Embedded approach for the FSI involving inflatable light-weight structures

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Outline

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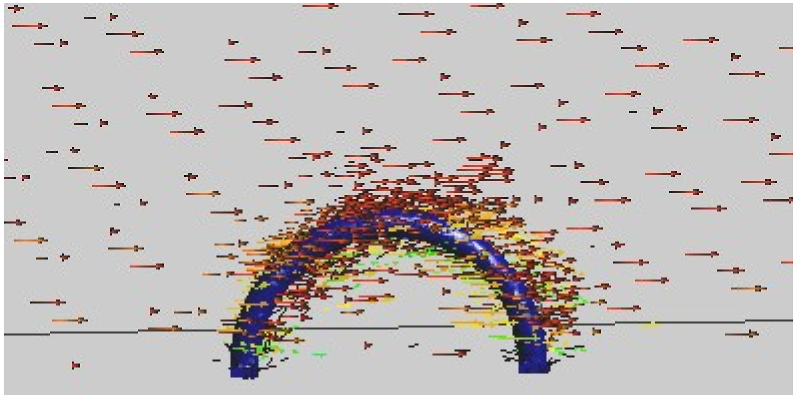
- 2. Intro & State-of-the art
- 3. Embedded approach
  - Formulation
  - Algorithm
- 4. Examples
  - “Practical” observations
- 5. Conclusions & Future work

1. Motivation

Problem of interest: **inflatable structures** exposed to wind loads: **uLites project**

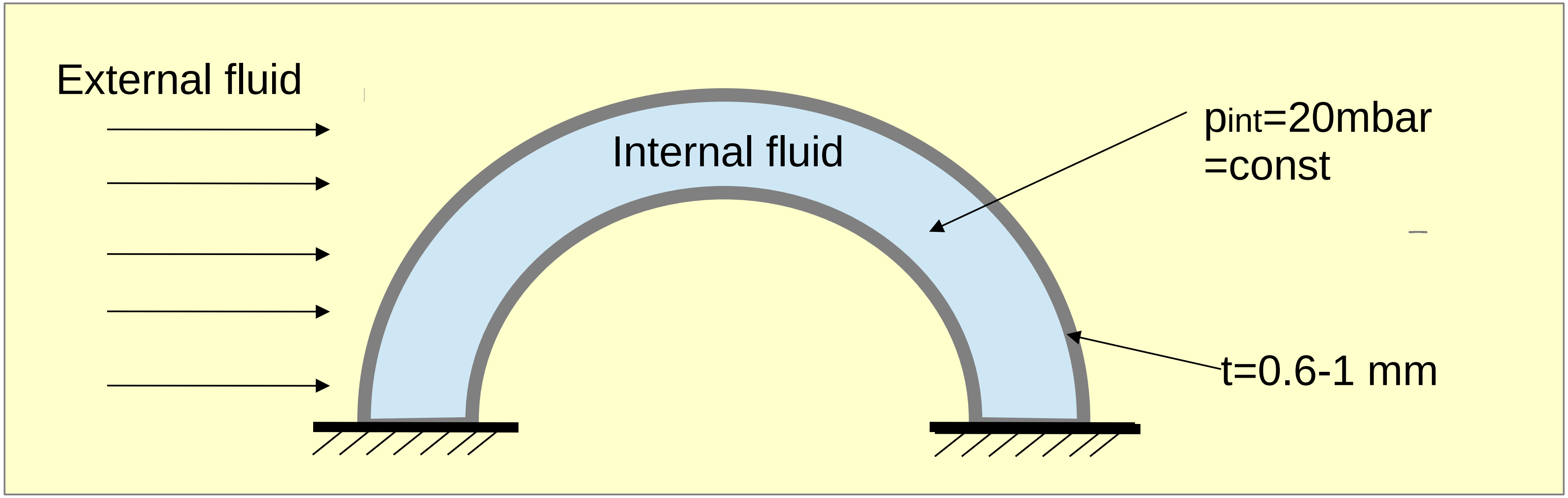
– Light-weight structures

– Fluid-structure interaction



Characteristics of the problem of interest

- Very thin and light fabric PLASTEL 8820 (**0.6 mm**, **1250 kg/m3**), **E=0,31 GPa**), without resistance to compression
- Constant internal pressure: **20 mba**r
- “Peculiarities” of the internal fluid are of no interest
- Operating conditions: wind velocity range = **1 m/s** up to **20 m/s**



What must be in the model...

