Coupling of compressible and incompressible codes for the simulation of wave impact

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30 octobre 2017

Outline

Sommaire

Goal

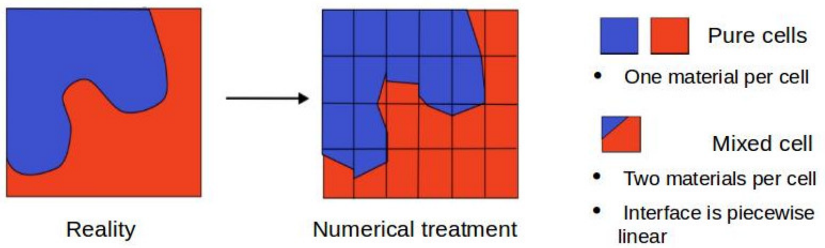
Design a 3D and 2D numerical modeling tool to evaluate the maximum wave impact pressures on solid walls

- Chaining of incompressible (Gerris, FSID) and compressible (FluxIC) codes for wave impact simulations.
- Development of an incompressible liquid and a low compressible gas model.
- Comparison of results with compressible code.

Sommaire

FluxIC : FVCF-NIP method

- FVCF-NIP method : pure Eulerian finite volume method developed for compressible multimaterial fluid flow simulations
- Perfect sliding condition at the interface between materials : consistency of the discretization with respect to the Euler equations model
- No diffusion of material is allowed through the interface
- Granted exact conservation of mass, momentum and total energy



Physical modeling : Euler equations (conservative form)

Conservation of mass :

$$\frac{\partial \rho}{\partial t} + div\ (\rho u) = 0 \quad (1)$$

Conservation of momentum :

$$\frac{\partial (\rho u)}{\partial t} + div\ \ (\rho u \otimes u) + \nabla p = \rho g \quad (2)$$

Conservation of total energy :

$$\frac{\partial (\rho E)}{\partial t} + div\ \ ((\rho E + p)u) = \rho g u \quad (3)$$

Equations of State :

Gas : perfect gas $p = (\gamma - 1)\rho.e$

Liquid : stiffened gas $p = (\gamma - 1)\rho.e - \pi$

Gerris

- Free open source software, GPL license
- Gerris is an incompressible variable density Navier-Stokes solver for surface-tension-driven interfacial flow.
- Immiscible fluids are considered using a sharp VOF representation of the interface
- Widely used in the CFD community
- Advanced users could develop their own solver in Gerris

Physical model

Navier Stokes equations (surface-tension-driven interfacial flows)

$$\frac{\partial \rho}{\partial t} + div\ (\rho u) = 0 \tag{4}$$

$$\rho(\frac{\partial u}{\partial t} + u.grad(u)) = \rho.g - grad(p) + div(2\mu D) + \sigma\kappa\delta_s n \tag{5}$$

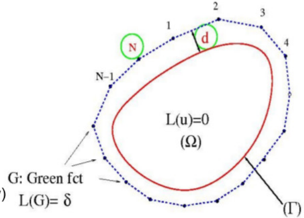
$$div(u) = 0 \tag{6}$$

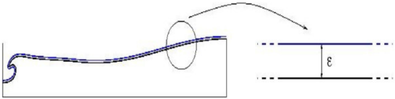
With :

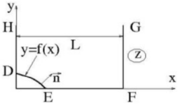
- μ : denotes the dynamic viscosity
- D : the deformation tensor.
- σ : denotes the surface-tension coefficient, κ the interface curvature.
- δ_s : is the Dirac distribution located on the interface, n its normal.

FSID

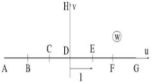
- Free Surface IDentification
- Potential flow in liquid and gas
- Desingularized technique + conformal mapping
- Robust and accurate (conservation of mass and energy)







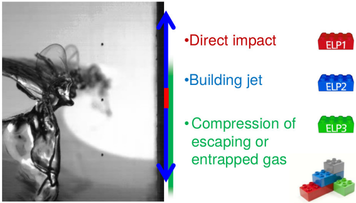
$$\begin{cases} \Delta\phi = 0 & \text{in the fluid} \\ \phi = e(\vec{M}, t) & \text{on the free surface} \end{cases}$$



Elementary Loading Processes

- ELP1 : associated with the impact of the liquid on the wall and the appearance of a pressure peak, which is very difficult to capture during the experiments, this EPL is called "Direct Impact".
- ELP2 : associated with a jet moving along the impact wall, characterized by changing the direction of the fluid after the impact ;
- ELP3 : associated with the capture of a gas pocket by the liquid, a peak pressure is observed in this zone with a later oscillating behavior.

Elementary Loading Process (ELP)



Lafeber et al., "Elementary Loading Processes (ELP) involved in breaking wave impacts" in Proc. of the 22th Int. Offshore and Polar Eng. Conf. (ISOPE), 2012.

Wave test case

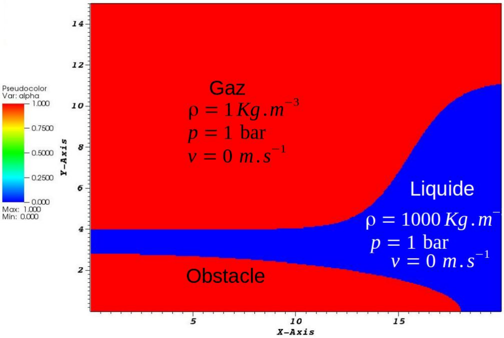
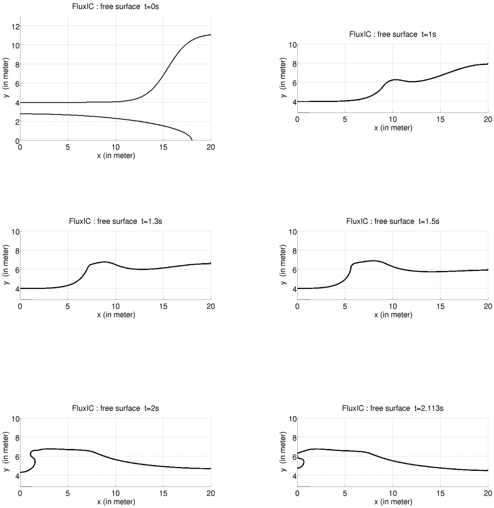
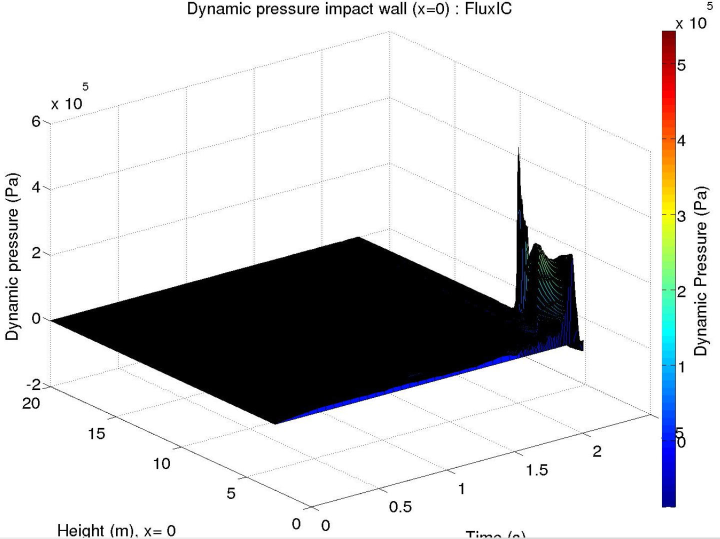


