SAND2022-7172C

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Non-intrusive coupling of multi-physics codes for Eulerian-Lagrangian solid-solid interaction using Immersed Finite Element Method

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Overview

- **Introduction**
- Review of modified Immersed Finite Element Method (mIFEM)
- Non-intrusive coupling of software
- Improvements in mIFEM algorithm
- Numerical test cases
- Summary and future work

Motivation

shock induced structural damage [1]

- **Simulation of hypervelocity impact and solid-solid interactions**
- **Applications:**
  - Ballistic penetration [2]
  - Geodynamics [3]
  - Spacecraft design [4]
- **Challenges:**
  - Non-linear wave propagation
  - Large plastic deformations, fragmentations

[1] https://commons.wikimedia.org/wiki/File:Shock_tube.JPG

[2] Shen Wei and Wu Cuisheng. Computer simulation for damage-failure process of composite plate under high-speed impact. Engineering fracture mechanics, 1992

[3] Francois E Heuz´e. An overview of projectile penetration into geological materials. In International journal of rock mechanics and mining sciences & geomechanics abstracts, Elsevier, 1990

[4] MV Silnikov, IV Guk, AF Nechunaev, and NN Smirnov. Numerical simulation of hypervelocity impact problem for spacecraft shielding elements. Acta Astronautica, 2018

Motivation

Hydrocode: codes used to simulate **highly dynamic events** involving shocks

Lagrangian Hydeocodes

- **Nodes are attached to material points.**
- Explicit material boundaries
- Easier to apply interface conditions.
- Mesh distortion
- Need re-meshing/ element deletion strategies
- DYNA [1], Camacho and Ortiz [2]

Eulerian Hydeocodes

- **Materials are tracked across a fixed mesh.**
- Fixed mesh, large plastic deformations.
- interfaces are not tracked explicitly
- Benson [3], Udaykumar et. al. [4]

Coupled Lagrangian-Eulerian

- **Projectile: Lagrangian description**
- **Target: Eulerian description**
- **Leverage advantages of both approaches**
- Zapotec [5]

[1] JO Hallquist and RG Whirley. Dyna3d user manual, nonlinear dynamic analysis in three dimensions. Report UCID-19592, Rev, 5, 1989.
[2] GT Camacho and M Ortiz. Adaptive lagrangian modelling of ballistic penetration of metallic targets. Computer methods in applied mechanics and engineering, 1997
[3] DJ Benson. A multi-material eulerian formulation for the efficient solution of impact and penetration problems. Computational mechanics, 1995.
[4] HS Udaykumar, L Tran, DM Belk, and KJ Vanden. An eulerian method for computation of multimaterial impact with eno shock-capturing and sharp interfaces. Journal of Computational Physics, 2003
[5] Bessette et. al., Zapotec: A Coupled Euler-Lagrange Program for Modeling Earth Penetration (2002)

Overview

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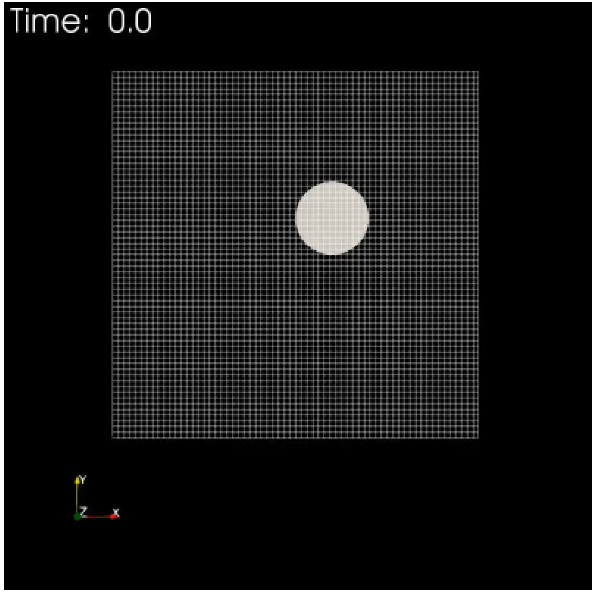
Background

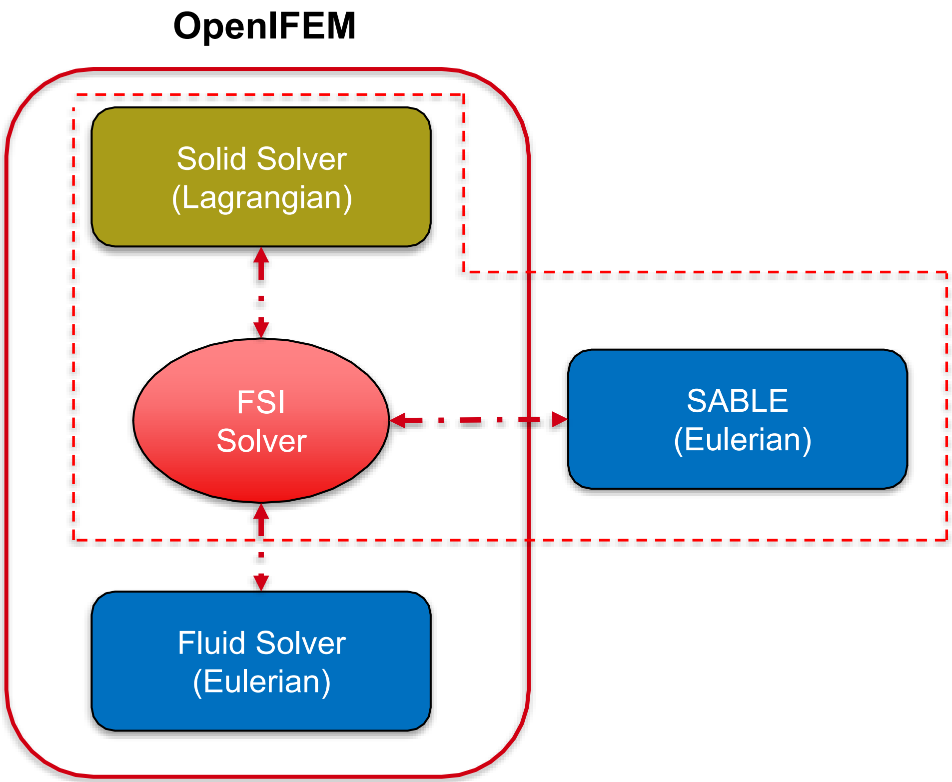


- **Modified Immersed Finite Element Method (mIFEM)** [1]
  - Non-conforming mesh method, partitioned approach
  - Inspired from IB method [2]

- **Comparison with classical IB:**
  - **Volume based** interpolation
  - **Solve solid dynamics** and enforce it on overlapping fluid
  - **Solid has constitutive relationship** and yields stress information

[1] Xingshi Wang and Lucy T. Zhang. Modified immersed finite element method. Computer Methods in Applied Mechanics and Engineering, 267:150–169, 2013.
[2] Charles S Peskin. The immersed boundary method. Acta Numerica, 11:479–517, 2002

Background

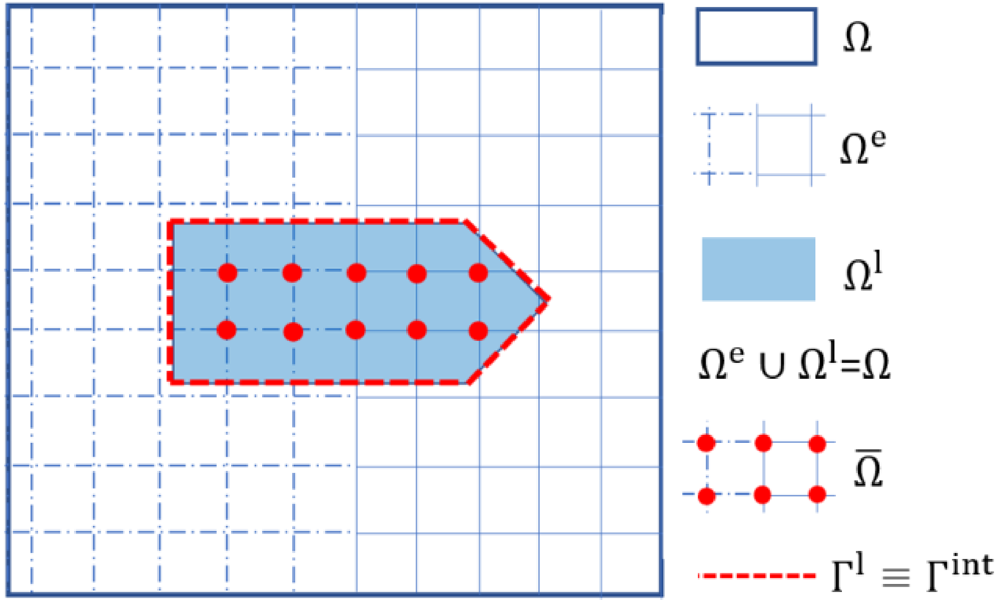


- **OpenIFEM** [1]:
  - Opensource, C++
  - Modular implementation of mIFEM

- **Objectives:**
  - Couple a multi-material Eulerian shock physics code **SABLE** [2] with **OpenIFEM** for simulation of solid-solid impacts.
  - Couple OpenIFEM and SABLE non-intrusively.
  - Provide framework for coupling two hydrocodes.

[1] https://github.com/OpenIFEM
[2] KM Hays et al. A users guide to sable 2.0: The sandia automated boolean logic evaluation software. Sandia National Lab. (1996)

mIFEM Algorithm: Domain decomposition



virtual work done by the Eulerian material — virtual work done by the Lagrangian material

$$\int_{\Omega^e}\delta v_i\left(\rho^e\frac{Dv_i^e}{Dt}-\sigma^e_{ij,j}-\rho^e g_i\right)d\Omega+\int_{\Omega^l}\delta v_i\left(\rho^l\frac{Dv_i^l}{Dt}-\sigma^l_{ij,j}-\rho^l g_i\right)d\Omega=0$$

$$\int_{\Omega}\delta v_i\left(\rho^l\frac{Dv_i^e}{Dt}-\sigma^e_{ij,j}-\rho^l g_i\right)d\Omega+\int_{\Omega^l}\delta v_i\left(\rho^l\left(\frac{Dv_i^l}{Dt}-\frac{Dv_i^e}{Dt}\right)-\left(\sigma^l_{ij,j}-\sigma^e_{ij,j}\right)\right)d\Omega$$

$$\bar\rho=\begin{cases}\rho^l & \text{in } \Omega^l\\ \rho^e & \text{in } \Omega^s\end{cases}$$

$$-F_i^{\mathrm{int}}$$

$$\int_{\Omega}\delta v_i\left(\bar\rho\frac{\partial v_i^e}{\partial t}+\bar\rho v_j^e v_{i,j}^e-\sigma^e_{ij,j}-\bar\rho g_i\right)d\Omega=\int_{\Omega^1}\delta v_i F_i^{\mathrm{int}}\,d\Omega$$

Lagrangian

$$\rho^{\mathrm{l}} u_{,tt} = \sigma^{\mathrm{l}}_{ij} \qquad \text{in } \Omega^{\mathrm{l}}$$

