PFEM-FEM coupling for fluid-structure interaction problems involving free surfaces and large solid deformations

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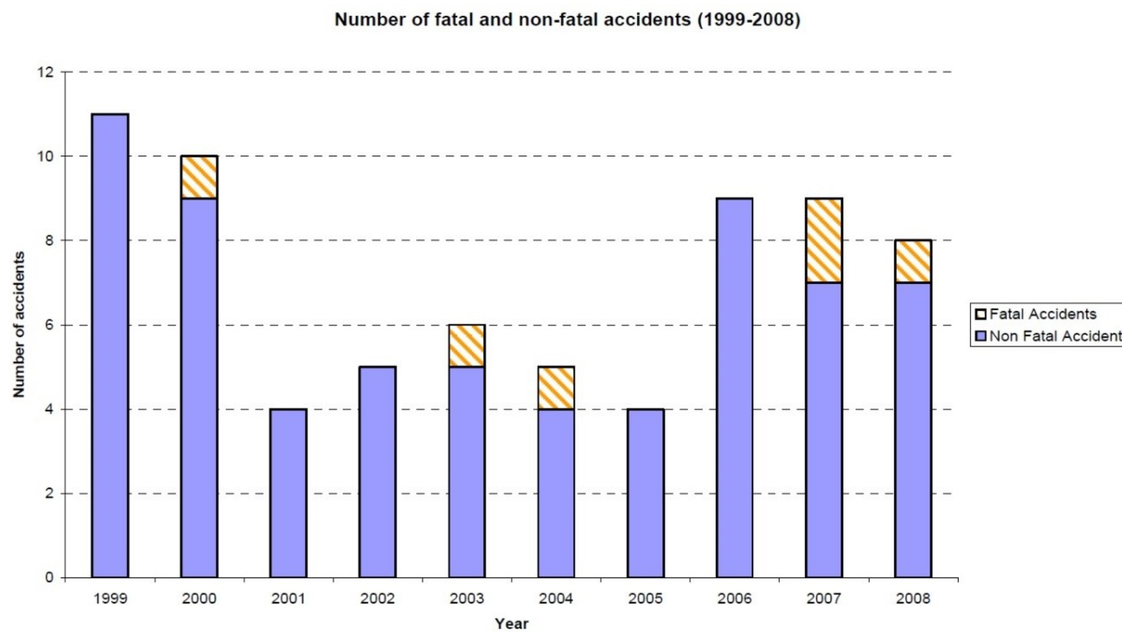
MOTIVATION

On 15 January 2009 the 1549 US Airways flight landed on the Hudson river after a collision with a flock of geese

Damages caused by bird strike represent a real threat in an aircraft life-cycle



[EASA - Bird population trends and their impact on Aviation safety 1999-2008]

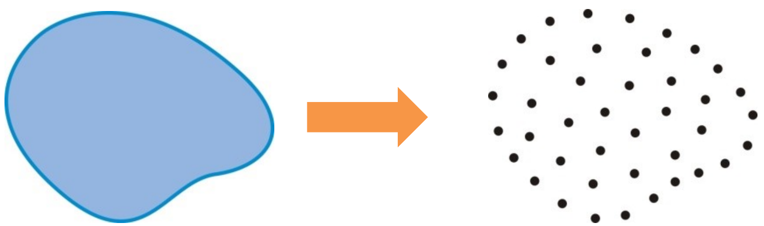
Bird strike is a complex free-surface fluid-structure interaction problem involving large deformations

Bird strike on a wind shield test

THE PFEM
(Particle-Finite Element Method)

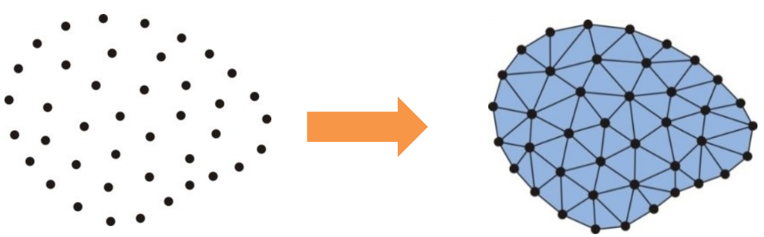
PFEM basics

1. The first step in the PFEM is discretizing the continuum with some particles/nodes:

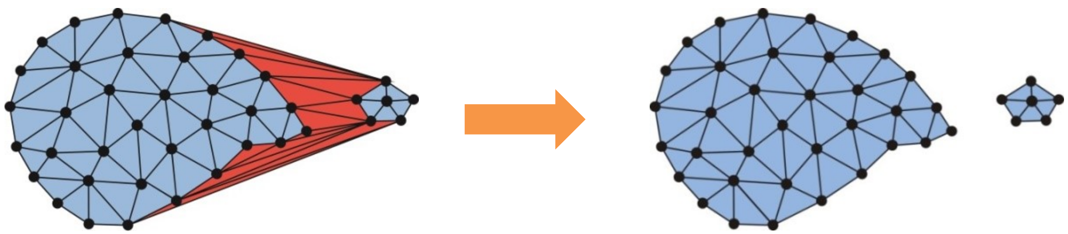


2. The particles carry all the physical and mathematical information (density, viscosity, velocity, pressure, …)

3. At each time step a new mesh is quickly built using a Delaunay triangulation:



4. The boundaries of the domain are identified via the α-shape algorithm:

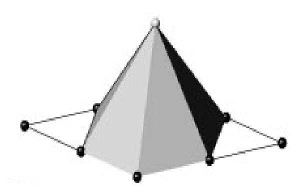


All the triangles whose circumcircle has a radius $r(x)$ larger than $\alpha h(x)$ are canceled.

α=scalar parameter (usually between 1.2 and 1.5!)
$h(x)$= mean distance between two neighboring nodes

5. This new mesh is used to discretize the weak form using linear Finite Element shape functions:

$$\begin{cases} \rho \dfrac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = \mathrm{div}\,\boldsymbol{\sigma} + \rho \boldsymbol{b} \\ \dfrac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\,\mathrm{div}(\boldsymbol{u}) = 0 \end{cases} \quad +$$

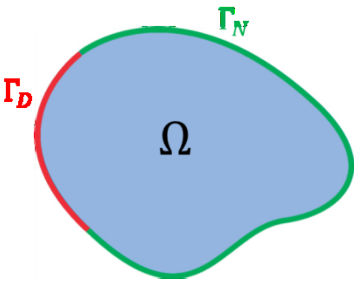


FEM shape functions

$$+ \int \ldots \mathrm{d}\Omega$$

From now on I will focus on Newtonian incompressible fluid flows

$$
\begin{cases}
\rho_0 \dfrac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} = -\mathrm{div}(p\mathbf{I}) + \mu\,\mathrm{div}\big(\mathrm{grad}(\boldsymbol{u}) + \mathrm{grad}(\boldsymbol{u})^{\mathrm{T}}\big) + \rho_0 \boldsymbol{b} \quad \text{in } \boldsymbol{\Omega} \\
\mathrm{div}(\boldsymbol{u}) = 0 \quad \text{in } \boldsymbol{\Omega} \\
\boldsymbol{u} = \bar{\boldsymbol{u}} \quad \text{on } \Gamma_D \quad , \boldsymbol{\sigma}\cdot\boldsymbol{n} = \bar{\boldsymbol{t}} \quad \text{on } \Gamma_N
\end{cases}
$$