FIGURE : The volume fraction at time t = 0s

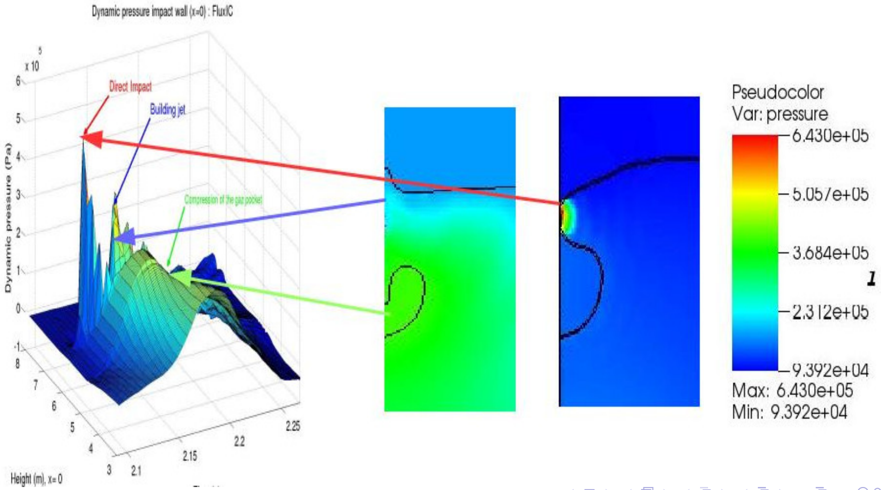
FluxIC : Free surfaces



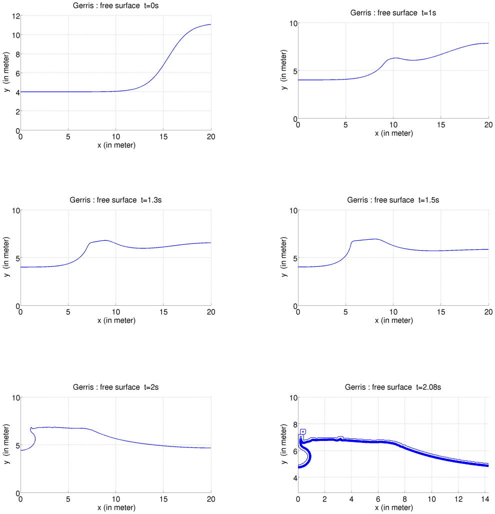
FluxIC : Pressure evolution on the impact wall



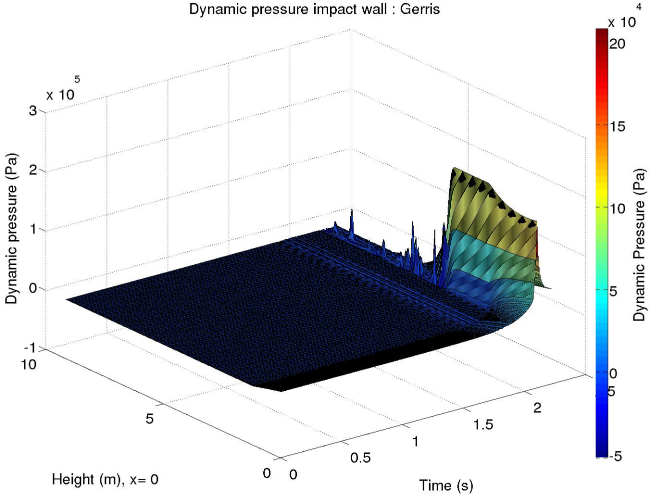
FluxIC : highlighting of ELPs



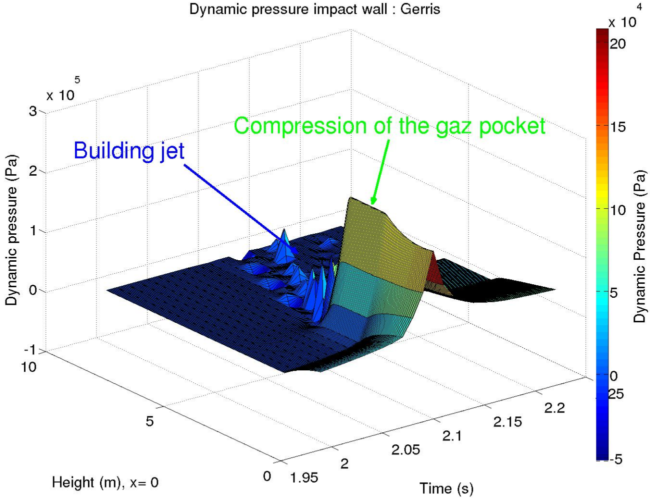
Gerris : Free surfaces



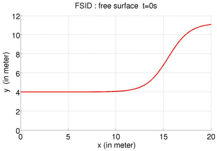
Gerris : Pressure evolution on the impact wall

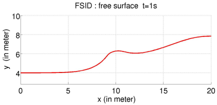


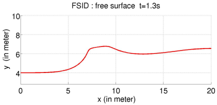
Gerris : Pressure evolution on the impact wall