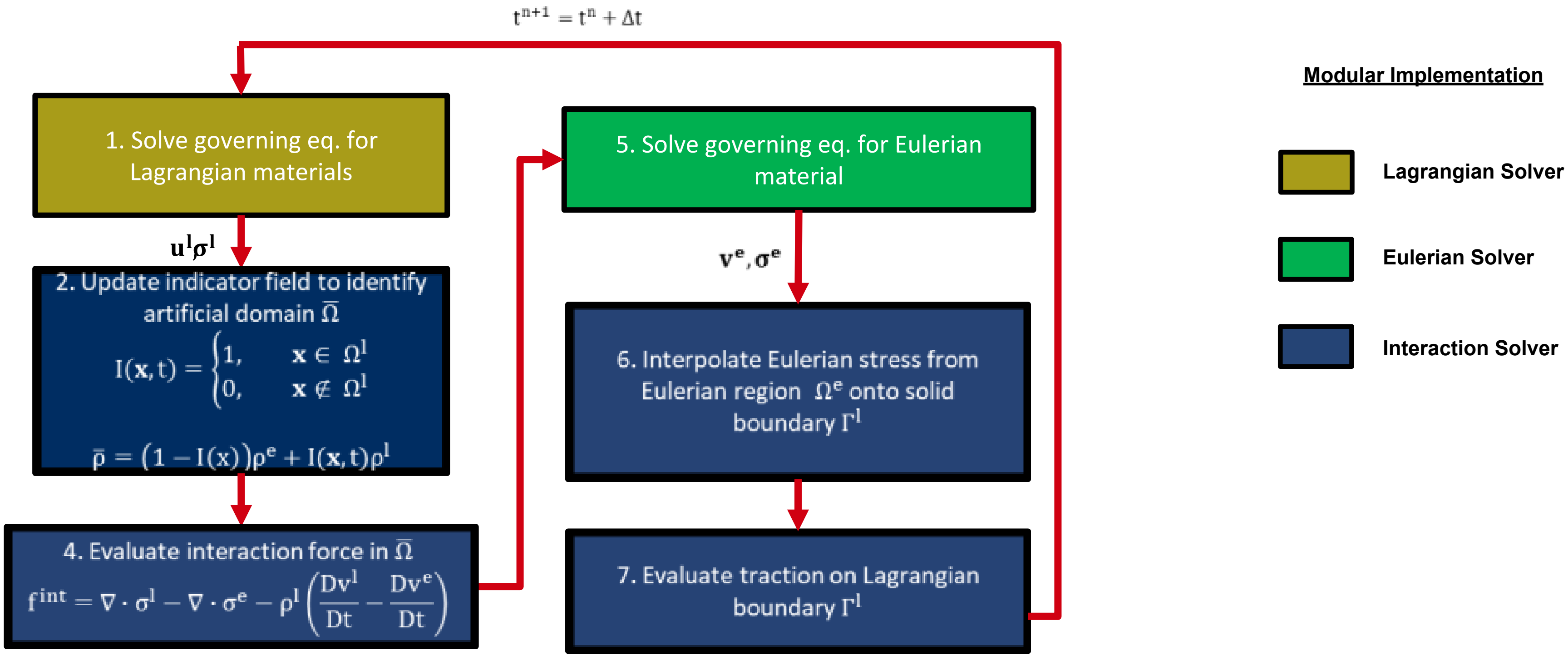
$$u_i = g_i = v_i^{\mathrm{e}} \Delta t \qquad \text{on } \Gamma^{\mathrm{sq}}$$

$$\sigma^{l}_{ij} n_j = h_i = -\sigma^{e}_{ij} n_j \qquad \text{on } \Gamma^{\mathrm{sh}}$$

Eulerian

$$\bar{\rho}\left(\frac{\partial v_i^{\mathrm{e}}}{\partial t} + v_j v^{\mathrm{e}}_{i,j}\right) = \sigma^{\mathrm{e}}_{ij,j} + F_i^{\mathrm{int}}(\mathbf{x}, t)$$

mIFEM Algorithm



Cheng J et al., OpenIFEM: A high performance modular open-source software fluid-structure interactions. (2019)

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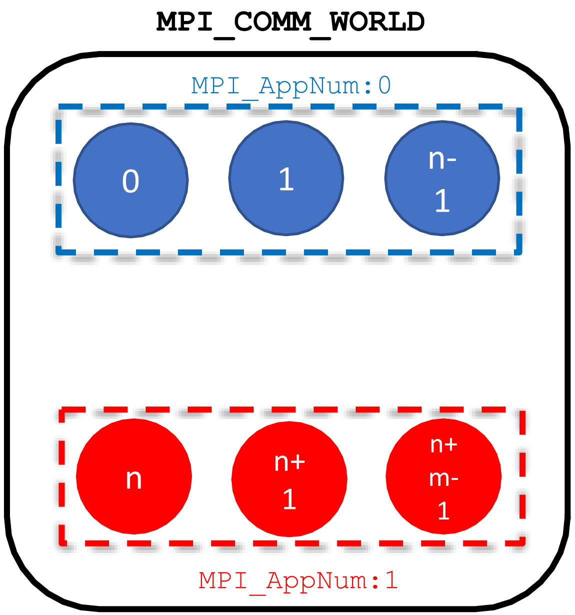
OpenIFEM-SABLE Coupling