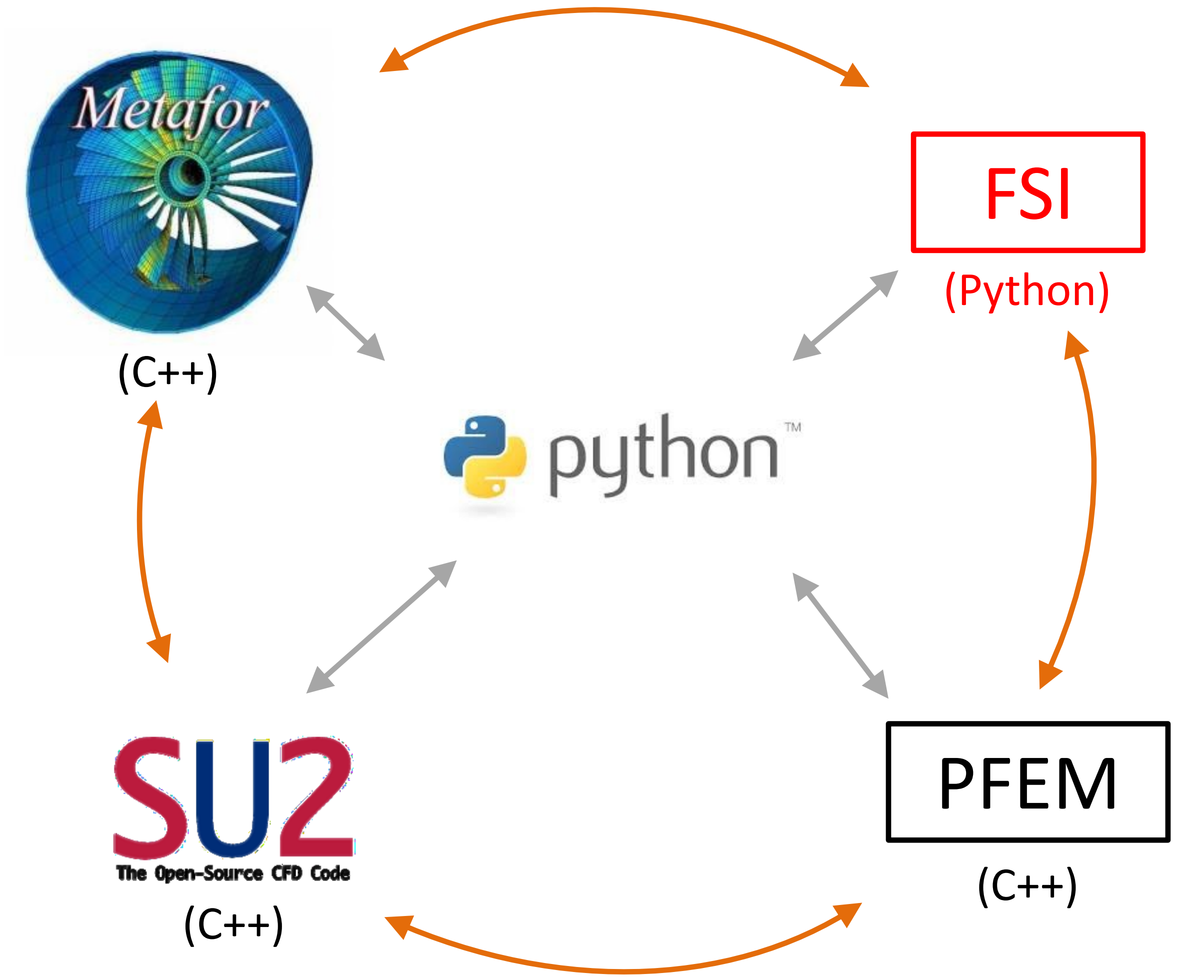


$$
\begin{cases}
\displaystyle\int_\Omega \rho_0 \frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t}\cdot\boldsymbol{w}\,\mathrm{d}\Omega = \int_\Omega p\mathbf{I} : \mathrm{grad}(\boldsymbol{w})\,\mathrm{d}\Omega - \int_\Omega \mu\,\mathrm{grad}(\boldsymbol{u}) : \mathrm{grad}(\boldsymbol{w})\,\mathrm{d}\Omega \; + \\
\qquad - \displaystyle\int_\Omega \mu\,\mathrm{grad}(\boldsymbol{u})^{\mathrm{T}} : \mathrm{grad}(\boldsymbol{w})\,\mathrm{d}\Omega + \int_\Omega \rho_0\,\boldsymbol{b}\cdot\boldsymbol{w}\,\mathrm{d}\Omega + \int_{\Gamma_N} \bar{\boldsymbol{t}}\cdot\boldsymbol{w}\;\mathrm{d}\Gamma \\
\displaystyle\int_\Omega \mathrm{div}(\boldsymbol{u})q\,\mathrm{d}\Omega = \sum_{e=1}^{N_{el}} \int_{\Omega_0^e} \tau_{\mathrm{pspg}}^e \frac{1}{\rho_0}\mathrm{grad}(q)\left(\rho_0 \frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} + \mathrm{div}(p\mathbf{I}) - \mu\,\mathrm{div}\big(\mathrm{grad}(\boldsymbol{u}) + \mathrm{grad}(\boldsymbol{u})^{\mathrm{T}}\big) - \rho_0\boldsymbol{b}\right)
\end{cases}
$$