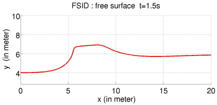


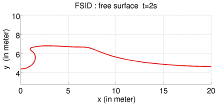
FSID : Free Surfaces

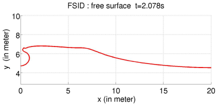




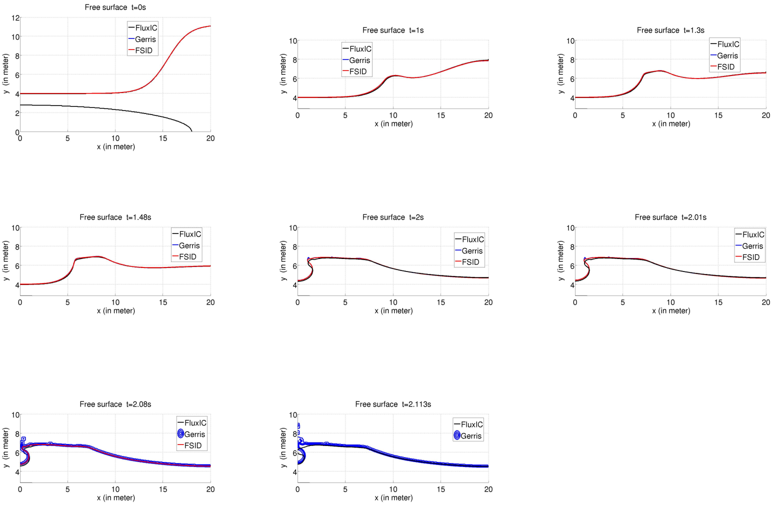








Results comparison



Results comparison

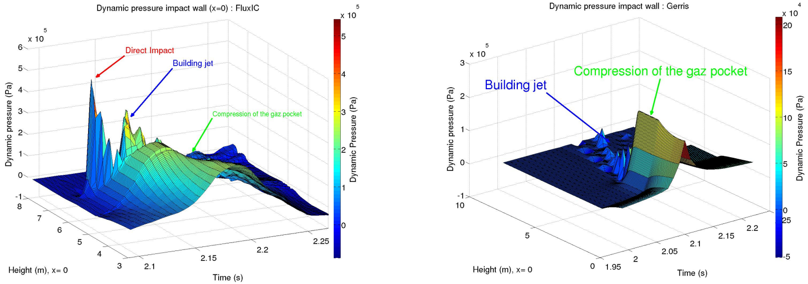
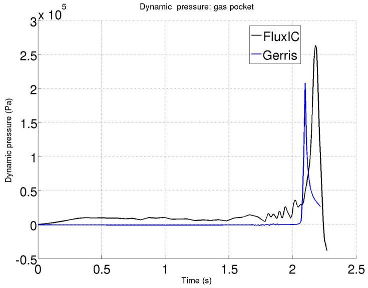
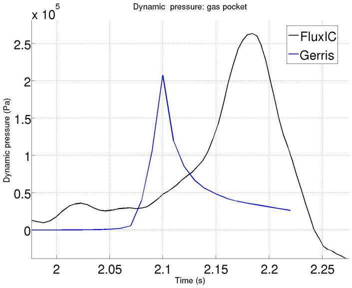


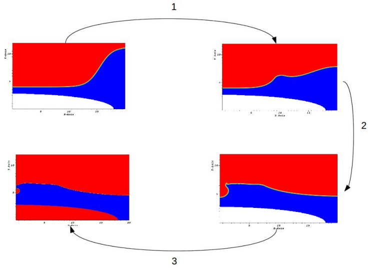
TABLE : Pressure evolution on the impact wall, Flux-IC(left) and Gerris(right)

Results comparison : gas pocket



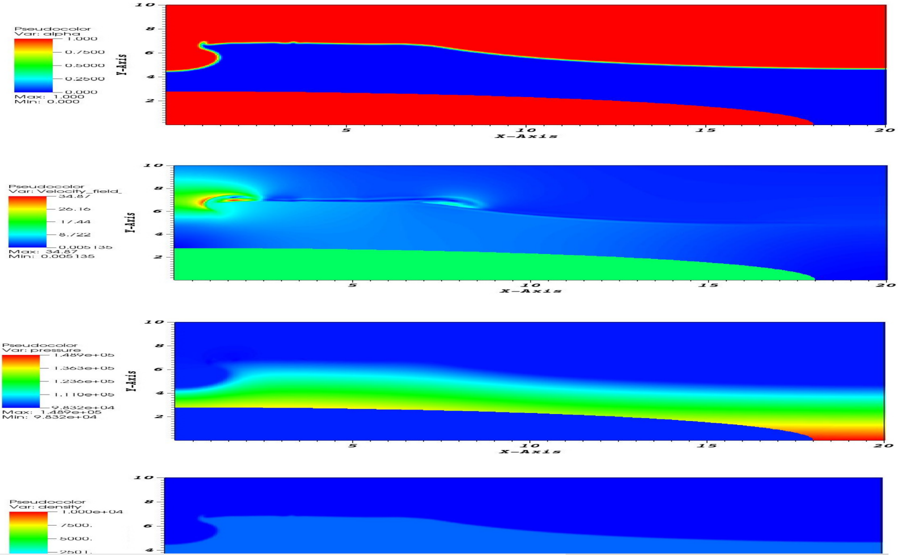


Principle of chaining Incompressible(Gerris/FSID)/Compressible

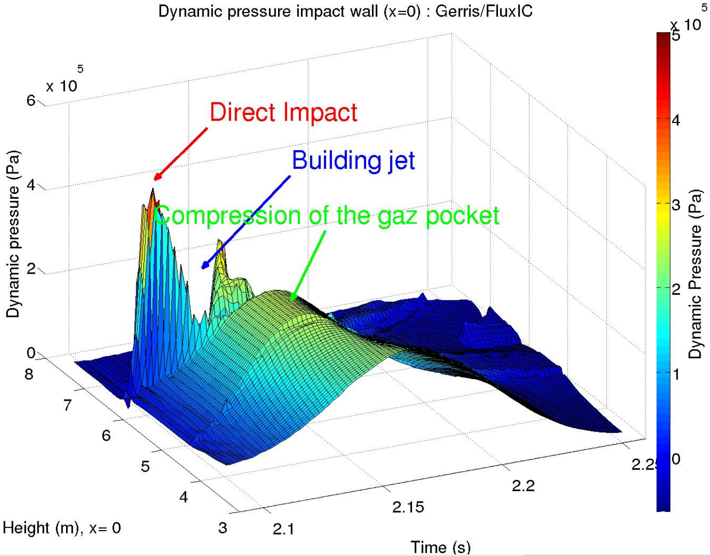


- Step 1 :Initialization with an incompressible code (Gerris / FSID) and free fall of water block ;
- Step 2 : Wave breaking with the incompressible code.
- Step 3 : Initialization of compressible code with incompressible data and simulation of the impact.