- Coupling via information exchange using MPI protocols

1. Launch OpenIFEM and SABLE:
   - `mpirun -np n OpenIFEM : -np m SABLE`

2. Find total number of applications running simultaneously:
   - Get `MPI_APPNUM` using the function

     `MPI_Comm_get_attr`



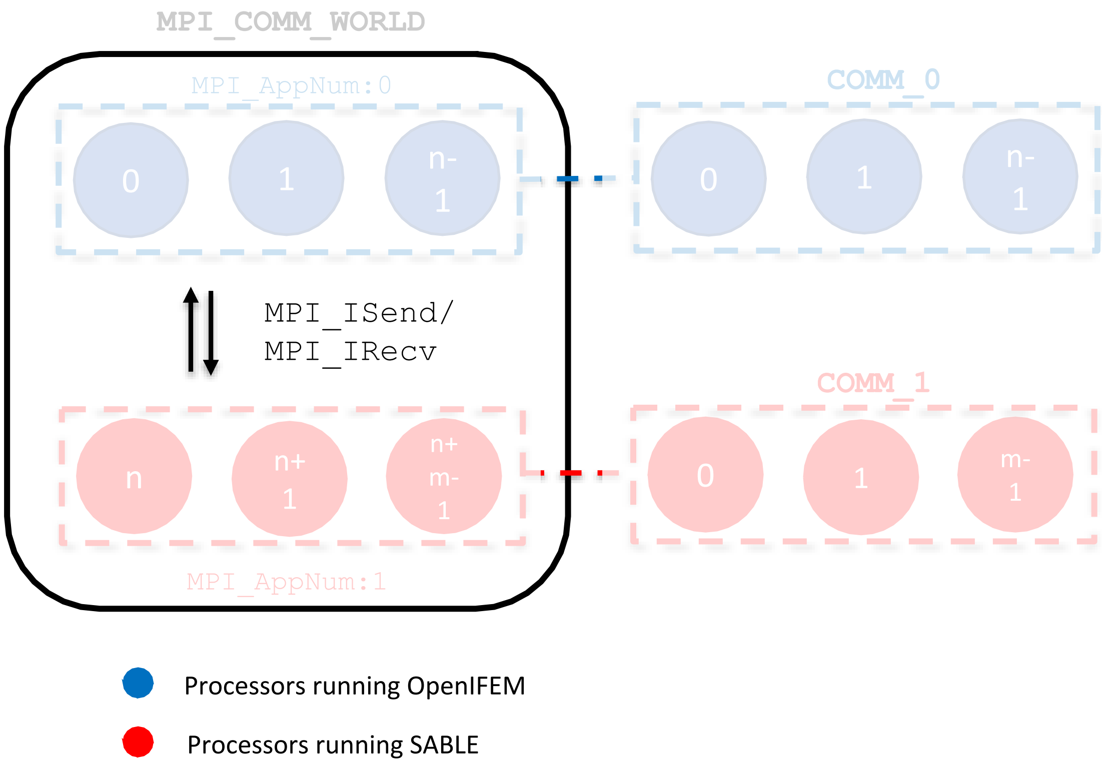
Processors running OpenIFEM

Processors running SABLE

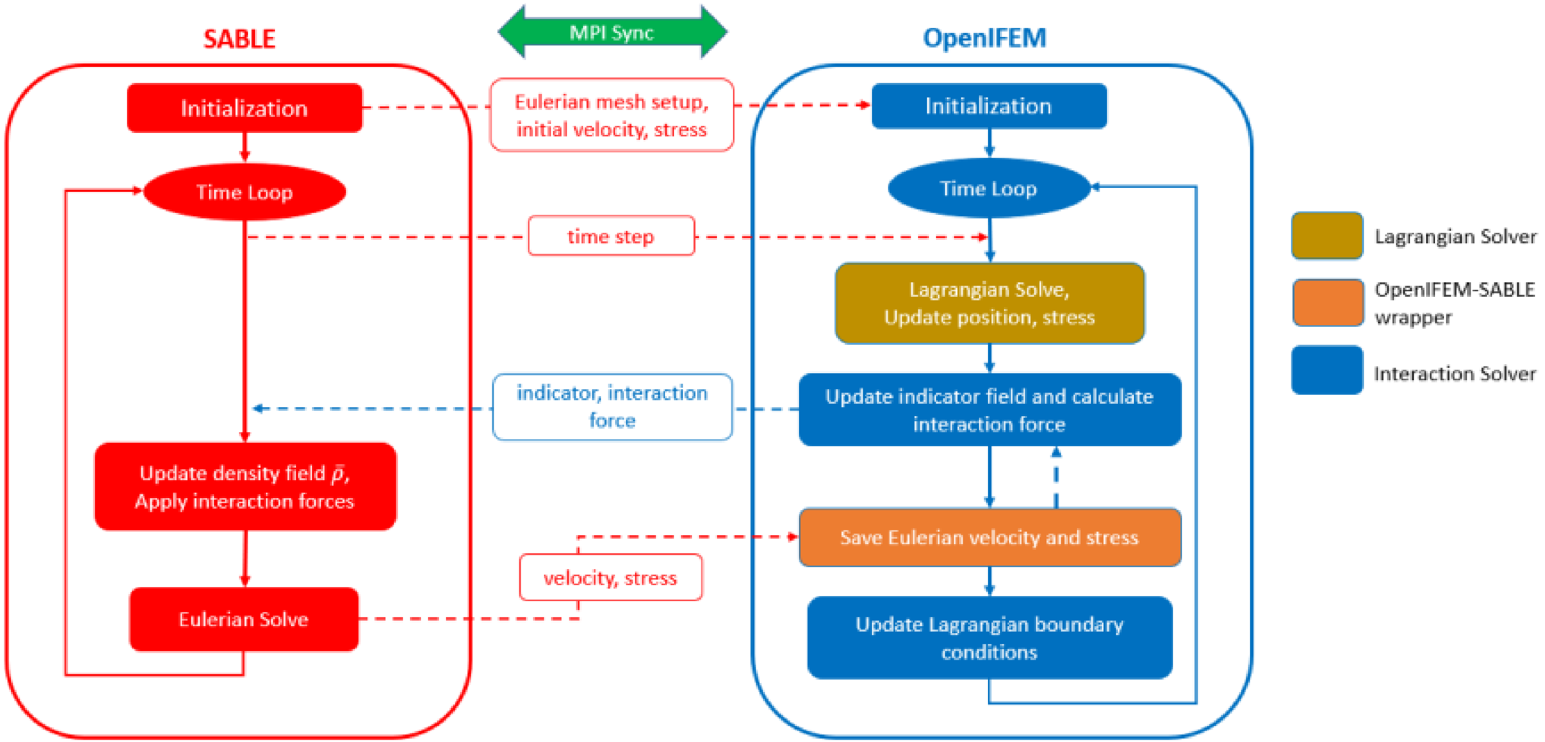
OpenIFEM-SABLE Coupling

3. Split MPI_COMM_WORLD into two communicators using function: MPI_COMM_split

4. Switch to MPI_COMM_WORLD and exchange data using MPI_ISend and MPI_IRecv



OpenIFEM-SABLE Coupling



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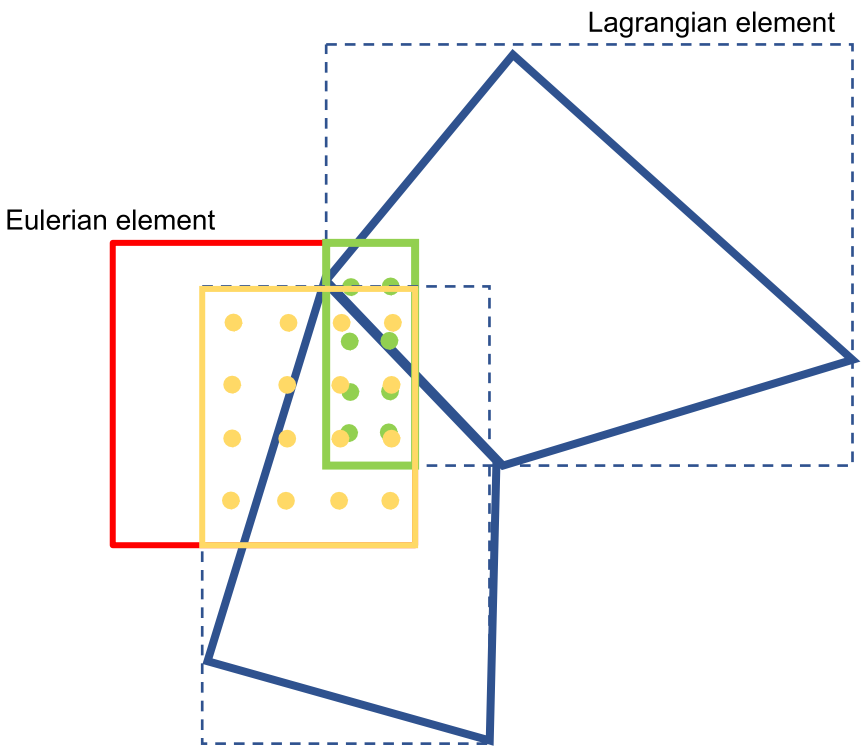
Improvements in mIFEM for solid-solid coupling

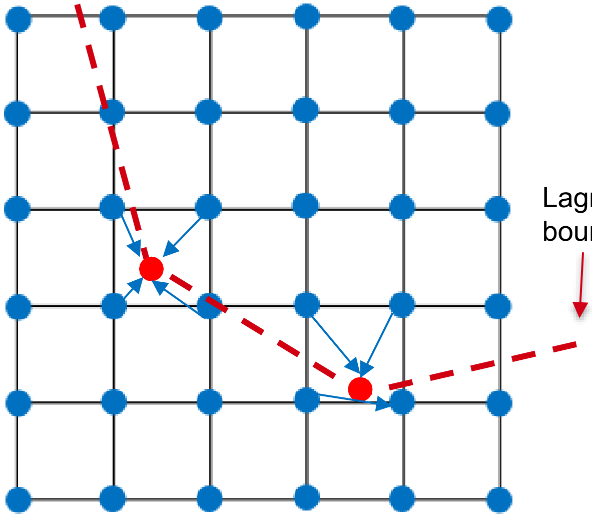


- **Improved Interface**
  - Check intersection of each Lagrangian cell bounding box with Eulerian cell
  - Sample points in bounding box.
  - Check if the point is inside the selected element.
  - Exact indicator from current Lagrangian cell

$$= \frac{\text{Area (intersection box)}}{\text{Area(cell)}} * \frac{\text{points inside solid cell}}{\text{total points sampled}}$$

  - Repeat for all the elements.

Improvements in mIFEM for solid-solid coupling



- **Added mass effect** [1], [2]:
  - Inertial effect of Eulerian solid
  - Increase effective forces on Lagrangian solid
  - Calculate lumped mass for Eulerian solid.
  - Interpolate Eulerian nodal mass to Lagrangian boundary nodes

- **Calculation of stable time step:**
  - SABLE: explicit hydrocode
  - Stable time step $\Delta t = \alpha * f(h, C^E)$
  - h: grid size, C^E: elastic wave speed for Eulerian material, α=0.85
  - Stable time step for coupled run:
    - $\beta = C^E / C^L$
    - $\Delta t = \beta * \alpha * f(h, C^E)$

[1] Panton, R.L., Incompressible Flow, JohnWiley and Sons (1984)
[2] Brown et. al. Coupled Eulerian–Lagrangian methods for earth penetrating weapon applications, Sandia National Laboratories (2002)

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- ➢ Introduction
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- ➢ **Numerical test cases**
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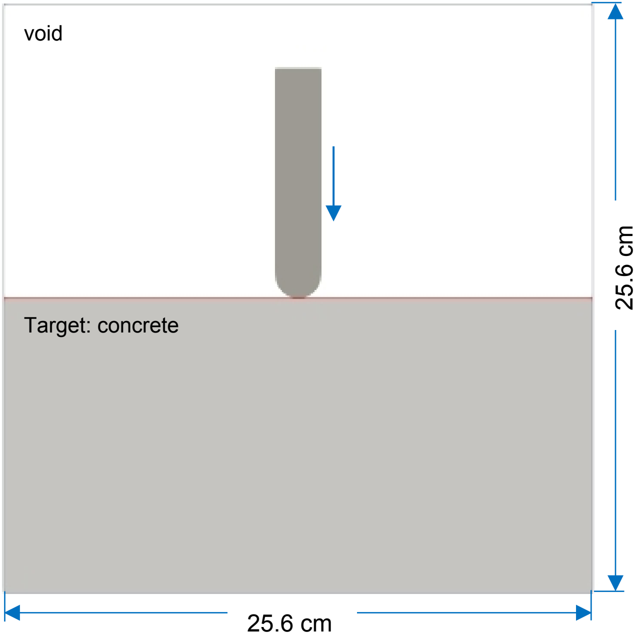
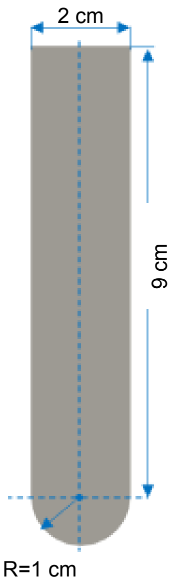
Test Case 1: Setup

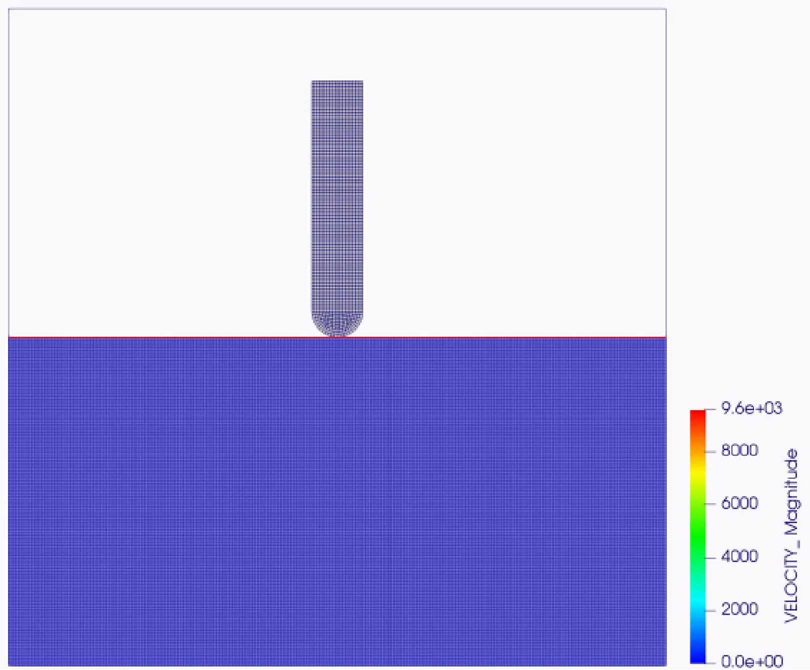




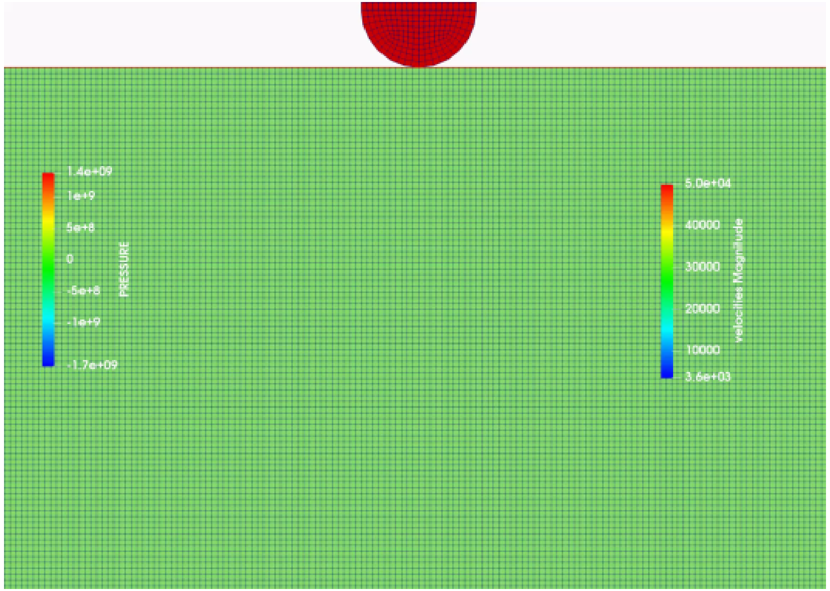
- **Eulerian (target):**
  - Material: void + concrete
  - Concrete:
    - Material mode: elastic-plastic
    - Compressive strength: 23 Mpa
    - Density: 2.03 g/cm^3
  - BCs: no displacement at all sides
  - Mesh: dx=dy=0.1 cm
- **Lagrangian (projectile):**
  - Material: 4340 steel
    - Material model: linear elastic
    - E: 20 GPa ν: 0.28
    - Density: 7.8 g/cm^3
  - Mesh: dx=dy=0.1 cm
  - Initial velocity: **-50,000 cm/s**
- Simulation time: 5e-4 s