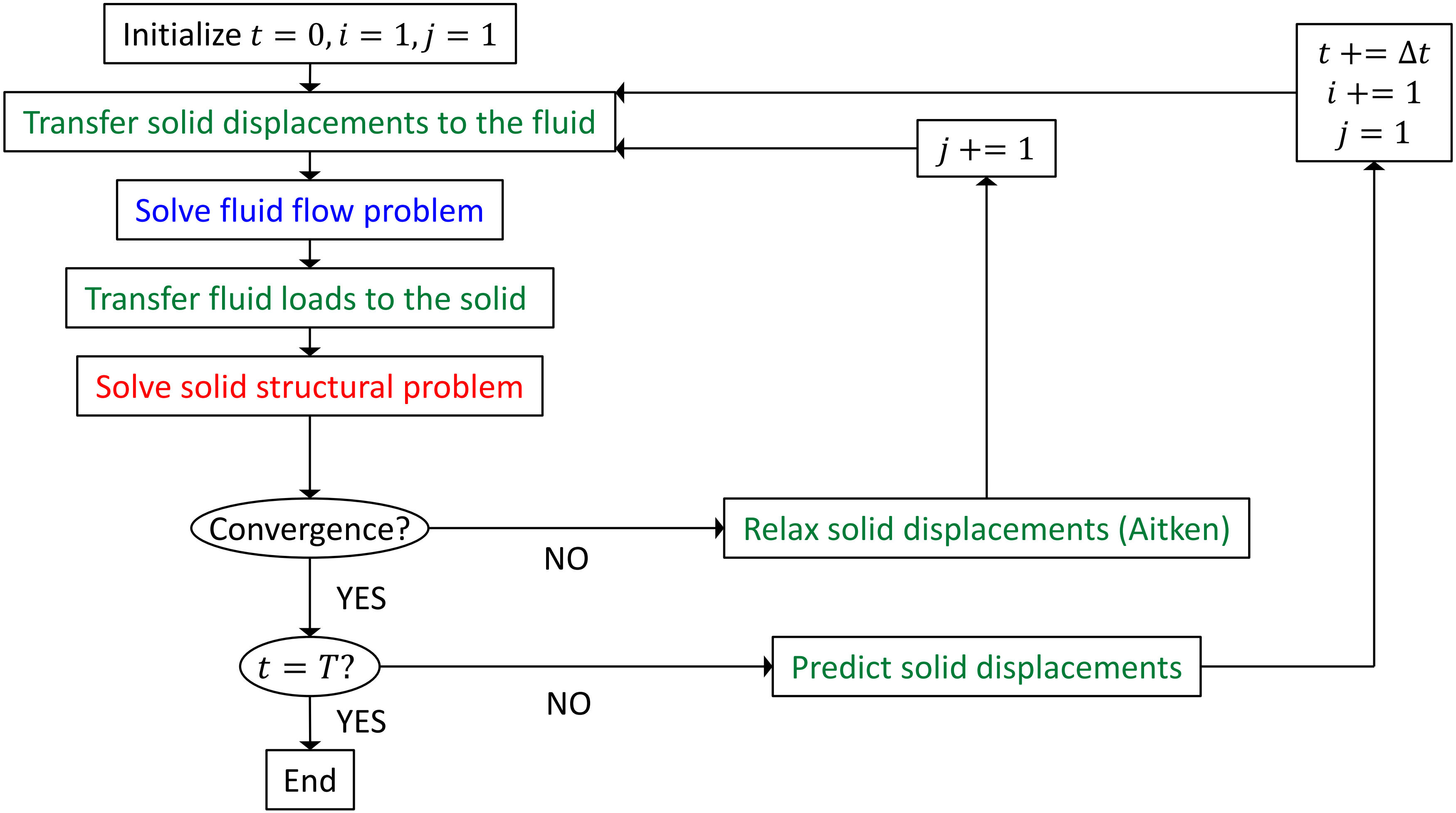
[Tezduyar *et al.* (1992), Cremonesi *et al.* (2010)]

COUPLING STRATEGIES

Implementation

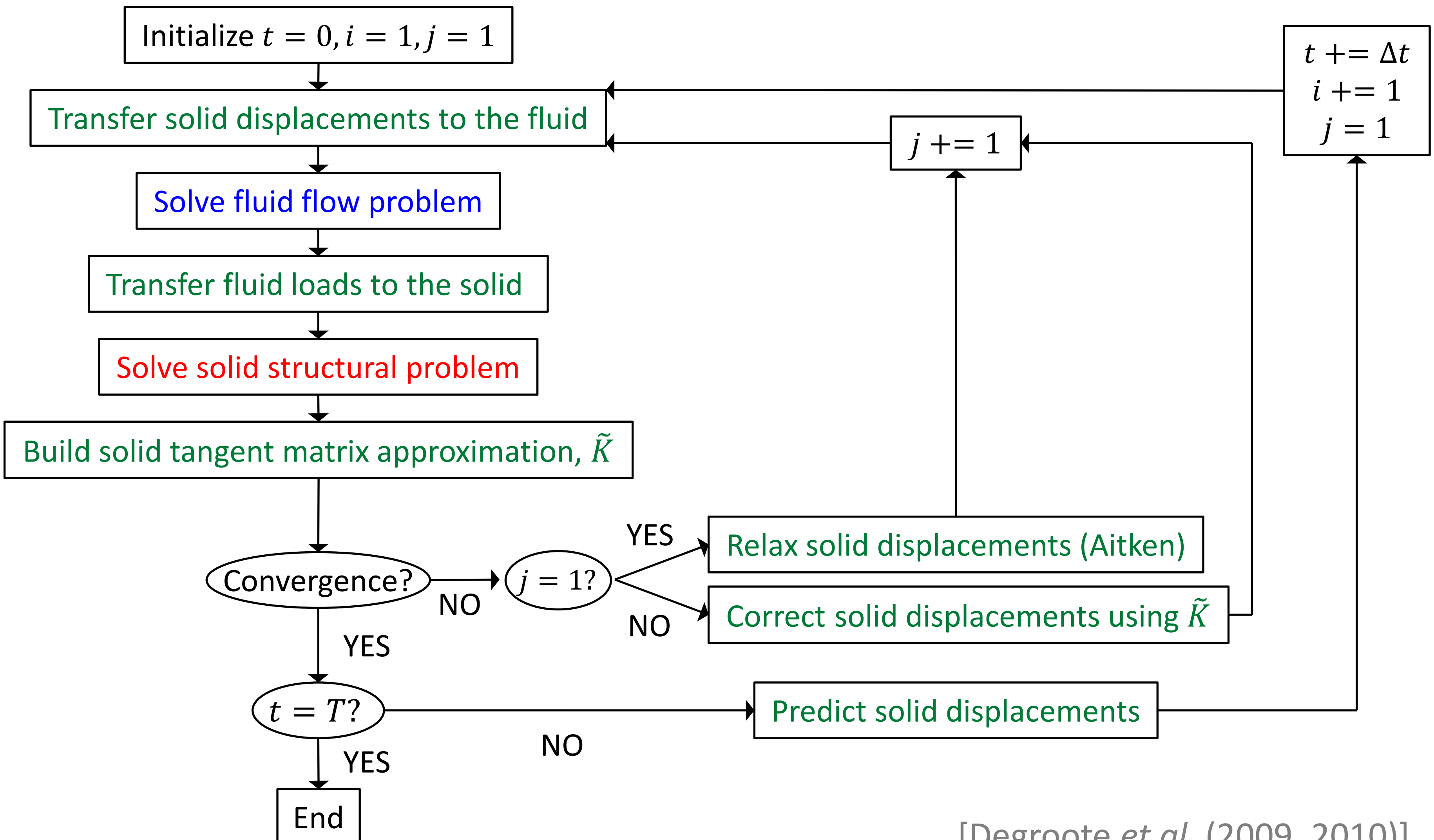


Block-Gauss Seidel with Aitken relaxation (BGS)



[Kuttler and Wall (2008), Habchi *et al.* (2012)]

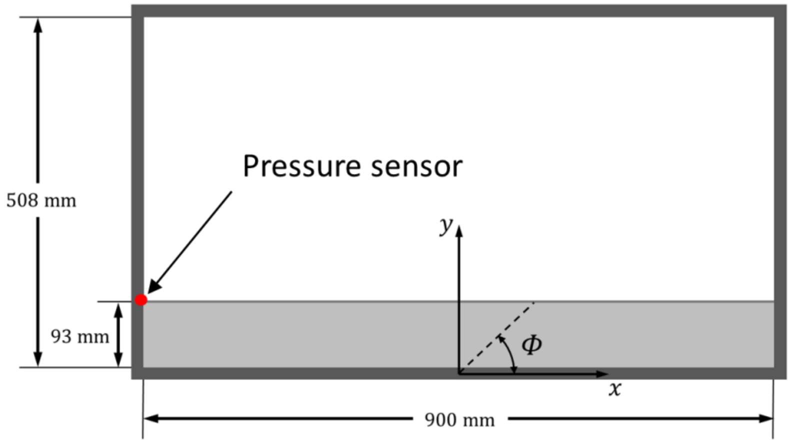
Interface Quasi-Newton - Inverse Least Squares (IQN-ILS)

