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

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30 octobre 2017
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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.
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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:
\[ \frac{\partial \rho}{\partial t} + \text{div} (\rho u) = 0 \] (1)

Conservation of momentum:
\[ \frac{\partial (\rho u)}{\partial t} + \text{div} (\rho u \otimes u) + \nabla p = \rho g \] (2)

Conservation of total energy:
\[ \frac{\partial (\rho E)}{\partial t} + \text{div} ((\rho E + p)u) = \rho gu \] (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)

\[ \frac{\partial \rho}{\partial t} + \text{div} (\rho u) = 0 \quad (4) \]

\[ \rho \left( \frac{\partial u}{\partial t} + u.\text{grad}(u) \right) = \rho\cdot g - \text{grad}(p) + \text{div}(2\mu D) + \sigma \kappa \delta_s \cdot n \quad (5) \]

\[ \text{div}(u) = 0 \quad (6) \]

With:

- \( \mu \): denotes the dynamic viscosity
- \( D \): the deformation tensor.
- \( \sigma \): denotes the surface-tension coefficient, \( \kappa \) the interface curvature.
- \( \delta_s \): 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)

\[ \begin{align*}
\Delta \phi &= 0 \quad \text{in the fluid} \\
\phi &= e(M, t) \quad \text{on the free surface}
\end{align*} \]
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.

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

![Dynamic pressure impact wall: Gerris](image)

- Building jet
- Compression of the gas pocket

**Coupling of compressible and incompressible codes for the simulation of wave impact**
FSID : Free Surfaces
Results comparison

Figure: Comparaison des surfaces libres, de l’initialisation à l’impact
Results comparison

**Table**: Pressure evolution on the impact wall, Flux-IC(left) and Gerris(right)
Results comparison: gas pocket

![Graphs showing dynamic pressure comparison between FluxIC and Gerris for a gas pocket over time.](attachment:image.png)
**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

Dynamic pressure impact wall ($x=0$): Gerris/FluxIC

- Direct Impact
- Building jet
- Compression of the gas pocket

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Gerris/FluxIC

Coupling of compressible and incompressible codes for the simulation of wave impact
Gerris/FluxIC : Free surfaces
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Initialization of FluxIC by FSID

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FSID/Gerris: Pressure evolution on the impact wall

Dynamic pressure impact wall (x=0): FSID/FluxIC

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Chaining with a reduced domain
Coupling of compressible and incompressible codes for the simulation of wave impact
Gerris/FluxIC

**Dynamic pressure : Direct impact**

- FluxIC
- Gerris/FluxIC
- Gerris/FluxIC reduced

**Dynamic pressure : gas pocket**

- FluxIC
- Gerris/FluxIC
- Gerris/FluxIC reduced
FSID/FluxIC

Dynamic pressure impact wall (x=0) : FSID/FluxIC

**Direct Impact**

**Building jet**

**Compression of the gaz pocket**
FSID/FLuxIC

Dynamic pressure: Direct impact

- FluxIC
- FSID/FluxIC
- FSID/FluxIC reduced

Dynamic pressure: gas pocket

- FluxIC
- FSID/FluxIC
- FSID/FluxIC reduced

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

![Comparison of dynamic pressure for Direct impact and gas pocket simulations.](image)

- **FluxIC**
- **FSID/FluxIC reduced**
- **Gerris/FluxIC reduced**
Summary

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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:

\[
\text{div}(u) = 0, \quad \rho = \rho_{0l}, \quad \text{dans } V_l(t), \quad (7)
\]

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

in the gas:

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

\[
\frac{\partial (\rho_{0g} u^i)}{\partial t} + \text{div}(\rho_{0g} u^i \otimes u^i) + \frac{1}{M^2} \nabla p^i = \rho_{0g} g \quad (10)
\]
A bifluid solver with low compressible gas and incompressible liquid

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

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

\[
u(x, y, t) = \nu^i(x, y, t) + M \nu_p(x, y, t) \tag{12}
\]

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

with:

- \(\rho^i, \nu^i\) et \(\nu^i\): the quantities calculated with the incompressible equations.
- With: \(p_0(t) = \frac{1}{|V|} \int_V p^i(x, y, t) dV\)
- \(p_2, \rho_2\): the hydrodynamic quantities calculated as follows:
  \(p_2(x, y, t) = p^i(x, y, t) - p_0(t)\),
  \(\rho_2(x, y, t) = p_2(x, y, t) / c_0^2\)
- \(p_p, \rho_p, \nu_p\): 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:

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

\[
\frac{\partial (u^p)}{\partial t} + (u_0 \cdot \nabla) u^p + \frac{1}{M \rho_0} \nabla p^p = -(u^p \cdot \nabla) u_0
\]  \hspace{1cm} (15)

\[
p_p(x, t) = c_0^2 \rho_p(x, t), \hspace{1cm} \text{dans } V_g(t)
\]  \hspace{1cm} (16)

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

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

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 impact 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 impact wall.
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.
Figure: Comparison of the evolution of the pressure at the center of the wall impact
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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.