Test Case 1: Results

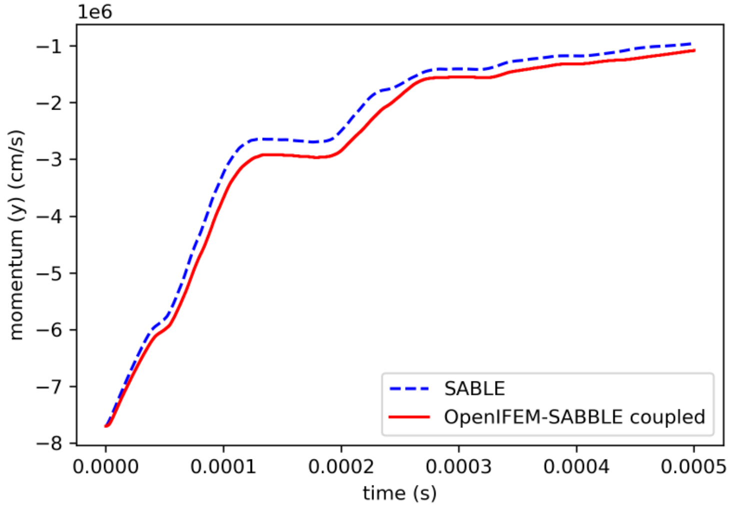
Target velocity (cm/s)

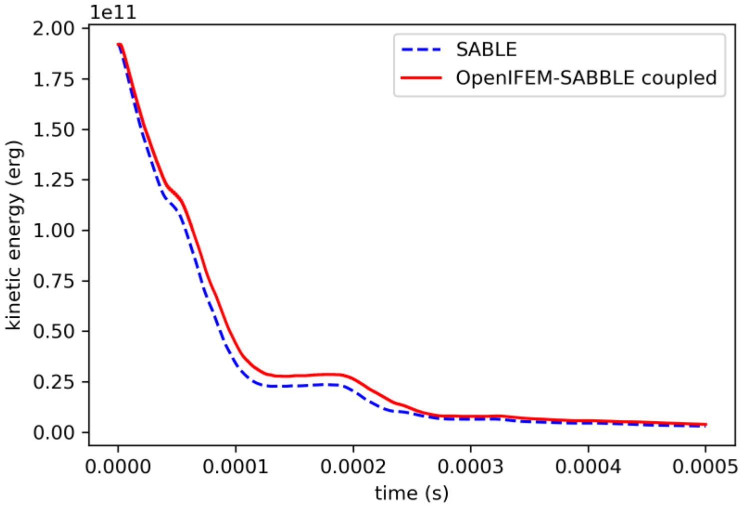


Target pressure $(\mathrm{dyn/cm^2})$ + Projectile velocity (cm/s)



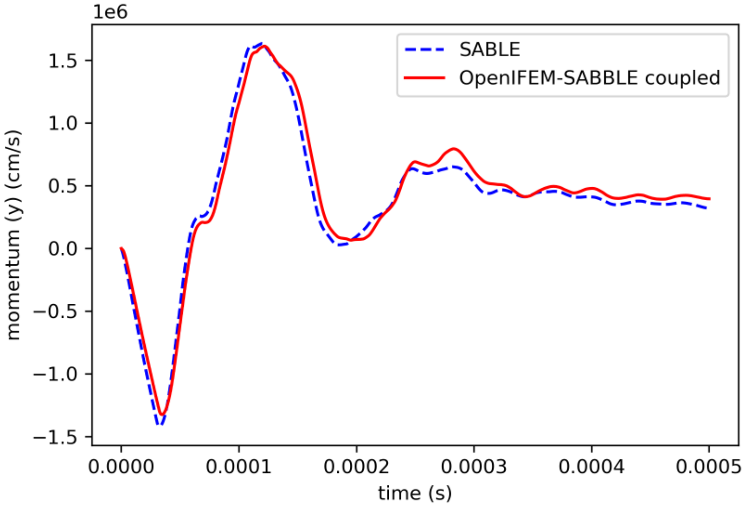
Projectile Results

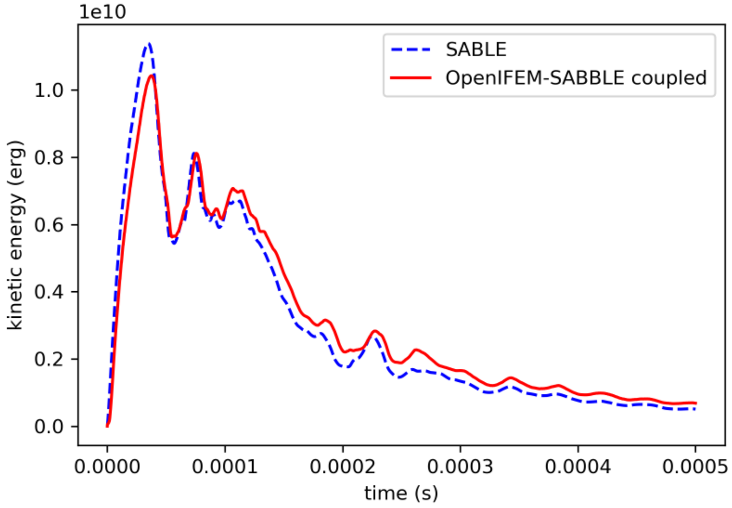




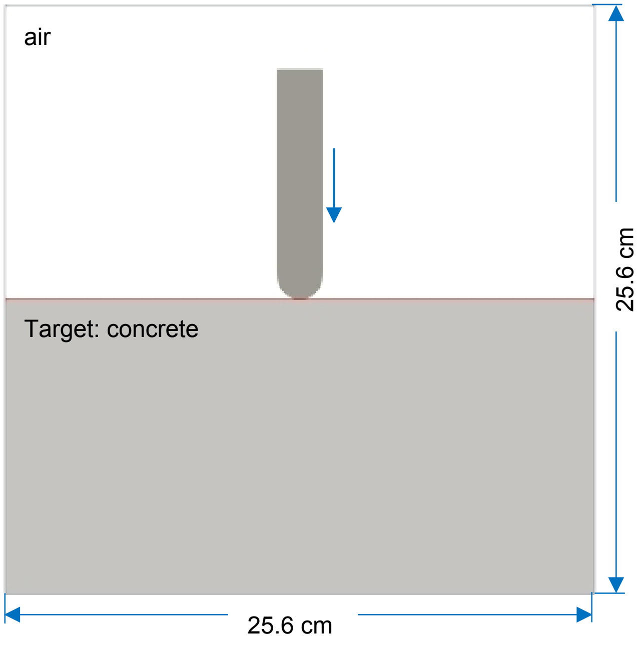
Test Case 1: Results

Target Results





Test Case 2: Setup



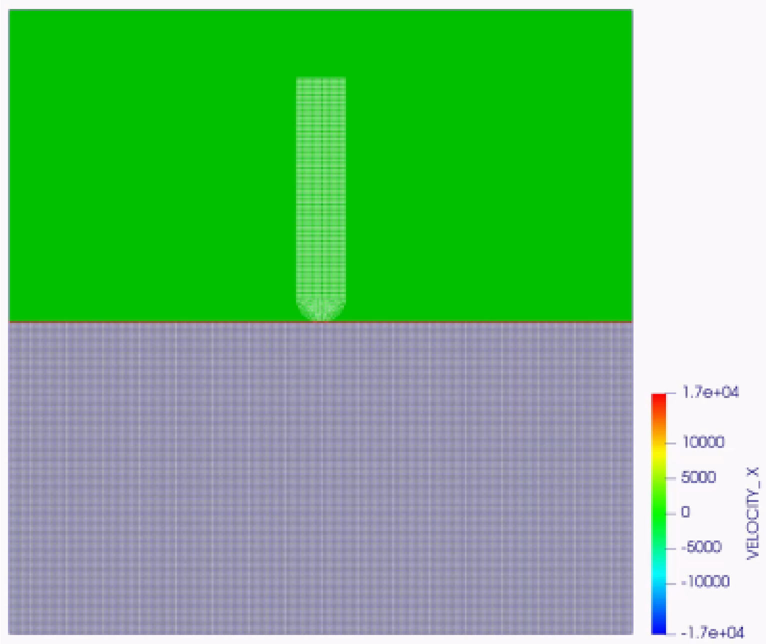
- **Eulerian (target):**
  - Material: air + concrete
  - Air:
    - Pressure: 1e6 $\mathrm{dyn/cm^2}$
    - Density: 1.2e-3 $\mathrm{g/cm^3}$
  - Concrete:
    - Material mode: elastic-plastic
    - Compressive strength: 23 Mpa
    - Density: 2.03 $\mathrm{g/cm^3}$
  - BCs: no displacement at all sides
  - Mesh: dx=dy=0.1 cm

- **Lagrangian (projectile):**
  - Material: 4340 steel
    - Material model: linear elastic
    - E: 20 GPa ν: 0.28
    - Density: 7.8 $\mathrm{g/cm^3}$
  - Mesh: dx=dy=0.1 cm
  - Initial velocity: **-50,000 cm/s**