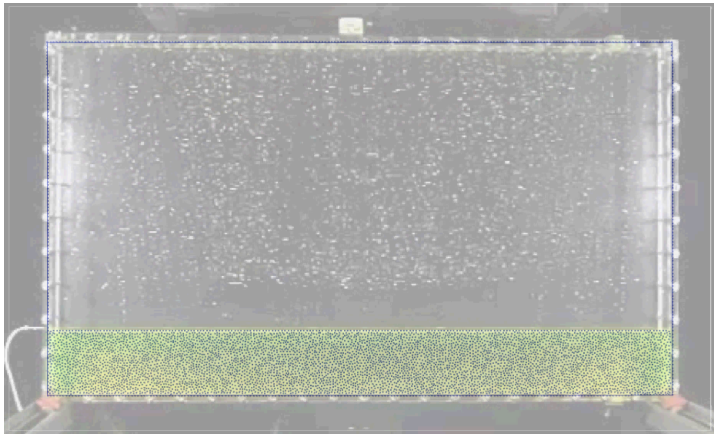


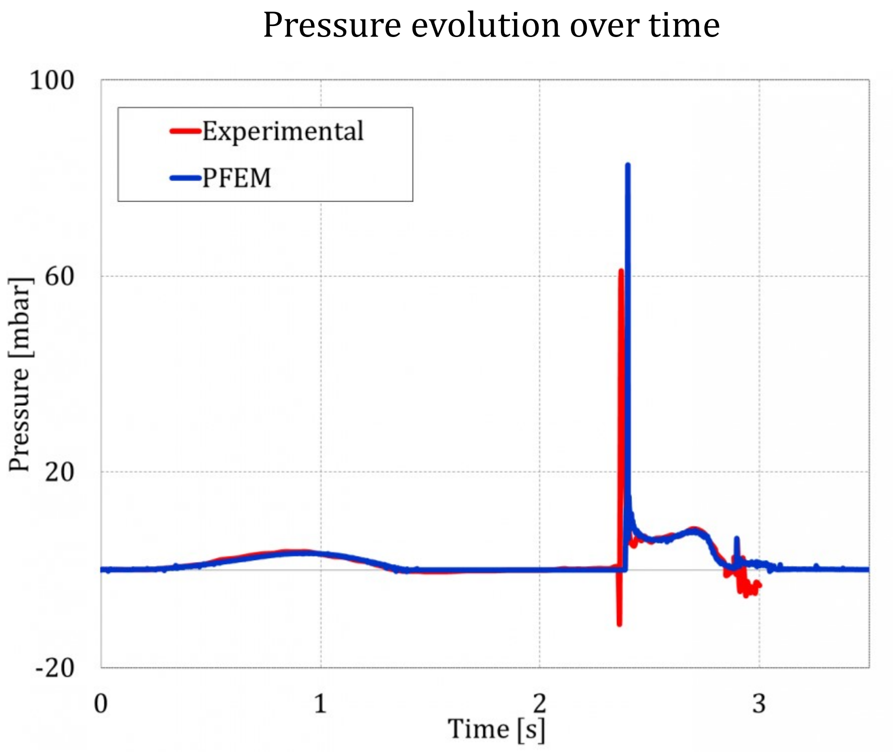
[Degroote *et al.* (2009, 2010)]

APPLICATIONS

Sloshing of an oscillating water reservoir





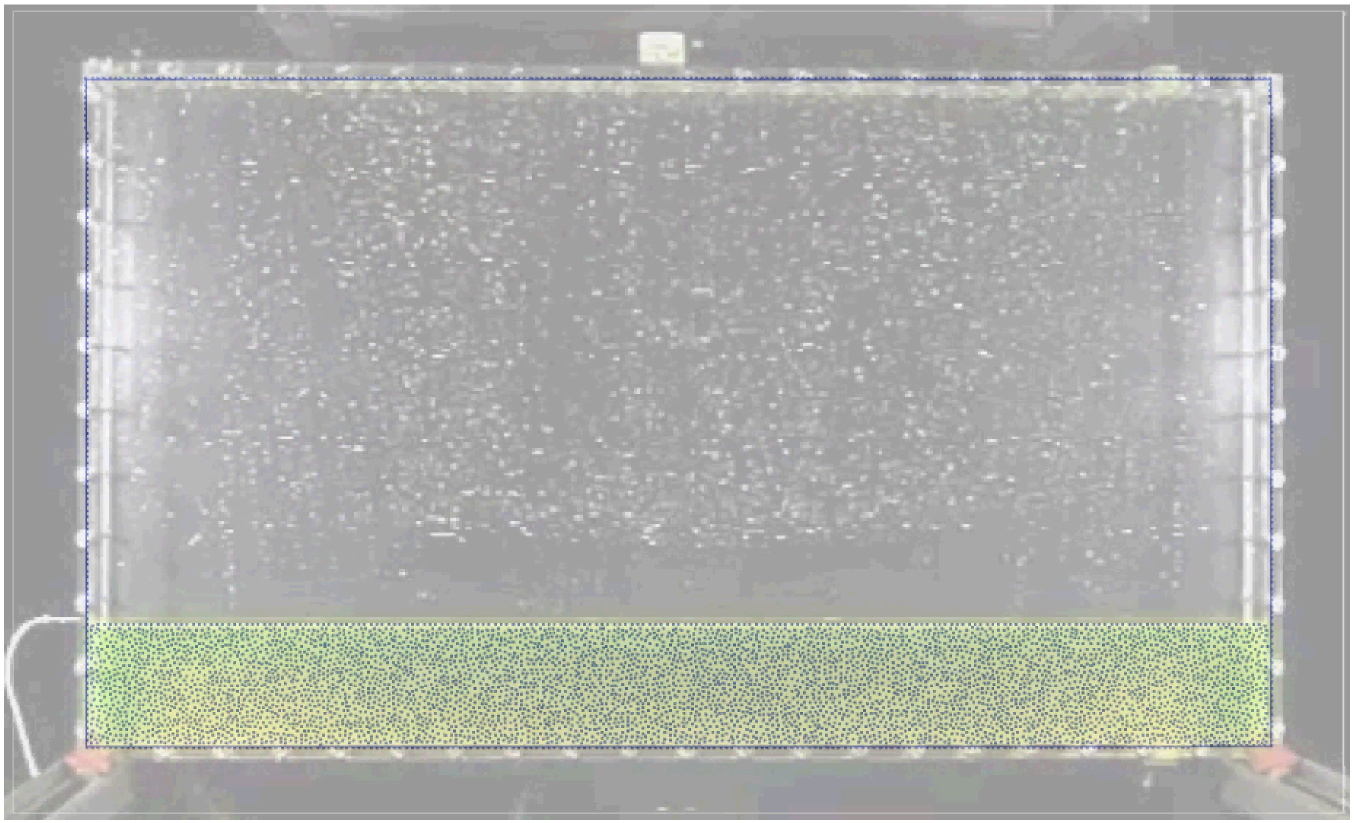


3.5s simulation **6000** particles

experimental numerical

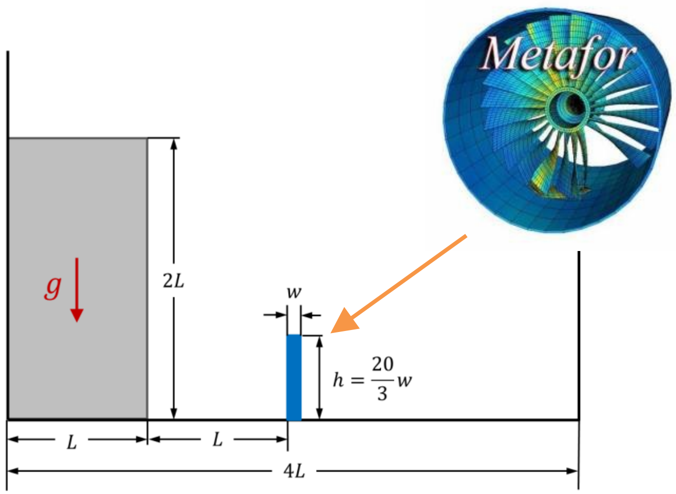
[Experimental results available online on the SPHERIC community website: https://wiki.manchester.ac.uk/spheric]