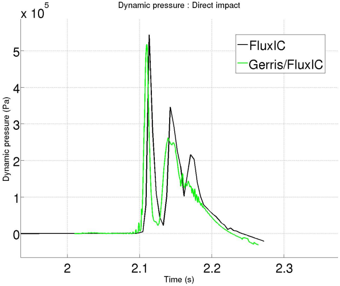
Initialization of FluxIC by Gerris

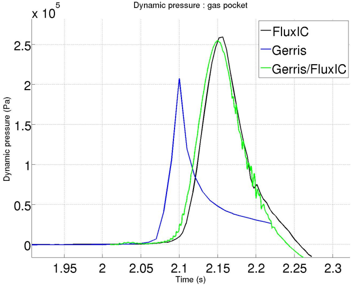


Gerris/FluxIC : Pressure evolution on the impact wall

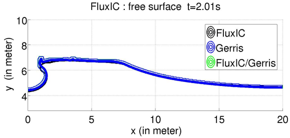


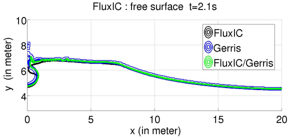
Gerris/FluxIC

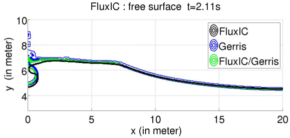


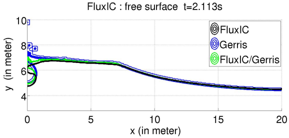


Gerris/FluxIC : Free surfaces

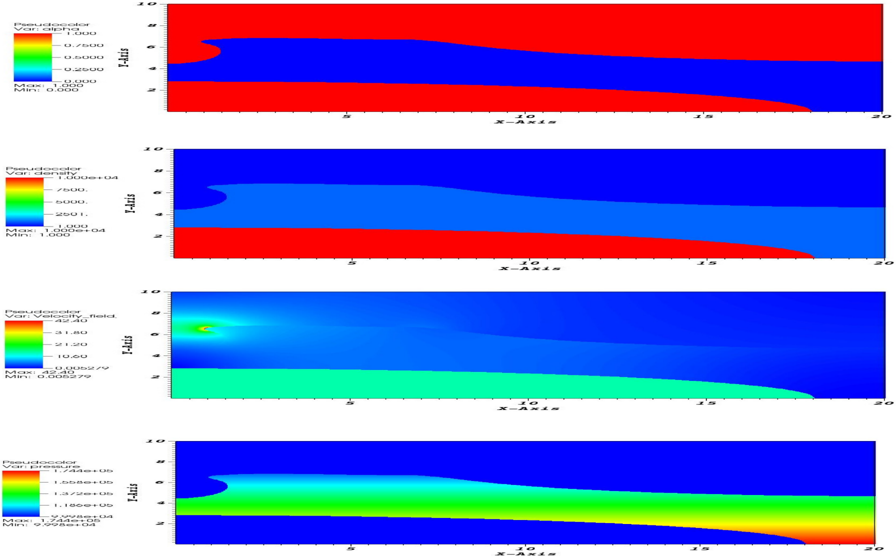




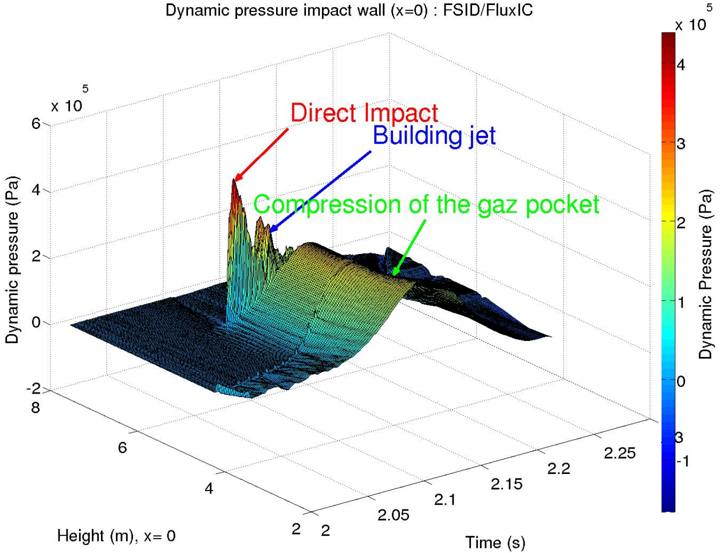




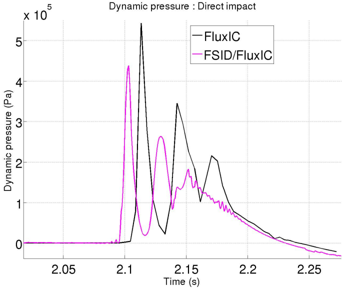
Initialization of FluxIC by FSID

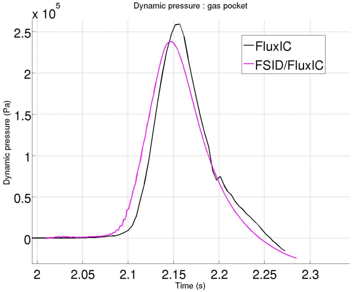


FSID/Gerris : Pressure evolution on the impact wall

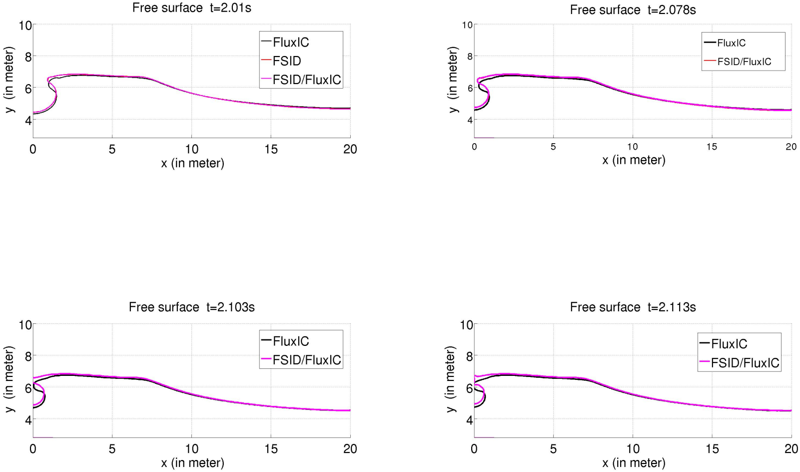


FSID/FluxIC

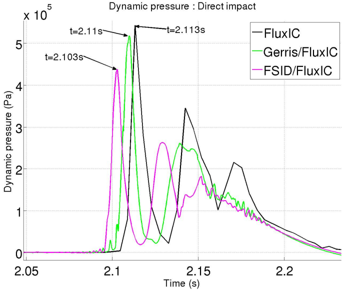

Dynamic pressure : Direct impact
x 10^5
5
4
3
2
1
0
Dynamic pressure (Pa)
FluxIC
FSID/FluxIC
2.05
2.1
2.15
2.2
2.25
Time (s)

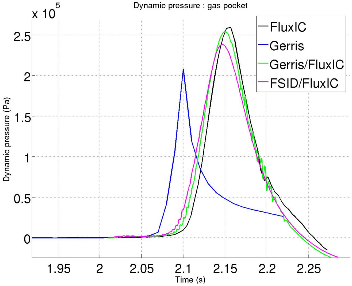

Dynamic pressure : gas pocket
x 10^5
2.5
2
1.5
1
0.5
0
Dynamic pressure (Pa)
FluxIC
FSID/FluxIC
2
2.05
2.1
2.15
2.2
2.25
2.3
Time (s)

FSID/FluxIC

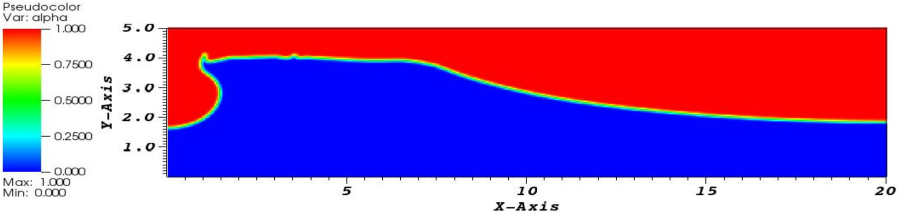

Free surface t=2.01s
FluxIC
FSID
FSID/FluxIC
y (in meter)
x (in meter)
Free surface t=2.078s
FluxIC
FSID/FluxIC
y (in meter)
x (in meter)
Free surface t=2.103s
FluxIC
FSID/FluxIC
y (in meter)
x (in meter)
Free surface t=2.113s
FluxIC
FSID/FluxIC
y (in meter)
x (in meter)