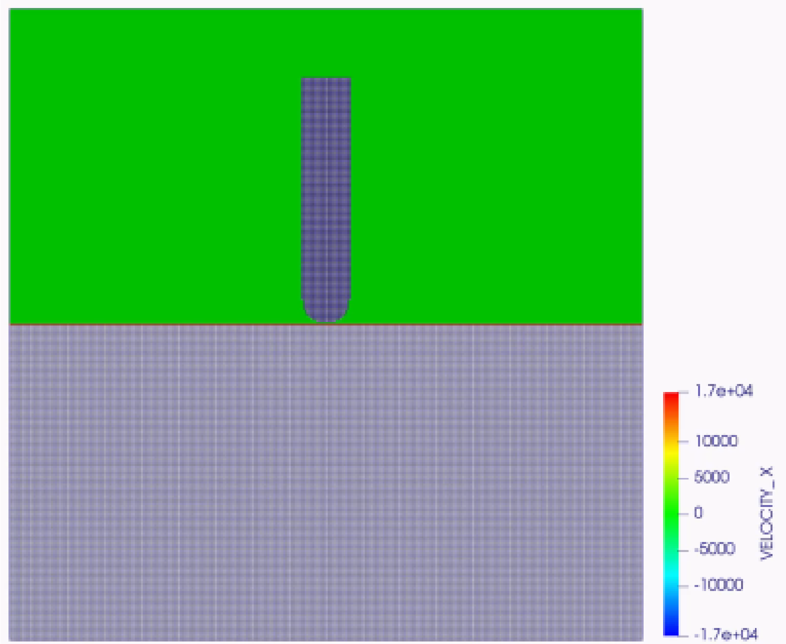
- Simulation time: 5e-4 s

Test Case 2: Results

Air velocity x (cm/s): **OpenIFEM-SABLE coupled**

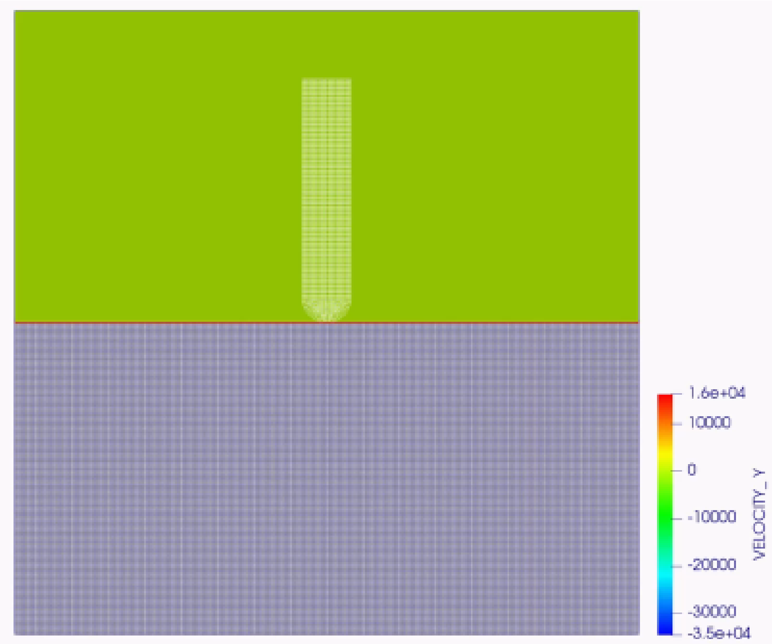


Air velocity x (cm/s): **SABLE**

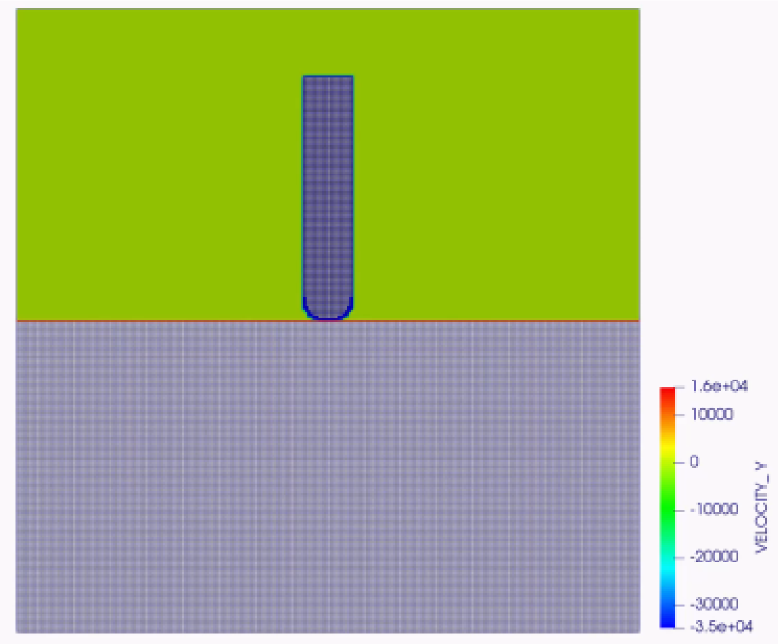


Test Case 2: Results

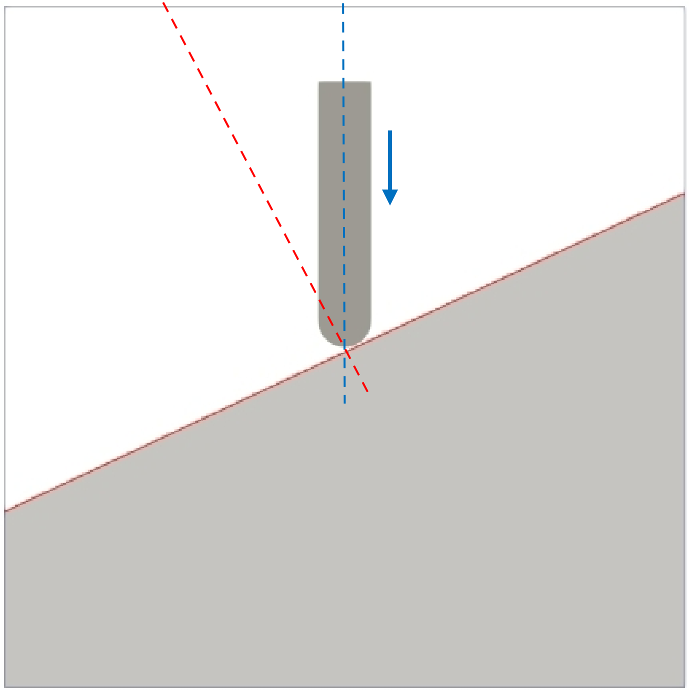
Air velocity y (cm/s): **OpenIFEM-SABLE coupled**



Air velocity y (cm/s): **SABLE**



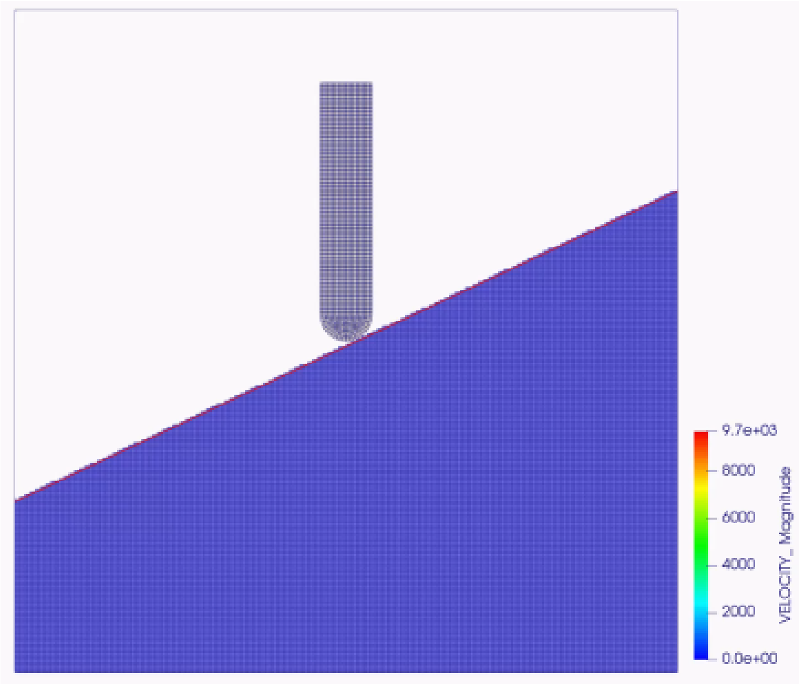
Test Case 3: Setup



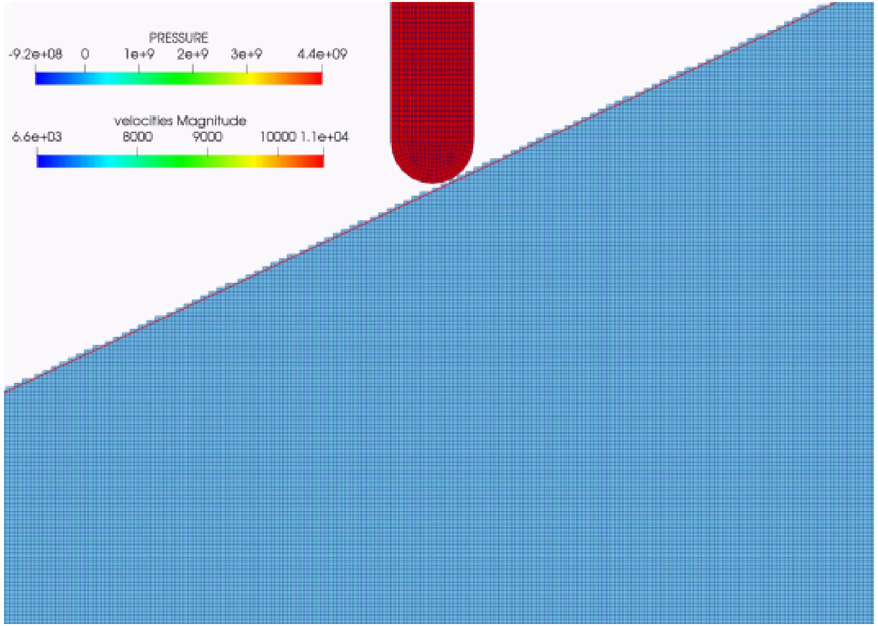
- **Oblique impact: $\theta = 25^0$**
- **Eulerian (target):**
  - Material: void + concrete
  - Concrete:
    - Material mode: elastic-plastic
    - Compressive strength: 23 Mpa
    - Density: 2.03 g/cm^3
  - BCs: no displacement at all sides
  - Mesh: dx=dy=0.1 cm
- **Lagrangian (projectile):**
  - Material: 4340 steel
    - Material model: linear elastic
    - E: 20 GPa ν: 0.28
    - Density: 7.8 g/cm^3
  - Mesh: dx=dy=0.1 cm
  - Initial velocity: **-50,000 cm/s**
- Simulation time: 5e-4 s

Test Case 3: Results

Target velocity (cm/s)

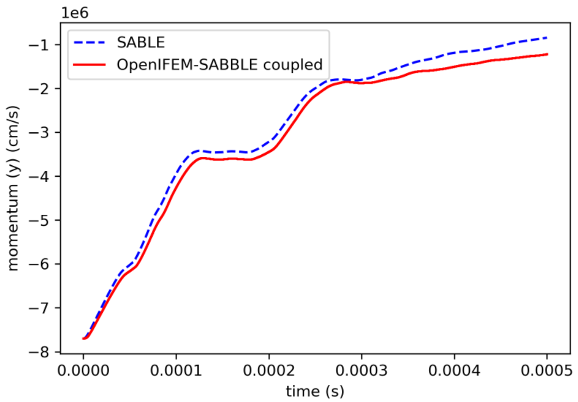


Target pressure $(\mathrm{dyn/cm^2})$ + Projectile velocity (cm/s)

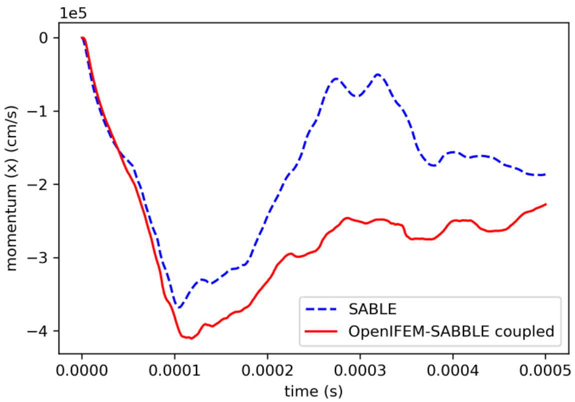


Test Case 3: Results

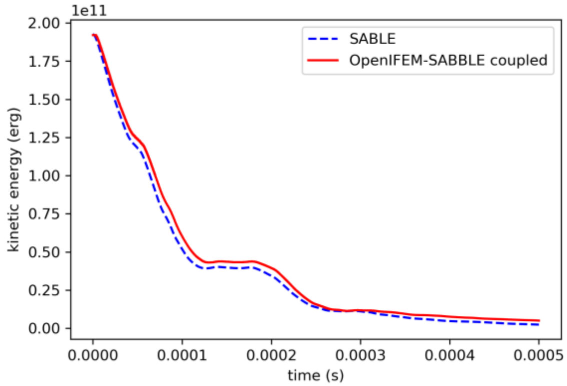
Projectile momentum (y)



Projectile momentum (x)