Sloshing of an oscillating water reservoir



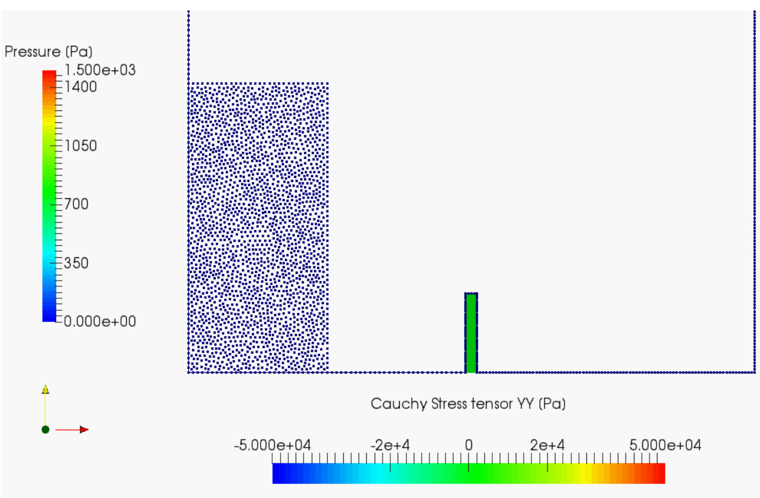
experimental   numerical

Dam break against an elastic obstacle

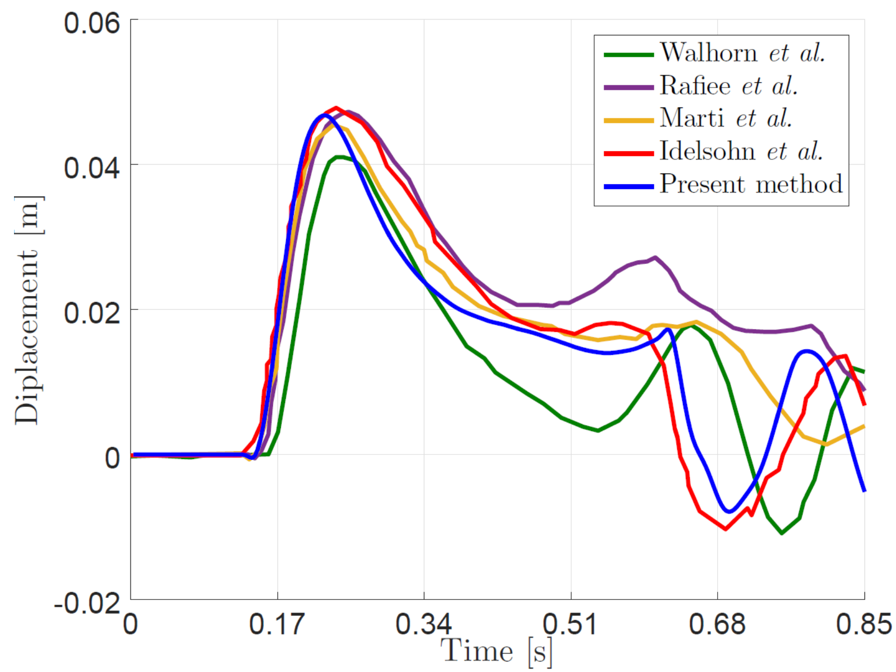


$L = 156$ mm $\quad w = 1.2$ mm

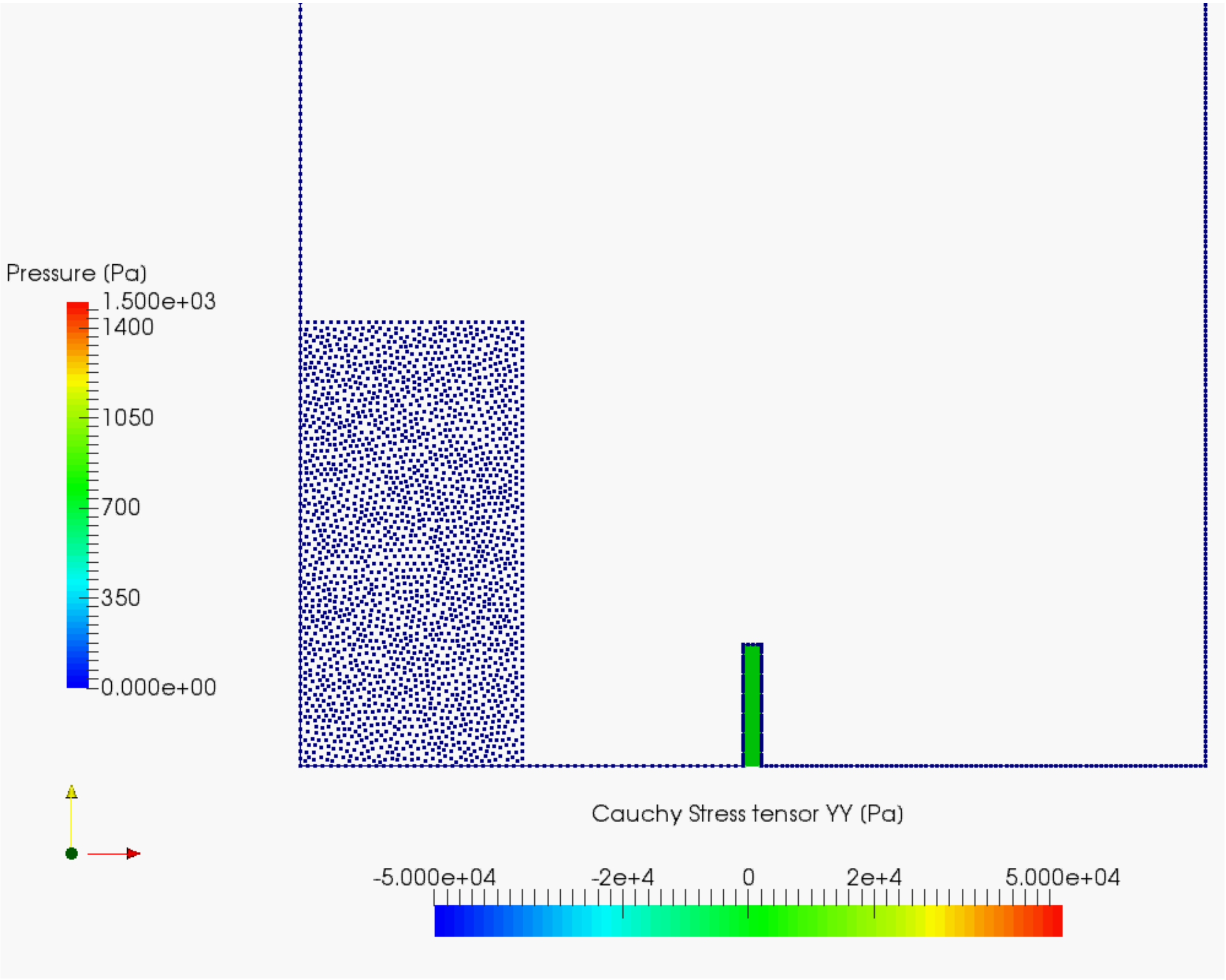
$\rho_{solid} = 1500\ \mathrm{kg/m^3} \quad E_{solid} = 1\mathrm{MPa}$