Results comparison

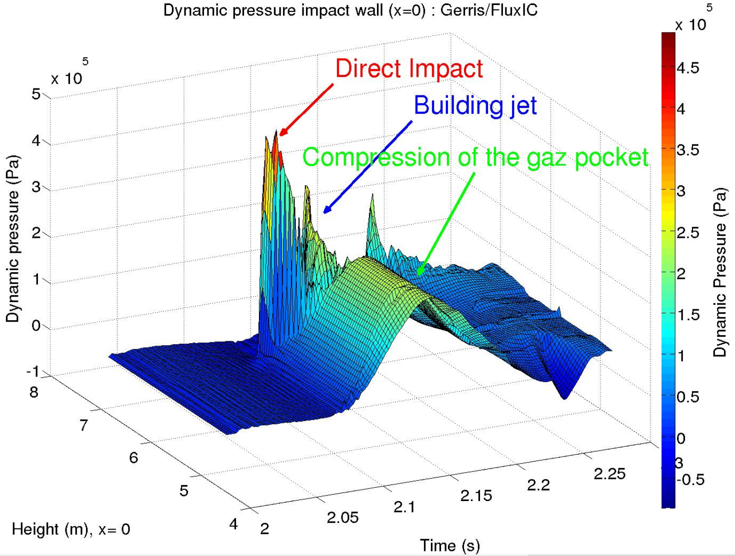




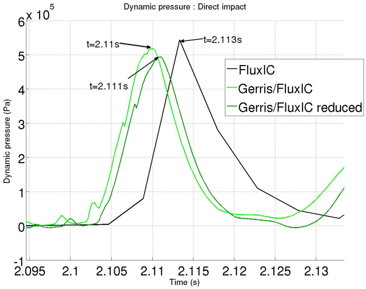
Chaining with a reduced domain

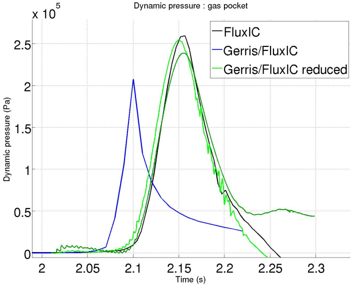


Gerris/FluxIC

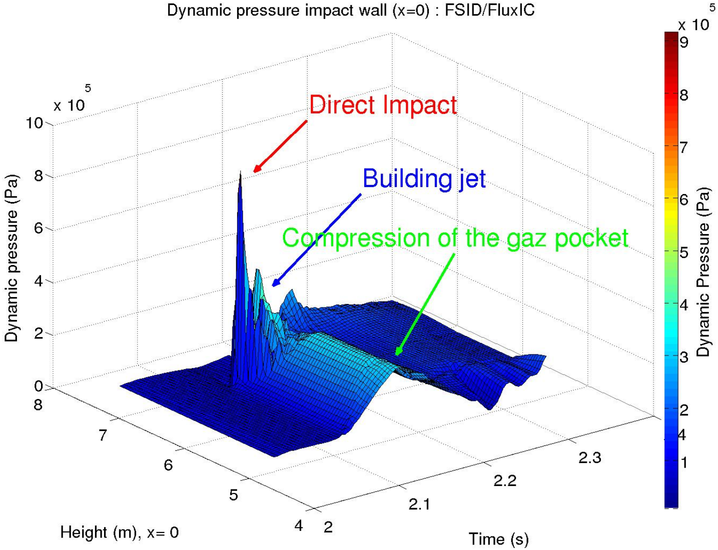


Gerris/FluxIC

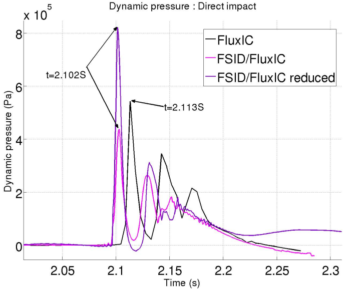


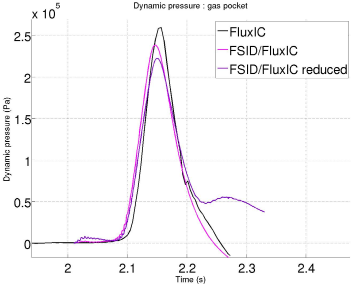


FSID/FluxIC

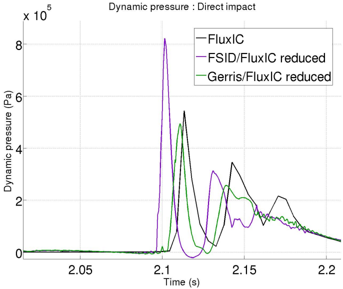

Dynamic pressure impact wall (x=0) : FSID/FluxIC
Direct Impact
Building jet
Compression of the gaz pocket
Dynamic pressure (Pa)
x 10^5
Height (m), x= 0
Time (s)
Dynamic Pressure (Pa)

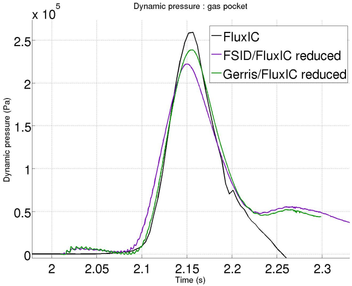
FSID/FLuxIC


Dynamic pressure : Direct impact
x 10^5
8
6
4
2
0
2.05
2.1
2.15
2.2
2.25
2.3
Time (s)
Dynamic pressure (Pa)
t=2.102S
t=2.113S
FluxIC
FSID/FluxIC
FSID/FluxIC reduced


Dynamic pressure : gas pocket
x 10^5
2.5
2
1.5
1
0.5
0
2
2.1
2.2
2.3
2.4
Time (s)
Dynamic pressure (Pa)
FluxIC
FSID/FluxIC
FSID/FluxIC reduced

Results comparison





Summary

A bifluid solver with low compressible gas and incompressible liquid

We solve two types of equations : Euler incompressible in the liquid, and Euler incompressible in the gas with a correction (incompressible / compressible) in the zones with a high compressibility.

In the liquid :

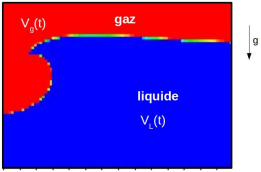
$$div(u) = 0, \qquad \rho = \rho_{0l}, \qquad dans \quad V_l(t), \qquad (7)$$

$$\frac{\partial(\rho_{0l} u)}{\partial t} + div(\rho_{0l} u \otimes u) + \frac{1}{M^2} \nabla p = \rho_{0l} g \qquad (8)$$

in the gas :

$$div(u^i) = 0, \qquad \rho^i = \rho_{0g}, \qquad dans \quad V_g(t), \qquad (9)$$

$$\frac{\partial(\rho_{0g} u^i)}{\partial t} + div(\rho_{0g} u^i \otimes u^i) + \frac{1}{M^2} \nabla p^i = \rho_{0g} g \qquad (10)$$



A bifluid solver with low compressible gas and incompressible liquid

The new variables in areas with high compressibility for gas will be replaced by :