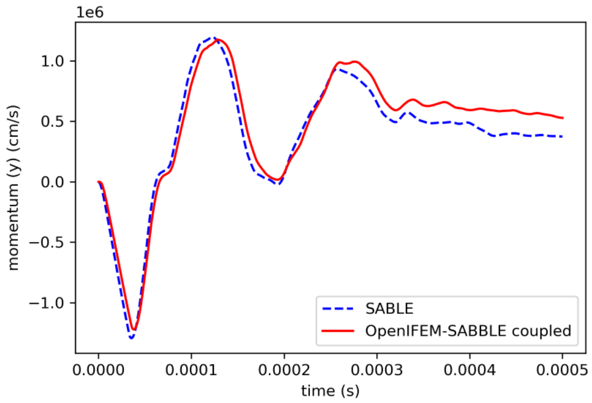


Projectile kinetic energy

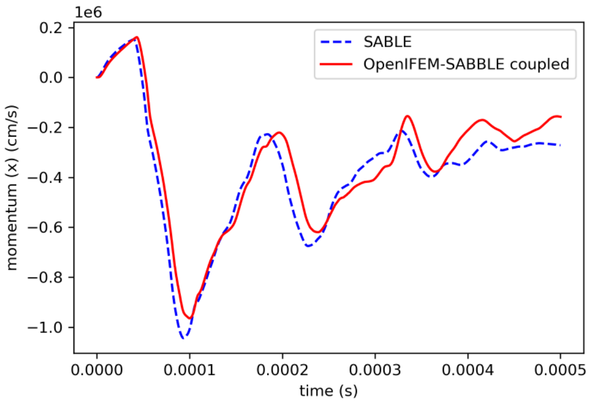


Test Case 3: Results

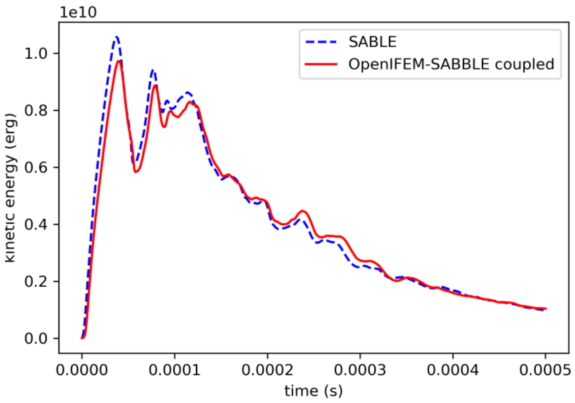
Target momentum (y)



Target momentum (x)

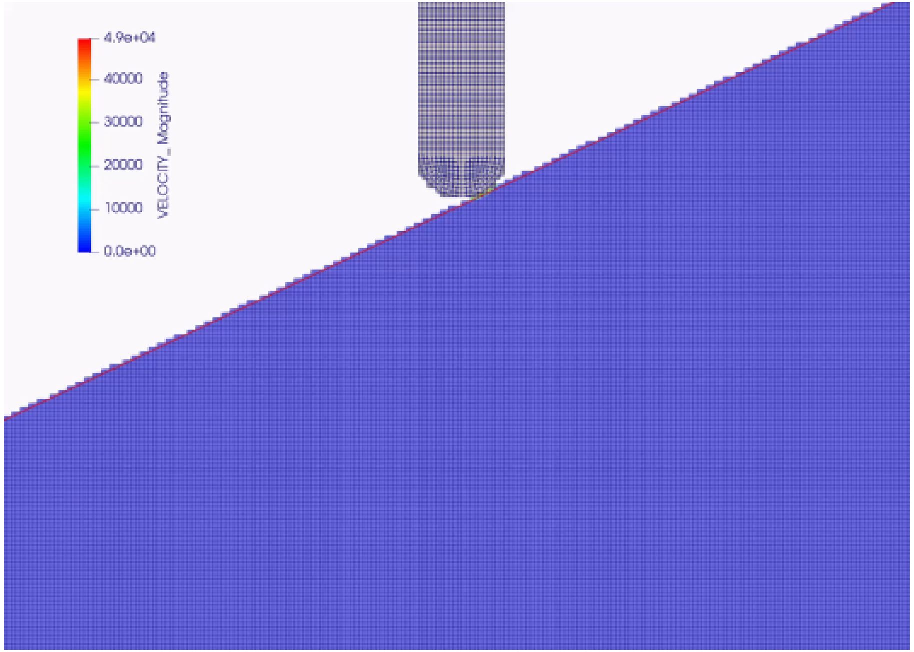


Target kinetic energy

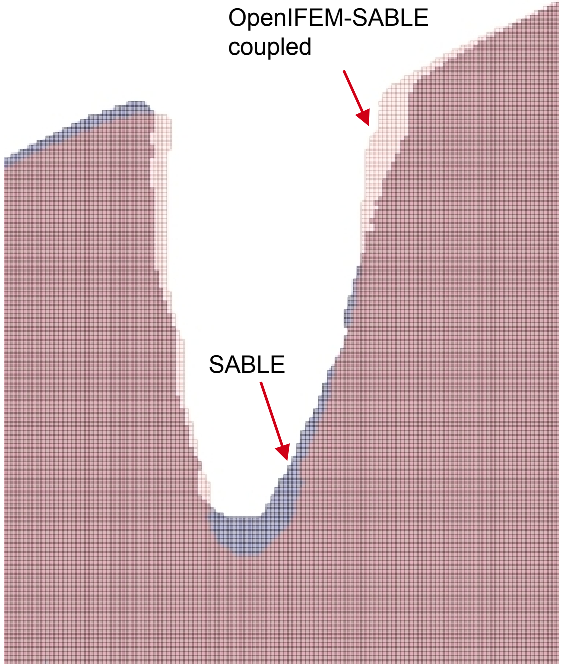


Test Case 3: Results

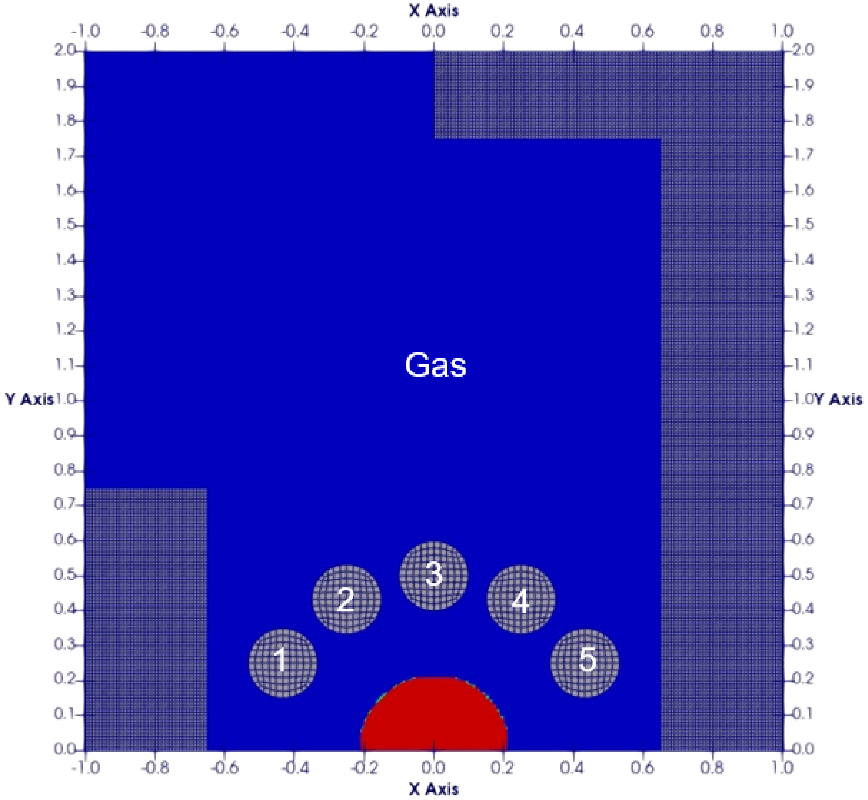
SABLE run: comparison with Lagrangian projectile



Target at t=5e-4 s



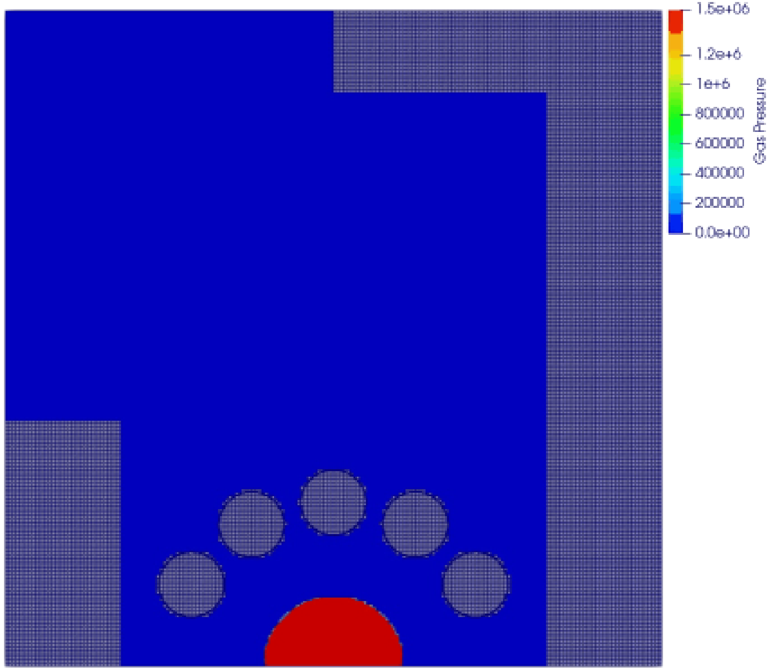
Test Case 4: Setup



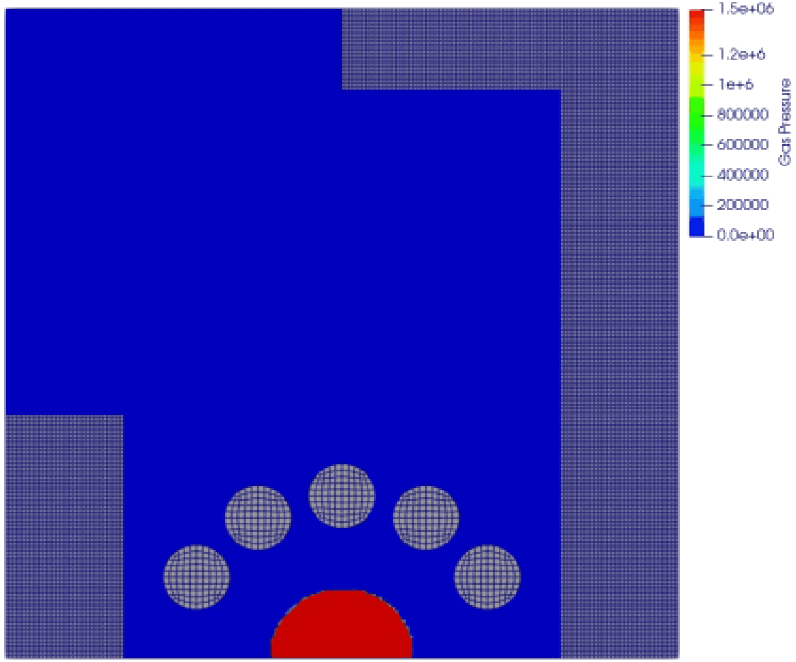
- **5 Plexiglass balls** loaded by **a high-pressure gas with moveable plexiglass walls**
- **Eulerian:**
  - **High-Pressure Gas Region**
    - (x,y) = (0.0, 0.0), Radius = 0.3 cm
    - Initial Pressure: 10^8 dynes/cm^2
  - **Low-Pressure Gas Region**
    - Initial Pressure: 10^{-5} dynes/cm^2
    - Initial Density: 1 gm/cm^3
- **Lagrangian:**
  - Plexiglass balls, Radius = 0.1 cm
    - Ball-1: (x,y) = (-0.4330,0.2500)
    - Ball-2: (x,y) = (-0.2500,0.4330)
    - Ball-3: (x,y) = (0.0000,0.5000)
    - Ball-4: (x,y) = (0.2500,0.4330)
    - Ball-5: (x,y) = (0.4330,0.2500)
  - Plexiglass properties
    - Hyperelastic Neo-Hookean material
    - c1 = 4.85e11 dynes/cm^2 c2 = 1.35e12 dynes/cm^2
    - Density: 1.18 gm/cm^3
- Simulation time: 6e-4 s

