Non intrusive FEM-SPH code coupling: application to FSI and damage prediction

Tsunami workshop Lyon

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This work is focused on FSI effects on damage on structures

In this simulation FLUID SPH Turbine (rigid body......)
In fact a pure Fluid simulation

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These turbines are often severely damaged due to

**Cavitation, small debris** transport **water droplets**
stone or **rock impacts**

For cavitation dropletys and small debris impact damage
There are **empirical rules to predict these damages**

But they are **based on empirical formulas** drawn from experiments
Good because pragmatic and **efficient but no real unstanding**
In this program we **try to go deeper into the understanding on physical reasons** on **why** this happens.

For **rock and stone impact effects** no solution: propose au fully coupled FSI for Predictions and parametric analysis of the problem.
This talk will introduce two Points

The FSI optimal coupling strategy

The damage predictions
Reasonable predictions are rather difficult.

- It is highly non linear
- Complex fluid physics,
- Very evolutive contact surface between the fluid and the structure,
- Fast transients

Existing good tools for Fluid (ALONE) and Structural response (ALONE)

Is it possible to « couple » them with no loss of precision meanwhile with minimum intrusion?

The key issue OF THIS PART is the time integration aspect of the coupling
Motivations: Damage prediction

Try to understand reasons of observed damages.

In case of rock and stone impact

In case of small debris cavitation or droplet impacts

**The key issue is the understanding of the main mechanisms**
FSI for large interface motions.

**For the fluid part** Meshless method seem rather good candidates for this type of simulations (Here SPH). **Use existing SPH code** (Here ASPHODEL ANDRITZ Hydro fluid code)

**For the solid part:**
**No fracture** and moderate strains **FEM model use existing FEM code** (Here EUROPLEXUS explicit FEM code)

A non intrusive BUT interface energy conserving **COUPLING method** => develop a specific Code to couple two existing ones
Outline

- SPH method
- FSI: Code Coupling Coupling strategy (no fracture) and Application examples
- Conclusions
The 3D SPH method (fluids)

→ **Spatial Discretization:** Nodes
DOF smooth interpolation functions

→ **SPH usually lagrangian formulation which is well adapted to large motions with splitting of domains in many parts**

→ **Application to fluid dynamics for large free surface evolutions**

- As often in fluid formulation unstable fluid responses controlled by a small amount of artificial viscosity

\[
\left( \frac{\partial \mathbf{v}}{\partial t} \right)_i = - \sum_{j \in \Omega_i} m_j \left( \frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) \nabla w_{ij} \quad \left( \frac{\partial \rho}{\partial t} \right)_i = \rho_i \sum_{j \in \Omega_i} \frac{m_j}{\rho_j} (\mathbf{v}_i - \mathbf{v}_j) \nabla w_{ij} \quad \Delta p_i = c^2 \Delta \rho_i
\]

*Momentum equation*  
*Continuity equation*  
*Energy equation*
Numerical methods used in the two subdomains

- Smoothed Particle Hydrodynamics (SPH) method for fluid
- Finite Element (FEM) method for solid

IFS SPH-FEM Code Coupling strategy in SPACE

- Coupling by the interface: Easy to track the fluid-structure interface
- Large structural displacement or deformation
- Complicated structural geometry
Coupling strategy in SPACE: same velocity and same normal pressure

- Interface conditions

\[ \forall x \in \Gamma_I \left\{ \begin{align*}
    v_f(x, t) &= v_s(x, t) \\
    \sigma_f(x, t) \cdot n_f(x, t) &= -\sigma_s(x, t) \cdot n_s(x, t)
\end{align*} \right. \]

Slipping condition

\[ \forall x \in \Gamma_I \left\{ \begin{align*}
    n_f(x, t) \cdot v_f(x, t) &= -n_s(x, t) \cdot v_s(x, t) \\
    n_f(x, t) \cdot [\sigma_f(x, t) \cdot n_f(x, t)] &= n_s(x, t) \cdot [\sigma_s(x, t) \cdot n_s(x, t)]
\end{align*} \right. \]

Normal velocity continuity

\[ \left\{ \begin{align*}
    n_f \cdot v_f &= -n_s \cdot v_s \\
    p_f &= p_s
\end{align*} \right. \]

Interface equilibrium \(p\)
Coupling strategy in SPACE:

In the fluid what is the pressure value on solid wall?