$$\rho(x,y,t) = \rho^i(x,y,t) + M^2\rho_2(x,t) + M^2\rho_p(x,y,t) \tag{11}$$

$$u(x,y,t) = u^i(x,,y,t) + Mu_p(x,,y,t) \tag{12}$$

$$p(x,y,t) = p_0(t) + M^2 p_2(x,y,t) + M^2\rho_p(x,y,t) \tag{13}$$

with :

- p^i,ρ^i et u^i : the quantities calculated with the incompressible equations. With : $p_0(t) = \frac{1}{|V|}\int_V p^i(x,y,t)dV$
- p_2,ρ_2 : the hydrodynamic quantities calculated as follows : $p_2(x,y,t) = p^i(x,y,t) - p_0(t)$, $\rho_2(x,y,t) = p_2(x,y,t)/c_{0g}^2$
- p_p,ρ_p,u_p : the quantities that will allow the incompressible / compressible correction.

Linearized Euler Equations

We introduce the decomposition (11-13) into the compressible Euler equations, and the terms of order higher than M are neglected.
The equations describing the problem are finally limited to :

$$\frac{\partial(\rho^p)}{\partial t} + u_0 \nabla \rho^p + \frac{1}{M}\rho 0 \nabla u^p = -\frac{D\rho_2}{Dt} \tag{14}$$

$$\frac{\partial(u^p)}{\partial t} + (u_0.\nabla)u^p + \frac{1}{M\rho_0}\nabla p^p = -(u^p.\nabla)u_0 \tag{15}$$

$$p_p(x,t) = c_{0g}^2 \rho_p(x,t), \qquad dans\ \ V_g(t) \tag{16}$$

$\frac{D}{Dt}$ is an abbreviation of $\frac{\partial}{\partial t} + u_0.\nabla$.

Basilisk

- Free open source software developed by S. Popinet, GPL license
- Solves the incompressible Navier-Stokes equations, using the VOF method for the interface tracking between the two fluids.
- Structured Cartesian grids, with automatic Quadtree mesh refinement.
- Intended to be the successor of Gerris (Developed by the same authors).
- Advanced users can develop their own solver in Basilisk.

Patch test Case : Initialization

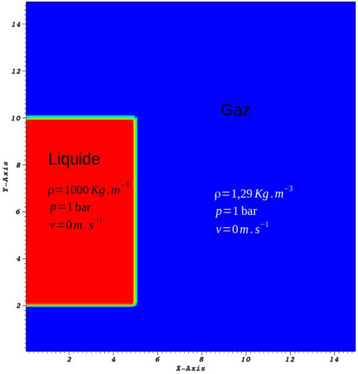
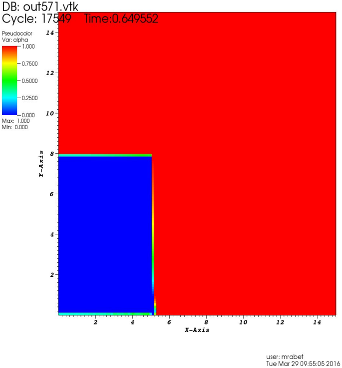


FIGURE : Cas test Patch

The simulations will be realized with a regular mesh, consisting of square cells of 0.11 m side (128x128).