Test Case 4: Results

Gas pressure $(\mathrm{dyn/cm^2})$: **SABLE**

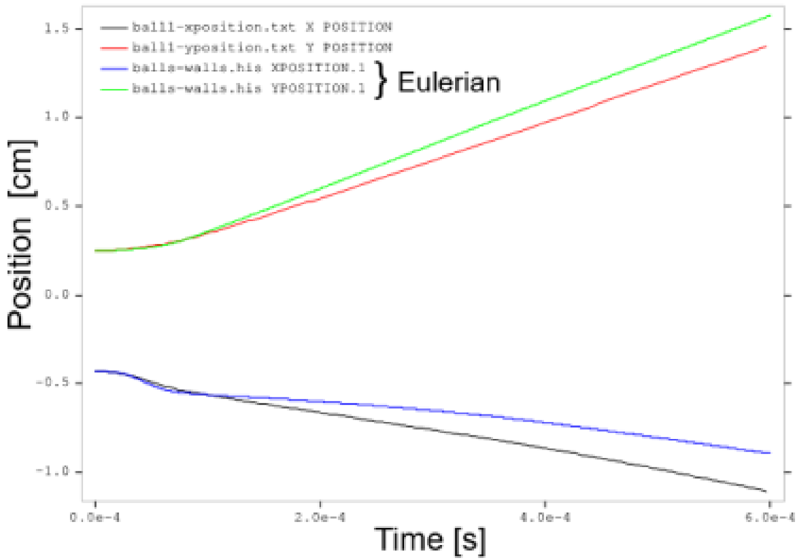


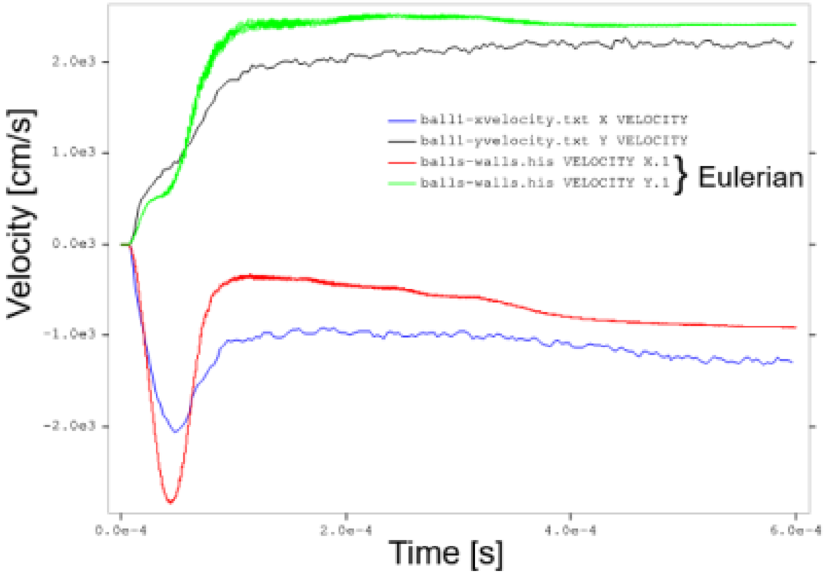
Gas pressure $(\mathrm{dyn/cm^2})$: **OpenIFEM-SABLE coupled**



Test Case 4: Results

Ball-1:





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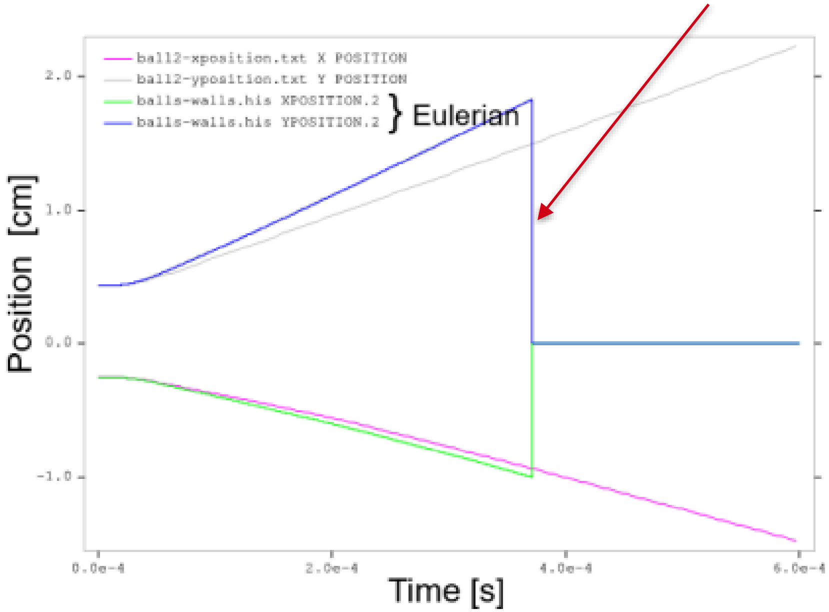
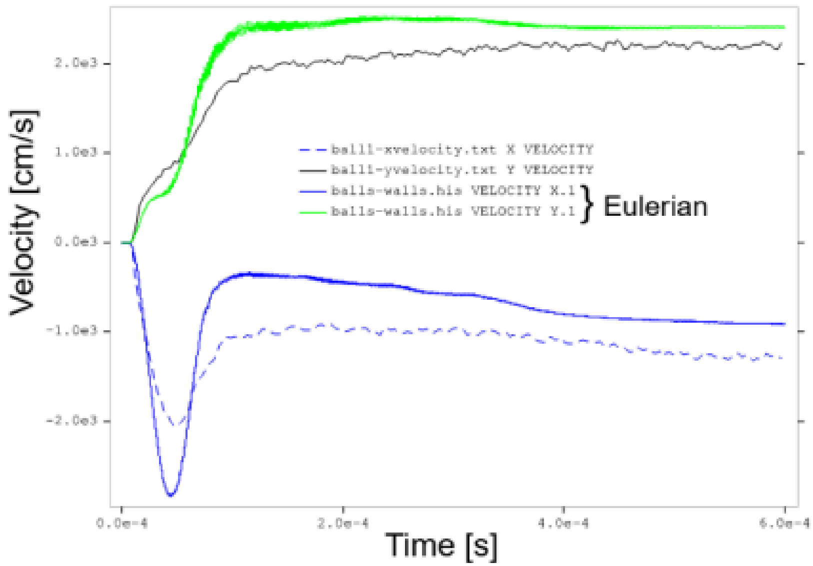
Ball-2:

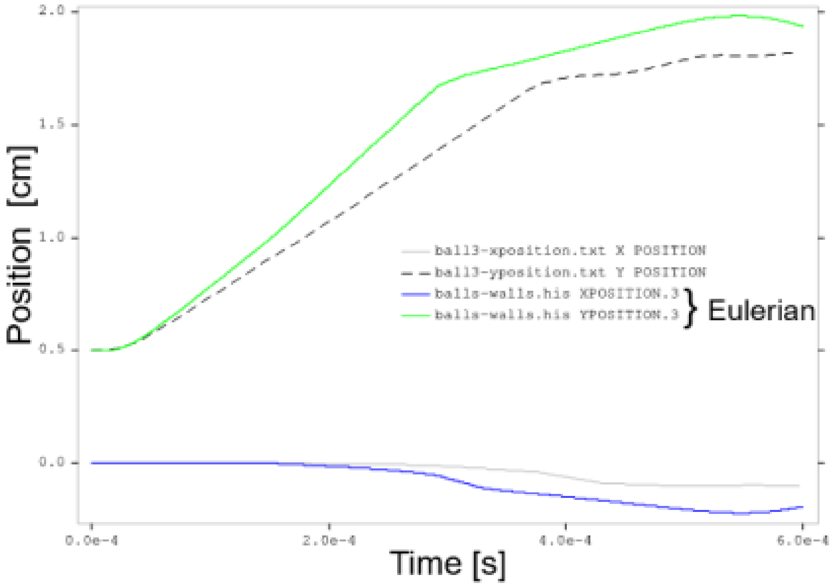
Ball-2 Leaves the Eulerian Domain

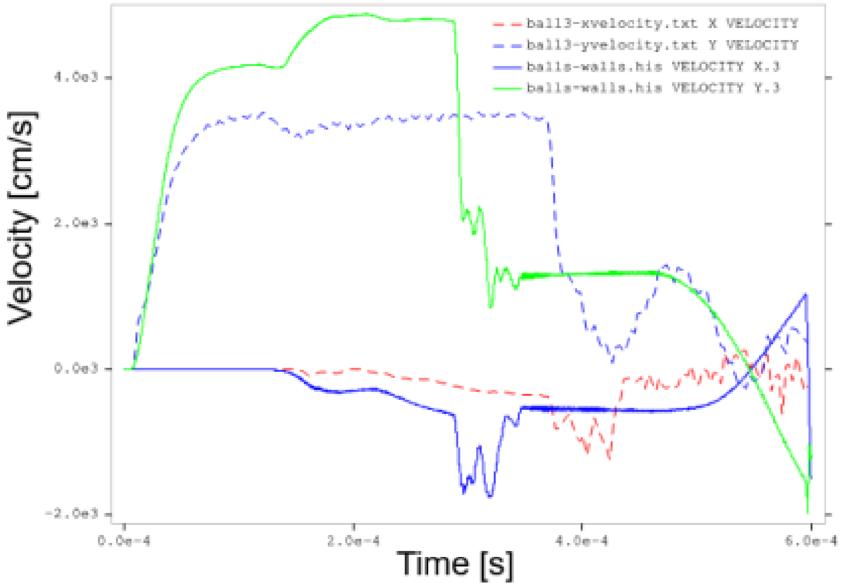




Test Case 4: Results

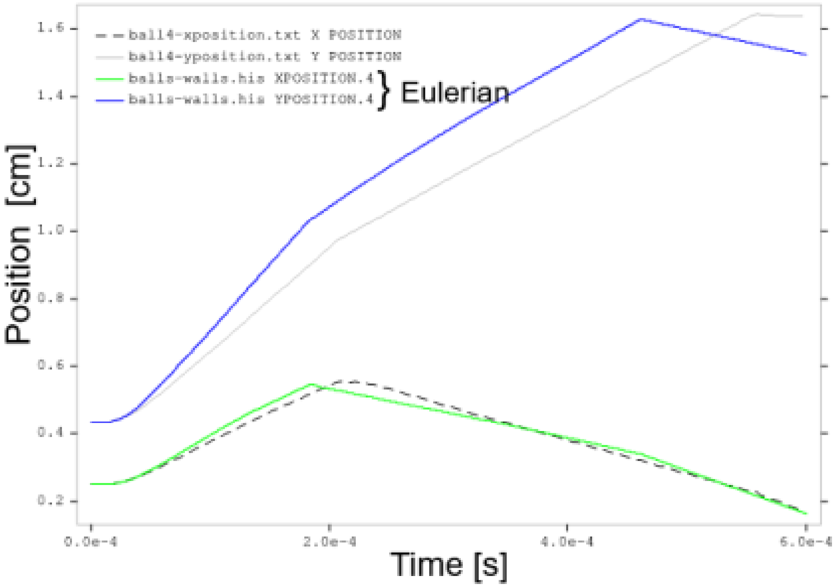
Ball-3:

