional level with factors 2, 2
- Node and element connectivity was processed with Gigabit Ethernet
- Beam-FEM: 12.25G on 2 fluid CPUs + 2 solid CPUs
- FEM-FSI: 22.75G in 14 fluid CPUs + 3 solid CPUs
- AMROC-FD: 15 fluid CPUs + 1 solid CPU, max. 600G on 24 CPUs

Plastic deformation – FSI validation

- 3D simulation of plastic deformation of thin copper plate attached to the end of a pipe due to water hammer
- Strong wave front is induced by rigid plate motion at end of tube
- Two-component model based on “simplified” gas equation of state
- Computational runs: \(t = 6.5, 10.7, 14.5\) ms
- Captures models with pressure cut-off at -8GPa
- Realistic pressure loading in simulations coupled with solving equation of motion for plastic elements
- Inviscid flow driven by pump connections with Gigabit Ethernet

Validation Test Case: Plate deformation from water hammer

- Comparison of the fluid and solid response showed agreement in terms of deformation (horizontal) and plastic zones.

Fracture demonstration

- 3D simulation of plastic deformation of thin copper plate attached to the end of a pipe due to water hammer
- Molded cohesive elements and sliding contact between solid elements
- Preliminary results show agreement with experimental results

Dimensions of time simulation scales between two subdomains for the panel motions: (parallel) hex elements and (serial) radial solid elements and thin shell elements

- Thickness of cohesive elements is usually made smaller than the thickness of solid elements