Results with compressible code : FluxIC



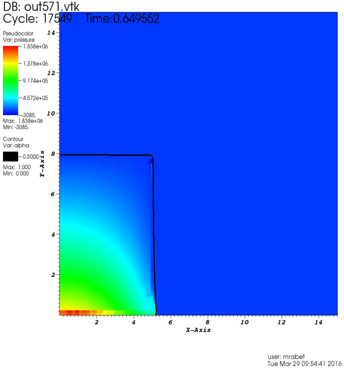


FIGURE : Patch test case, volume fraction and pressure profiles at the moment of the peak of pressure

Results with compressible code : FluxIC

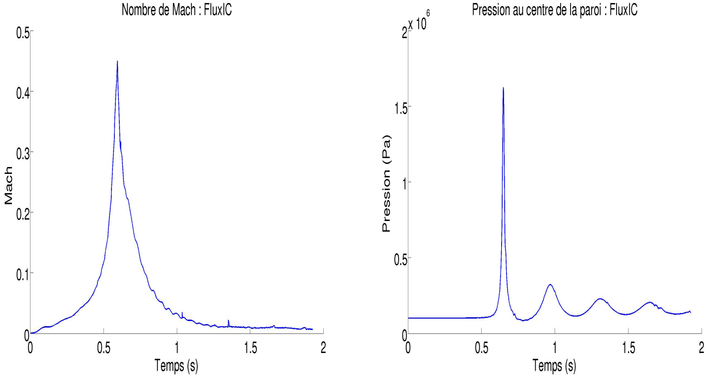


FIGURE : Patch test case, FluxIC, maximum of Mach number and pressure in the center of the mpact wall

Results with incompressible code : Basilisk

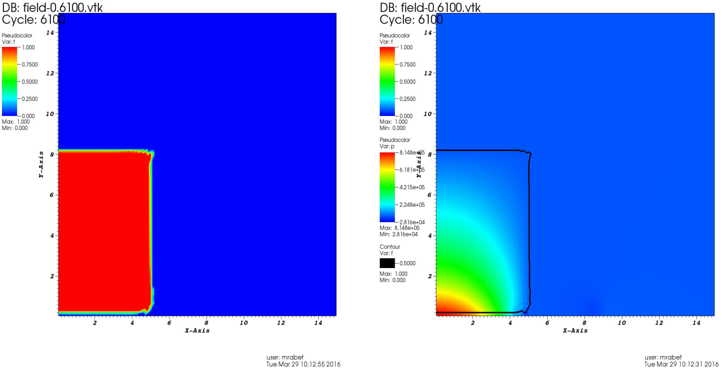


FIGURE : Patch test case, Basilisk, volume fraction and pressure profiles at the moment of the peak of pressure

Results with incompressible code : Basilisk

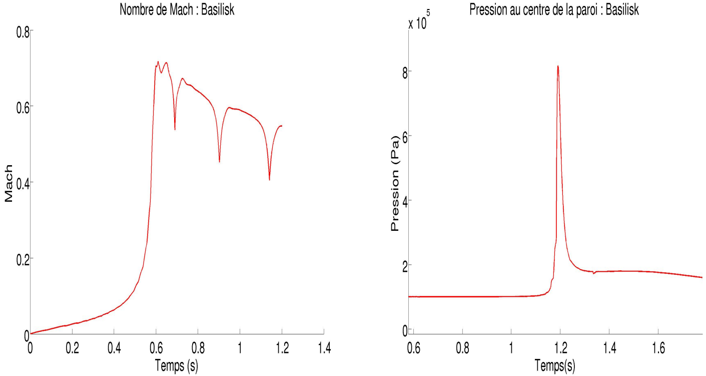


FIGURE : Patch test case, Basilisk, maximum of Mach number and pressure in the center of the mpact walle

Comparison of results between compressible and incompressible codes : Mach number

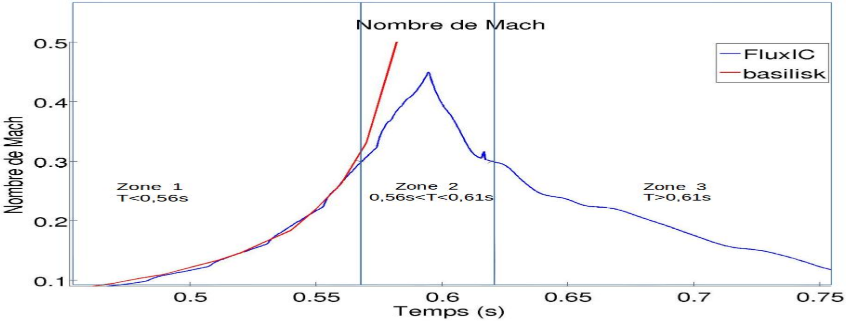
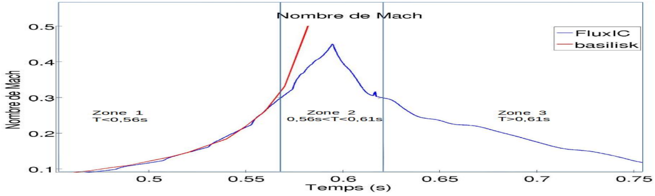


FIGURE : Évolution du nombre de Mach (Zoom)

Comparison of results between compressible and incompressible codes : Mach number



Three regions can be distinguished :

- Zone 1 : Mach number is less than 0.3, in this region we can consider that the flow is incompressible ;
- Zone 2 : the Mach number is greater than 0.3, in this region the compressibility of the gas is important ;
- Zone 3 : the Mach number becomes smaller than 0.3 in the FluxIC code, and remains greater than 0.3 in the Basilisk code, this region will be treated in the following as incompressible.