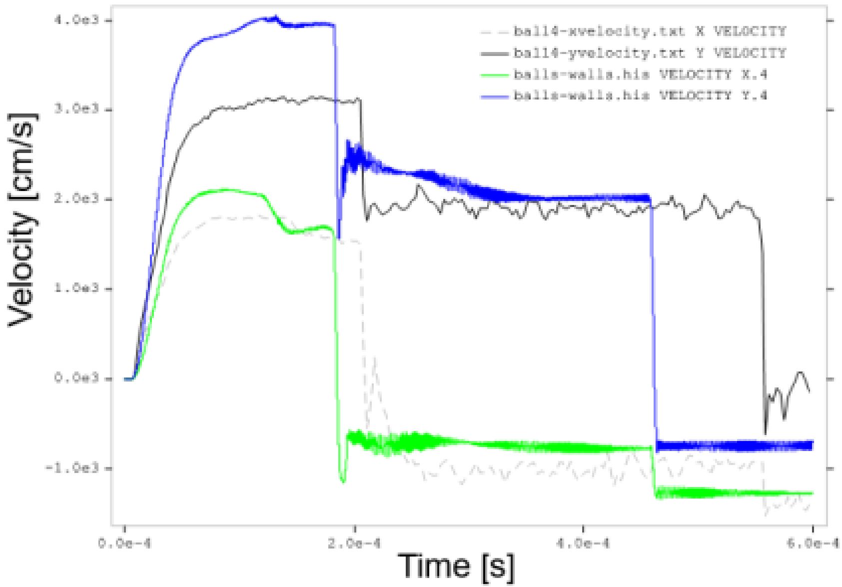




Test Case 4: Results

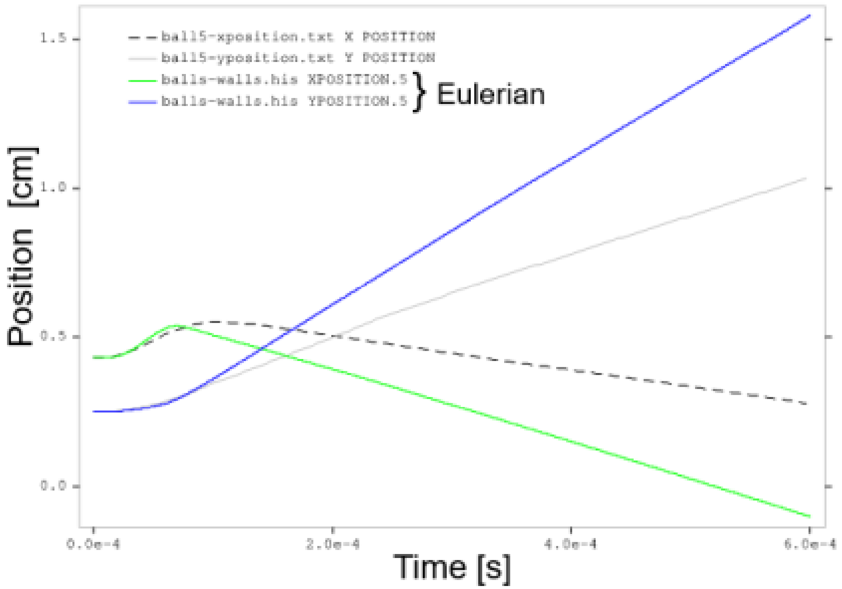
Ball-4:

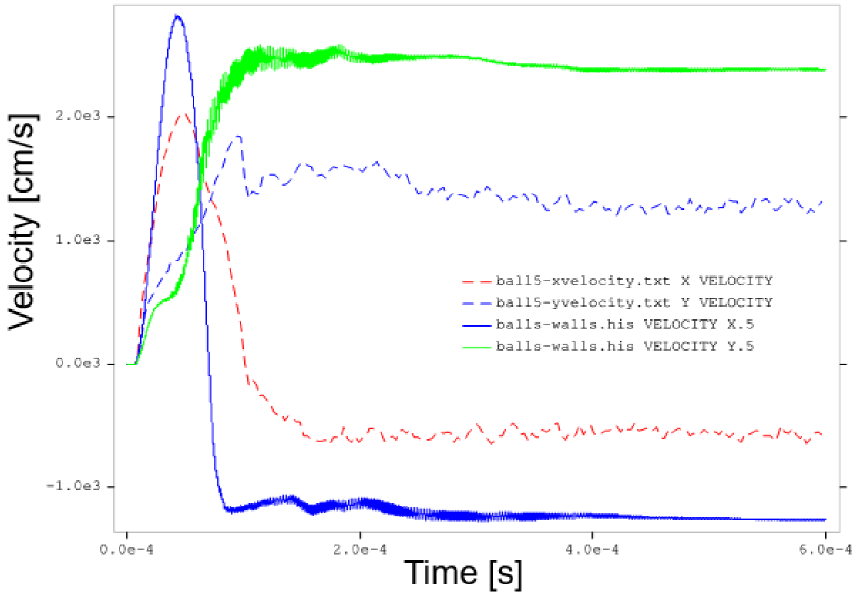




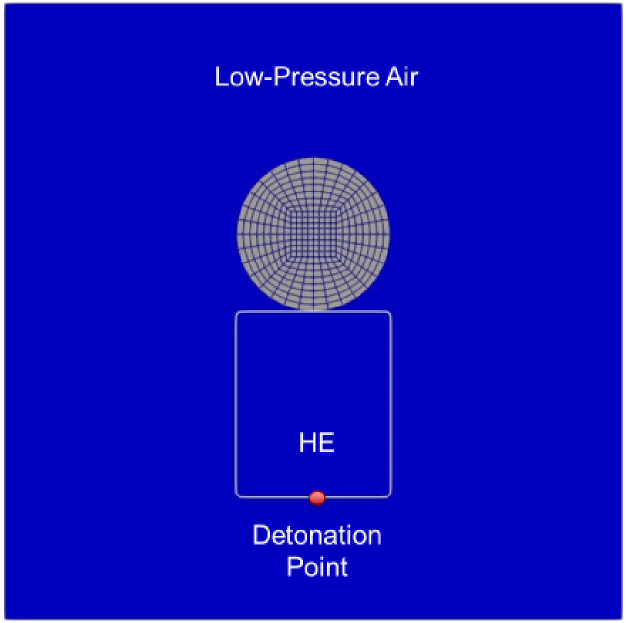
Test Case 4: Results

Ball-5:





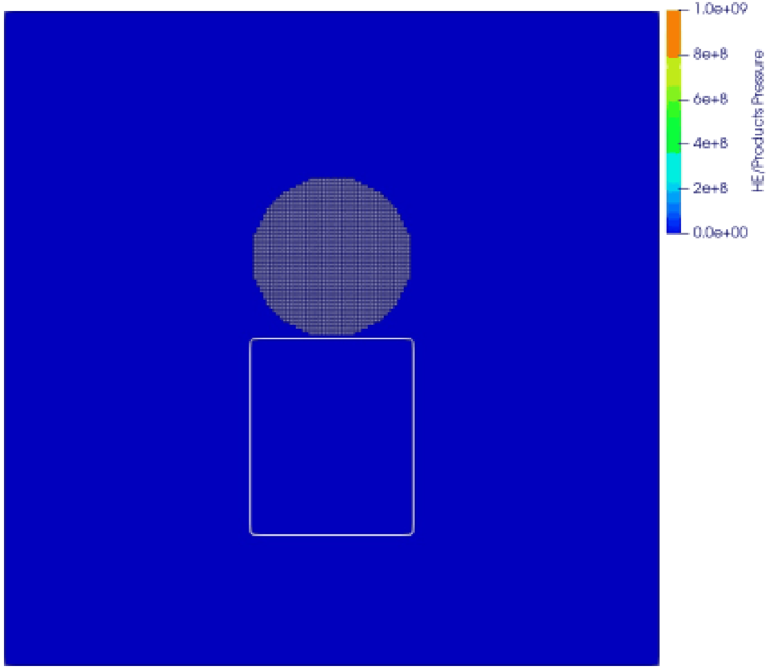
Test Case 5: Setup



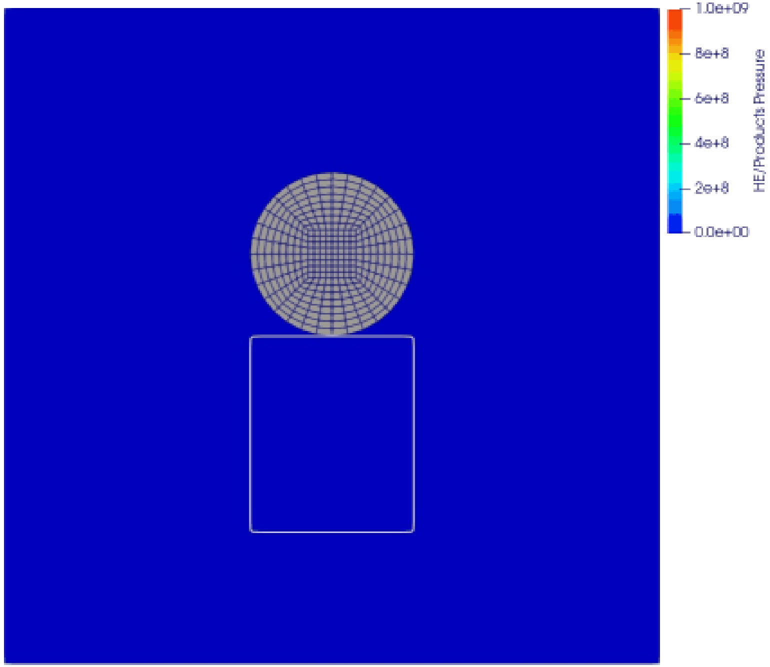
- **Eulerian Domain:**
  - $(-5.0, 0.0) \leq (x, y) \leq (15.0, 20.0)$ [cm]
  - Mesh size: h = 0.1 [cm]
  - Low-Pressure Air: P = 10^{-5} [dynes/cm^2]
  - High Explosive: $(2.5, 4.0) \leq (x, y) \leq (7.5, 10)$ [cm]
  - Tracer Location: (x,y) = (4.5, 12.5) [cm]
- **Lagrangian Solid:**
  - Ball Position: (x,y) = (4.5, 12.5)
  - Linear Elastic material
  - Density: 7.8724 [g/cm^3]
  - Young's Modulus: E = 200 x 10^{10} [dynes/cm^2]
  - Poisson's ratio: n = 0.28
  - Mie Gruenesien EOS for Eulerian simulation

Test Case 5: Results

Gas pressure $(\mathrm{dyn/cm^2})$: **SABLE**



Gas pressure $(\mathrm{dyn/cm^2})$: **OpenIFEM-SABLE coupled**



Summary

- Develop framework for **simulation solid-solid interaction** and impact **using modified Immersed Finite Element Method.**

- **Non-intrusively couple** OpenIFEM and SABLE.

- Penetrator**: Lagrangian** description, Target: **Eulerian** descritption

- Future Work:
  - Extend coupling for **3D simulations**.
  - Investigate application of a **contact model**.
  - Validate coupling with **literature reported test cases.**

Acknowledgment

- Funding and Resources:
- **Sandia National Laboratories**

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