- How to get the “good” fluid pressure at solid wall?
  - Truncation of support domain
  - Partial Riemann problem **Method of characteristics**

  \[
  p_k = \sum_{i \in D_k} \omega_i W_{ik} 2p_{E,ik}
  \]

  [Marongiu 2007]

  Fluid pressure at solid wall

  Wall pressure a mean value
  Partial Rieman pressures on
  All rays within the « bleue sphere »
Coupling strategy in SPACE:

Coupled equations

Finally one gets 3 set of equations to solve in space:

Equilibrium of the solid

$$\tilde{K}_S V_S = g_S + C^T p$$

Equilibrium of the fluid

$$\tilde{K}_F V_F = g_F - C^T p$$

Continuity of interface normal velocities and pressure equilibrium

(the equilibrium is solved using the same Lagrange multiplier $p$ on interface: it is the pressure)
Coupling strategy in SPACE:

Coupled equations

One observes that for Solid and Fluid \[ V = V^{Free} + V^{Link} \]

Insert in the 3 equations one get the solution in 3 steps:

1) Compute \( V^{free} \)
\[ V^{Free}_{S or F} = \left( \tilde{K}_{S or F} \right)^{-1} g_{S or F} \]

2) Compute Lagrange Multipliers (here Lagrange multiplier = Pressure)
\[ Hp = B \left( V^{Free} \right) \]

3) Compute \( V^{Link} \)
\[ V^{Link}_{S or F} = \left[ \tilde{K}_{S or F} \right] C^T p \]

Total speed = \( V^{Free} + V^{Link} \)
Coupling strategy in TIME

- Two categories of numerical coupling procedures

<table>
<thead>
<tr>
<th>Asynchronous</th>
<th>Synchronized procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time lag</td>
<td>No time lag</td>
</tr>
<tr>
<td>Asynchronous</td>
<td>Synchronous</td>
</tr>
<tr>
<td>Sometimes unstable</td>
<td>Numerically stable</td>
</tr>
<tr>
<td>Flexible</td>
<td>complex</td>
</tr>
</tbody>
</table>
Coupling strategy in TIME: typical staggered schemes

- Typical partitioned or staggered coupling procedure

1. Send the fluid pressure of the moment 'n' to the solid solver
2. Update the solid status to the moment 'n+1'
3. Send the new solid geometry to the fluid solver
4. Update the fluid status to the moment 'n+1'

Pressures not in equilibrium → possible Energy injection → Possible Numerical instability
Coupling strategy in SPACE and TIME: synchronous scheme

- AIM: Achieve Zero interface energy condition… **Space and Time INTEGRATION**

\[ \Delta W_I = \int_{t^n}^{t^{n+1}} \int_{\Gamma_I} \left[ \mathbf{n}_s \cdot (-p_s \mathbf{I}) \cdot \mathbf{v}_s + \mathbf{n}_f \cdot (-p_f \mathbf{I}) \cdot \mathbf{v}_f \right] d\Gamma \ dt \]

\[ \Delta W_I < 0 \quad \Delta W_I \equiv 0 \quad \Delta W_I > 0 \]

Spatial discretisation

**Interface Equilibrium**

\[ p_f(x_k) = p_s(x_k) = p_k \]

\[ \Gamma_I = \sum_{k}^{N_k} \Gamma_k \]

\[ \Delta W_{I} = \int_{t^n}^{t^{n+1}} \sum_{k}^{N_k} p_k \mathbf{n}_k \cdot \left[ \mathbf{v}_s(x_k) - \mathbf{v}_f(x_k) \right] s_k \ dt \]
Coupling strategy in Space and TIME

- Zero interface energy increment condition

\[ \Delta W_I^d = \int_{t_n}^{t_{n+1}} \sum_{k} p_k n_k \cdot \left[ \mathbf{v}_s(x_k) - \mathbf{v}_f(x_k) \right] s_k \, dt \]

Time integration

**Pressure is Piece-wise constant in time**

\[ \overline{p}_k = \frac{1}{\Delta t} \int_{t_n}^{t_{n+1}} p_k(t) \, dt \]

\[ \Delta W_I^d = \sum_{k} \overline{p}_k \int_{t_n}^{t_{n+1}} n_k \cdot \left[ \mathbf{v}_s(x_k) - \mathbf{v}_f(x_k) \right] s_k \, dt \]

Interface Velocity condition:
**Constant Normal and surface at mid step**
And **same velocities**
**For Solid and Fluid**

\[ \overline{n}_k \cdot \left[ \mathbf{v}_s(x_k) - \mathbf{v}_f(x_k) \right] s_k = 0 \]

\[ \Delta W_I^d = \sum_{k} \overline{p}_k \Delta t \left\{ \overline{n}_k \cdot \left[ \mathbf{v}_s(x_k) - \mathbf{v}_f(x_k) \right] s_k \right\} = 0 \]
Coupling strategy in Space and TIME: time integrators

*Unique time step*

- **Time integrators**
  - **SOLID:** Newmark: explicit 2nd ORDER (even in large deformation range)
  - **FLUID Runge Kutta** 2nd order (explicit)

- A coupling strategy which ensures stability and keeps 2nd order convergence for the coupled system.