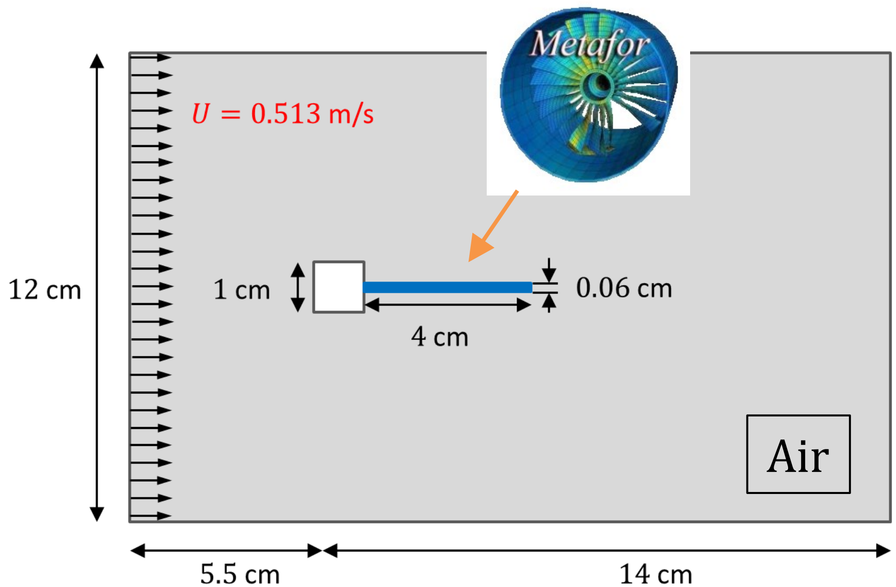
Horizontal tip displacement over time



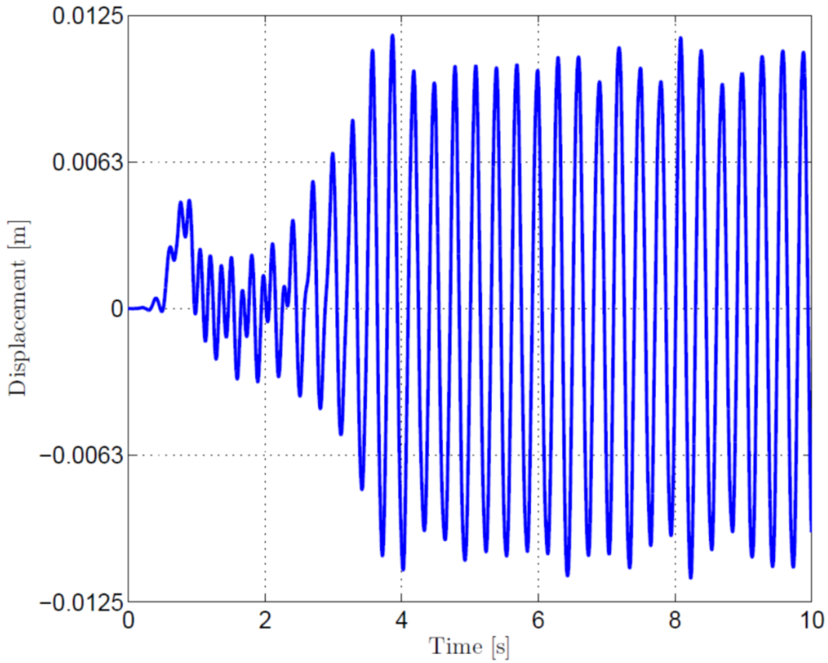
Dam break against an elastic obstacle



Vortex-induced vibrations (VIV) of a flexible cantilever

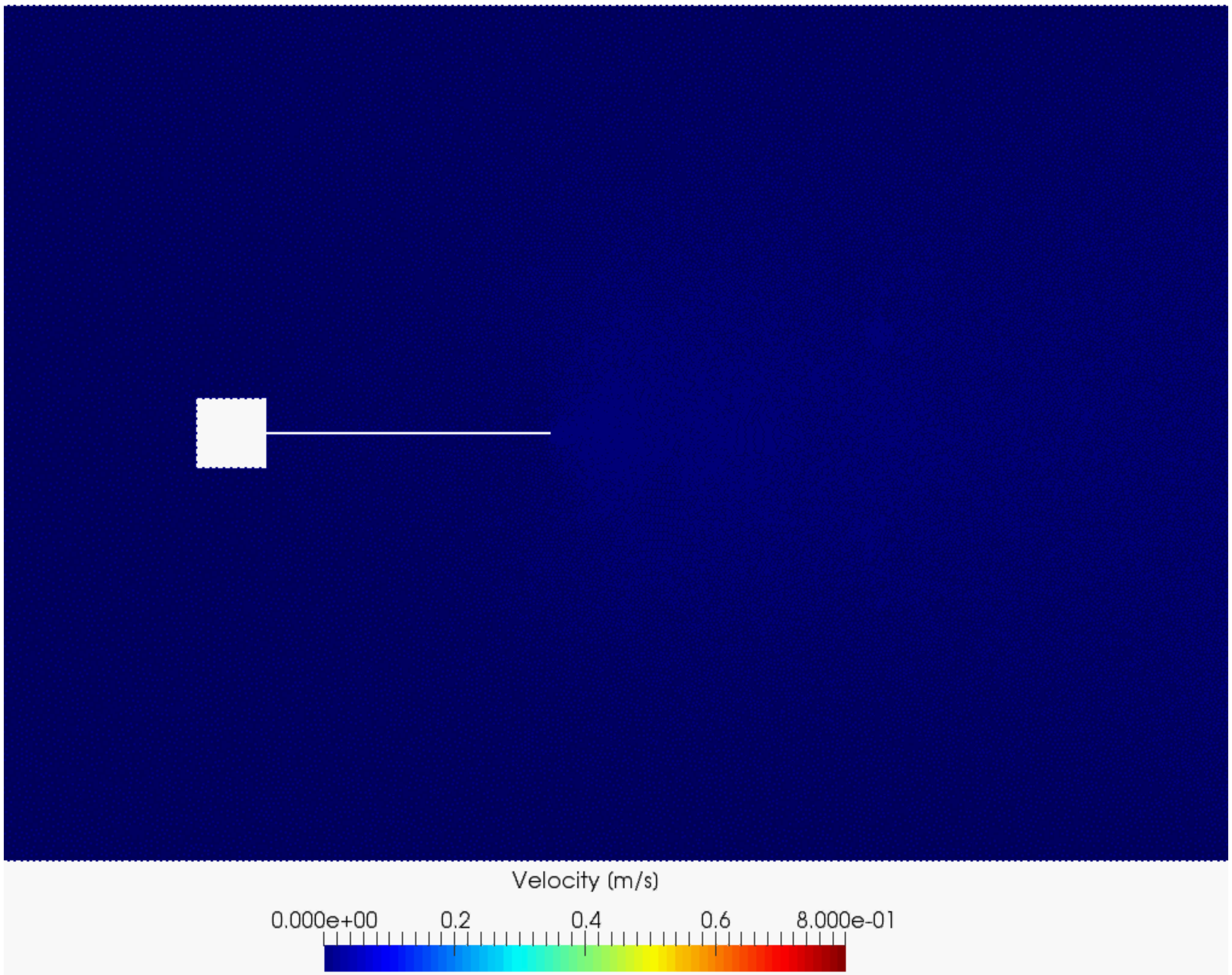


$\rho_{solid} = 100 \text{ kg/m}^3 \quad E_{solid} = 0.25 \text{ MPa}$

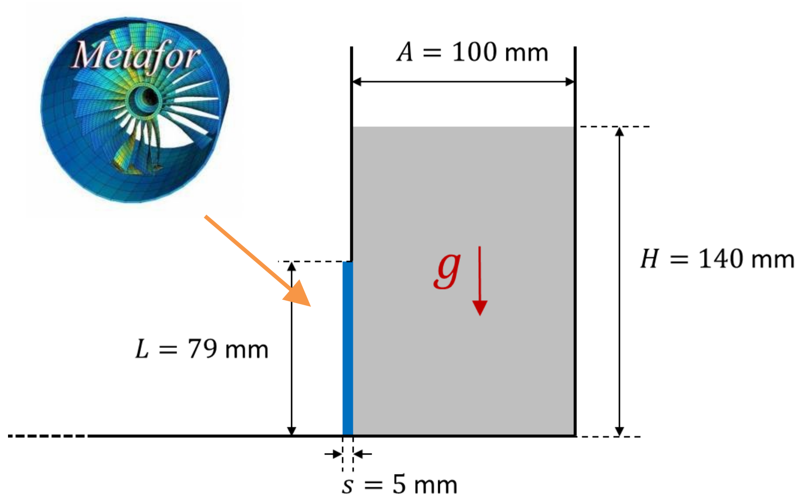


Quantity	PFEM-FEM	Literature
Maximum tip displacement	1.15 mm	0.95 – 1.25 mm