Comparison of results between compressible and incompressible : Pressure

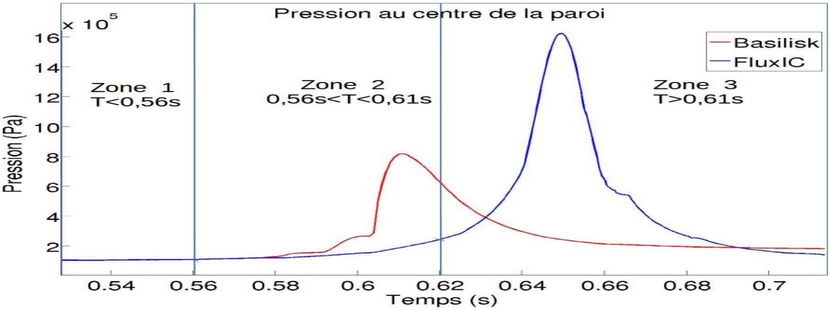


FIGURE : Evolution of the pressure in the center of the impact wall (Zoom)

Implementation of the incompressible liquid/ low compressible gas model in the Basilisk code

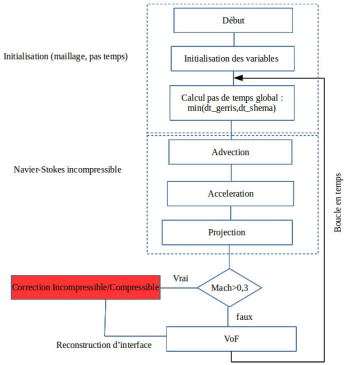
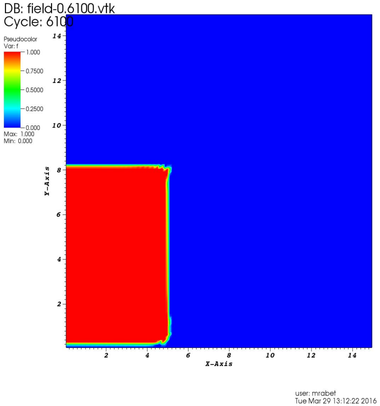


FIGURE : *algorithm Basilisk+correction incompressible/compressible*

Results



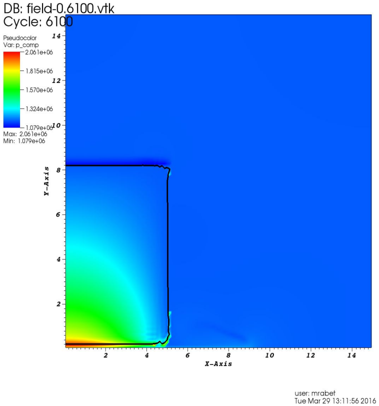


FIGURE : Patch test case, code Basilisk + correction incompressible/compressible, fraction profil and pressure at the time of the preak pressure

Results

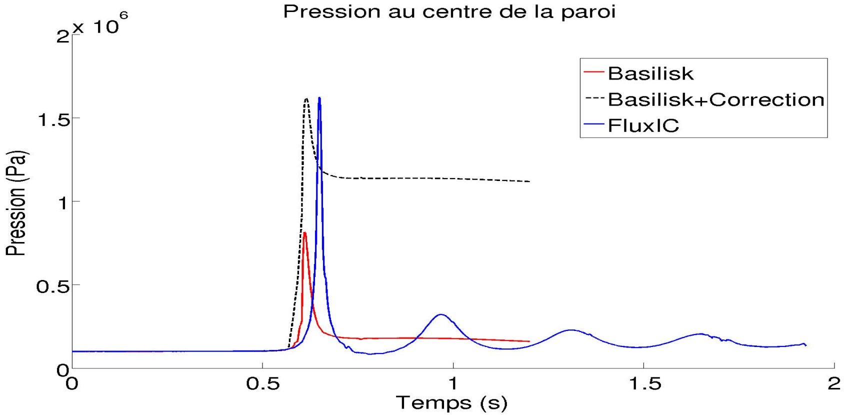


FIGURE : Comparison of the evolution of the pressure at the center of the wall impact

Results

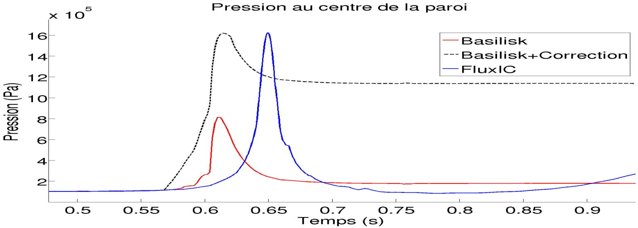


FIGURE : Comparison of the evolution of the pressure at the center of the wall impact (zoom)

The impact pressure at the center of the wall with the Basilisk + compressible / incompressible correction code is close to that computed with a compressible code (FluxIC) but the moment of impact remains identical to that of the Basilisk code

Result

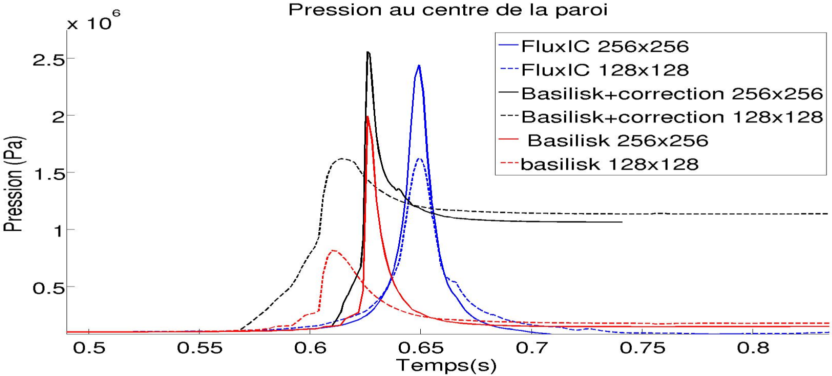


FIGURE : Comparison of the evolution of the pressure at the center of the wall impact)

Summary

Conclusions et perspectives

- The chaining of incompressible and compressible codes allows generation of the wave in a reasonable time, with comparable free surfaces and close time of impact.
- The model of the linearized Euler equations gives results similar to those obtained with a compressible solver with the 1D test case, as well as with a mono-material test case in the 2D case.
- The impact pressure at the center of the wall with the Basilisk + incompressible/ compressible correction code is close to that computed with a compressible code (FluxIC) but the moment of impact remains identical to that of the Basilisk code.
- Perspectives :
  - The parametric study on the choice of the interval ($[t_0, t_1]$) of the incompressible/ compressible correction in the Basilisk code to understand the pressure behavior in zone 3 (pressure after impact) and the behavior of leak rates ;
  - Apply schema to more meshed test cases and with automatic refinement (Quadtree) ;
  - Apply the schema to a wave type test case.