Zhe Li IJNMF 2013 and Computers and Fluid 2014
Computational Mechanics 2015
**Coupling strategy in Space and TIME:**

*different time steps*

- **Time steps:** explicit time integrators (CFL stability condition $Dt < h/C$)

- In many physical problems very different time steps in the fluid and in the solid domains (e.g., water sound speed 1000m/s steel 5000m/s)

- Optimal computation time $\Leftrightarrow$ different time steps in solid and fluid domains

- A coupling strategy which permits to use different and optimal time step in each domain

While ensuring stability and keeping 2$^{nd}$ order
Coupling strategy in TIME: CODES

\[
(II) \begin{cases} 
(II-S): & K_s^c v_s^{n+1} + L_p^{n+1} \Lambda^{n+1} = g_s^n \\
(II-F): & K_f^c v_f^{n+1} + \Lambda^{n+1} = g_f^n \\
(II-C): & L_s^{n+1} v_s^{n+1} + v_{fB}^{n+1} = -L_s^n v_s^n - v_{fB}^n 
\end{cases}
\]
Instability illustration

Water SPH
Bottom shell FEM (ASTER)
Loading=gravity
Linear elastic application.
New results: non intrusive coupling
Fluid SHP (Asphodel) Solid FEM (EUROPLEXUS)

- ASPHODEL ALE SPH code
- EUROPLEXUS dynamic explicit F code
- Typical FS Problem

Walhorn
Walhorn Example ... time responses comparisons

- Walhorn example
- Rather good comparison up to first maximum
- Differences after first peak.... A lot of « damping » in all cases...why?...Time space convergence study on going
Different time steps: non intrusive coupling

- ASPHODEL ALE SPH code
- EUROPLEXUS dynamic explicit FE code
- DAMAGE different time steps in FLUID and STRUCTURE
Conclusion of coupling part

- A general non intrusive method to couple Fluid and Solid Solvers

- Zero numerical interface energy

- Optimal CPU time (different time steps)
- Deformable structures as well as large fluid motions optimal for TSUNAMI or Snow damage of floating objects predictions

- First 3D results: not presented here
Small impact damage predictions: work with prof. J. Ishimoto IFS

- Small sand particules, droplets, cavitation bubbles

- Droplets impacts on a wall: high velocities 100 to 500 m/s
  Fluid codes SPH or FD give Pressure histories on wall interface

- Cavitation bubles explosion: now possible to get pressure histories on wall. (complex two phase codes...See for instance Prof Ishimoto work)
Small impact damage predictions

- For droplets and cavitation huge pressure pulse on a very small surface during a very small time.

- Structural response: nearly zero plastic strain... because the implusion of these signals is very small

- What is then the reason of observed Huge damage?

![Graph showing time vs. pressure pulse and radius vs. pressure distribution](image-url)
Small impact damage predictions

- What is then the reason of observed Huge damage?
- Transient analysis in the solid part (dynamic explicit)
- A stress wave => a Fatigue Damage for each event
Small impact damage predictions

- Fatigue Damage for one event => Nb of events (i.e. nb of droplets of cavitation bubbles) which cause damage => Fatigue type erosion criterion
- When erosion criterion is reached remove the element and go on
- Use coupled codes => Direct life prediction

- A consensus of material science people which have observed the damaged objects. Fatigue is the damage mechanism....
Conclusion on Small impacts effects in FSI

- A rather simple mechanism

- Still a lot to do, but Coupled FSI with element erosion is a nice way to really progress in the predictions and understanding

- Coupling with micro structural response would be a very nice 3 science collaborative project

- Complex fluid response, Fatigue damage at micros scale material science, Solid mechanics for fast transient response
Acknowledgment

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Failure predictions With FSI
Tin perforation by a Bullet

Source (internet...
Cylinder impact experiment *(Timm, 2003)*

→ **Expérimentation**
- H=600mm, D=300mm
- Steel
- Bullet Vimp=730m/s
- Empty or full of water

→ **Model**
- JC Plasticity *(Timm, 2003)* + Lemaître&Chaboche ductile damage
- Rigid Projectile
- 46000 fluid SPH, 127000 SPHC and 75000 Pinballs (contact)

**Steel Cylinder two cases:**
- Empty
- Full of water
Cylinder impact \textit{(Timm, 2003)}

Experimental computation comparison on

Final Shapes

\textbf{EMPTY Shell} \hspace{1cm} \textbf{Full of water Shell}

\textit{Timm, 2003} \hspace{1cm} \textbf{SPHC} \hspace{1cm} \textit{Timm, 2003} \hspace{1cm} \textbf{SPHC}
Computation of the experiments with SPHS + SPH fluid

- EMPTY
- FULL of water