Frequency	3.25 Hz	2.94 – 3.25 Hz

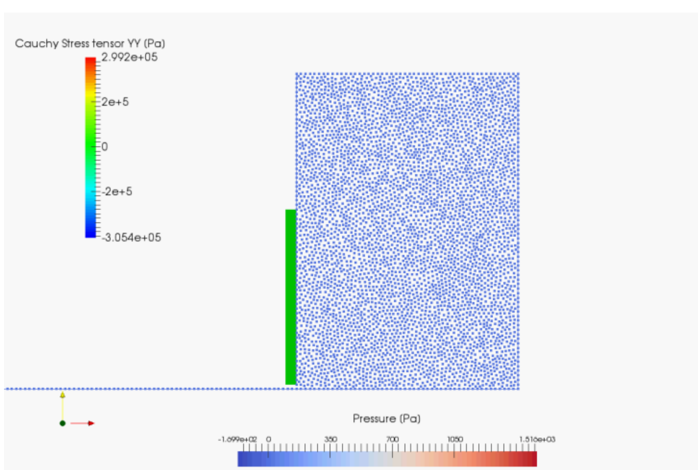
Vortex-induced vibrations (VIV) of a flexible cantilever

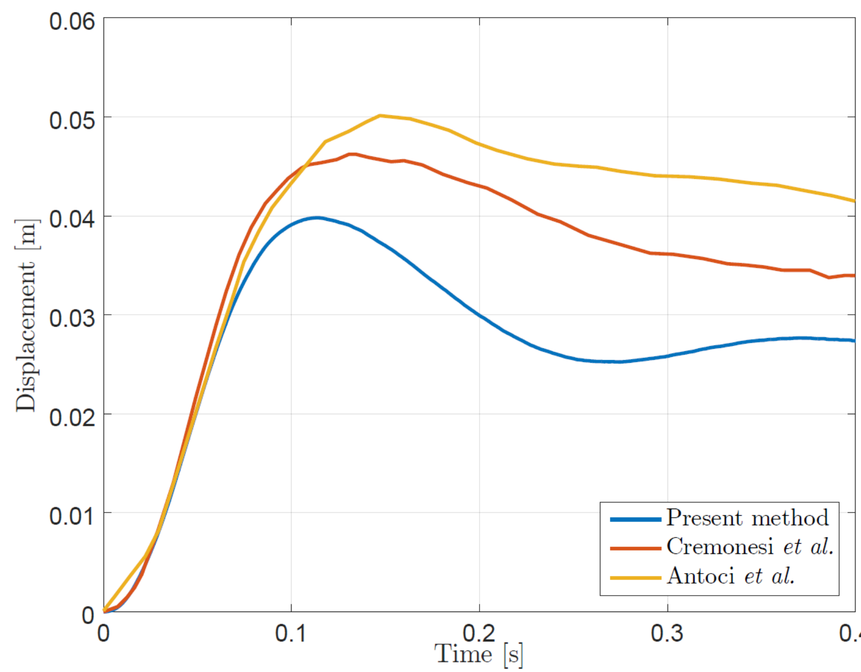


Dam break with an elastic gate (Ongoing work)



$$\rho_{solid} = 1100\ \mathrm{kg/m^3} \quad E_{solid} = 10\ \mathrm{MPa}$$





[Antoci *et al.* (2007)]

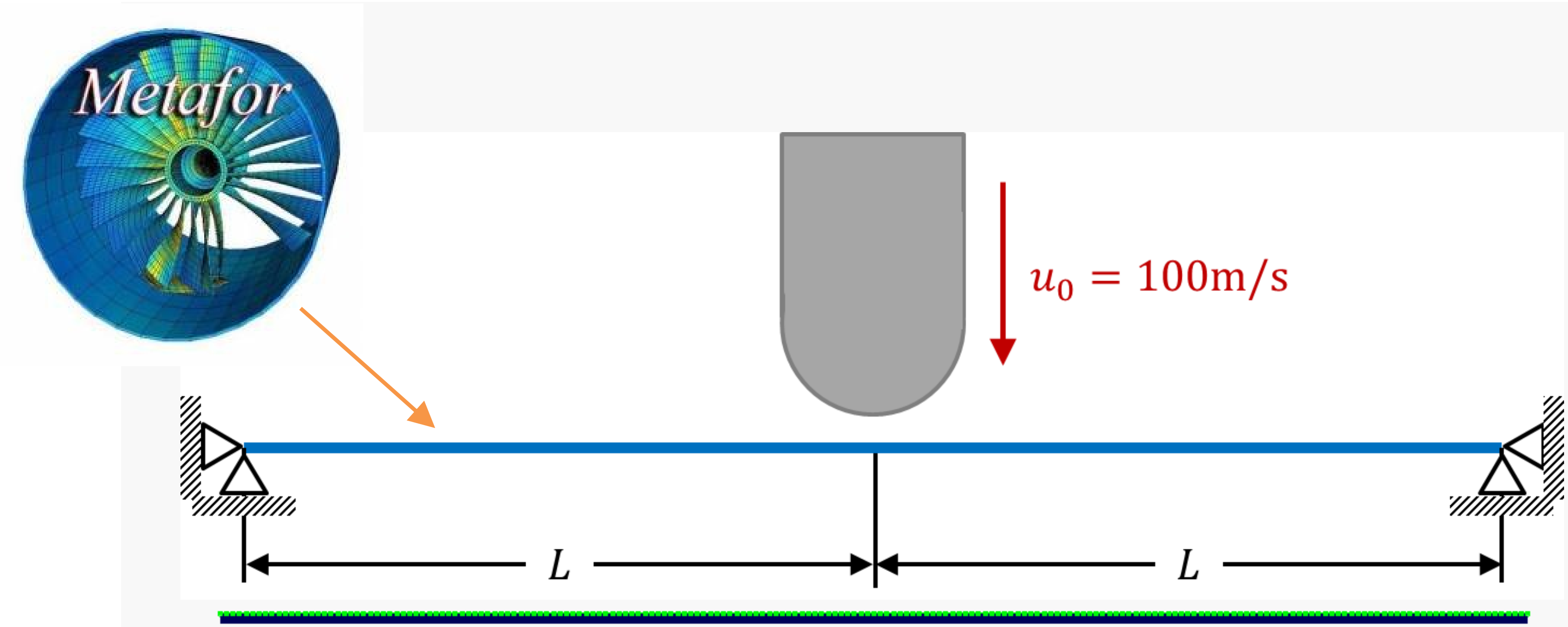
Dam break with an elastic gate (Ongoing work)

Coupling strategy	n. Iterations per step	CPU Time [s]
BGS	6.53	1378.46
IQN-ILS	6.22	1309.98
IQN-ILS (1)	5.20	1154.64
IQN-ILS (2)	5.67	1247.68
IQN-ILS (4)	6.39	1349.33
IQN-ILS (6)	6.38	1336.14

Gain ~16%

IQN-ILS (*i*) → information from '*i* ' previous time steps is used for the approximation of the tangent matrix in the IQN-ILS strategy

Bird strike on a metallic flexible panel at 100 m/s

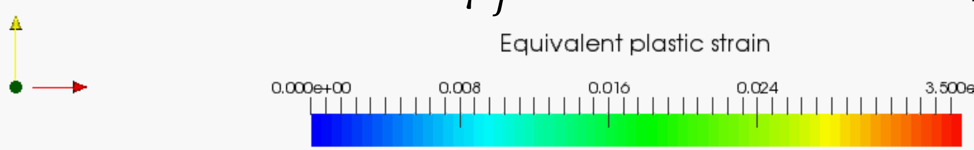


$L = 0.4$ m

$w = 0.00635$ m

$\rho_f = 1000\ \text{kg/m}^3$

$\mu_f = 0.001\ \text{Pa} \cdot \text{s}$



$\rho_s = 7800\ \text{kg/m}^3$

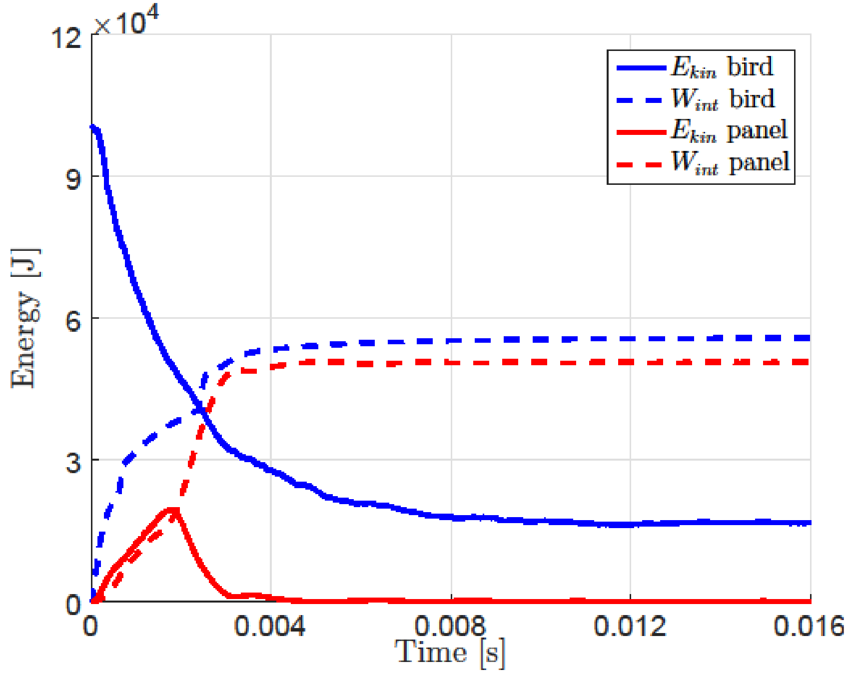
$E = 210$ GPa

$E_H = 1$ GPa

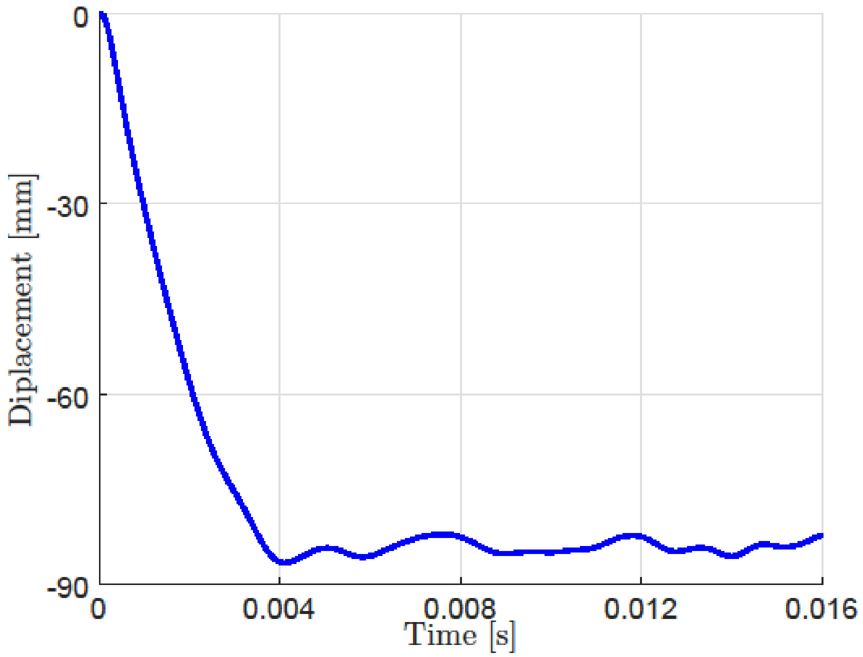
$\nu = 0.3$

$\sigma_Y = 300$ MPa

Bird strike on a metallic flexible panel at 100 m/s



Energy evolution



Panel center vertical displacement

CONCLUSIONS

Conclusions

- An original PFEM – FEM fluid-structure coupling taking into account complex structural behavior has been proposed
- Results have been compared to experimental and other numerical results and good agreement was found
- Classical (BGS) and more sophisticated (IQN-ILS) coupling techniques are available in the proposed framework
- In the future, 3D problems will be addressed and the use of a compressible fluid will be investigated.

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