- Flow around the structure (“external” flow)

  Navier-Stokes, FEM

- “Internal” fluid=> constant pressure,

  no continuum mechanics equations

- Light-weight structure=>

  Membrane, FEM

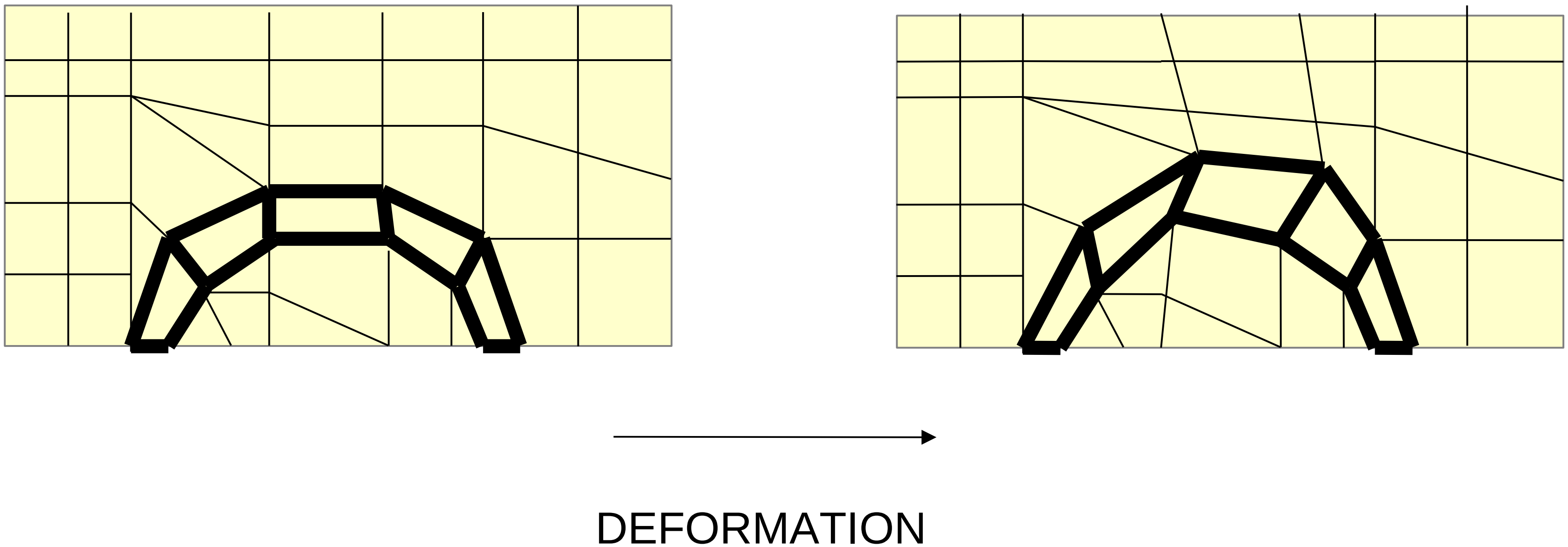
- Interaction: strong 2-way coupling, accounting for large structural displacements

2. State-of-the-art

- Interface fitting moving mesh approaches: **ALE, Lagrangian**

  +Interface exactly defined by the nodes of the mesh

  - large motions of the structure=> re-meshing is necessary



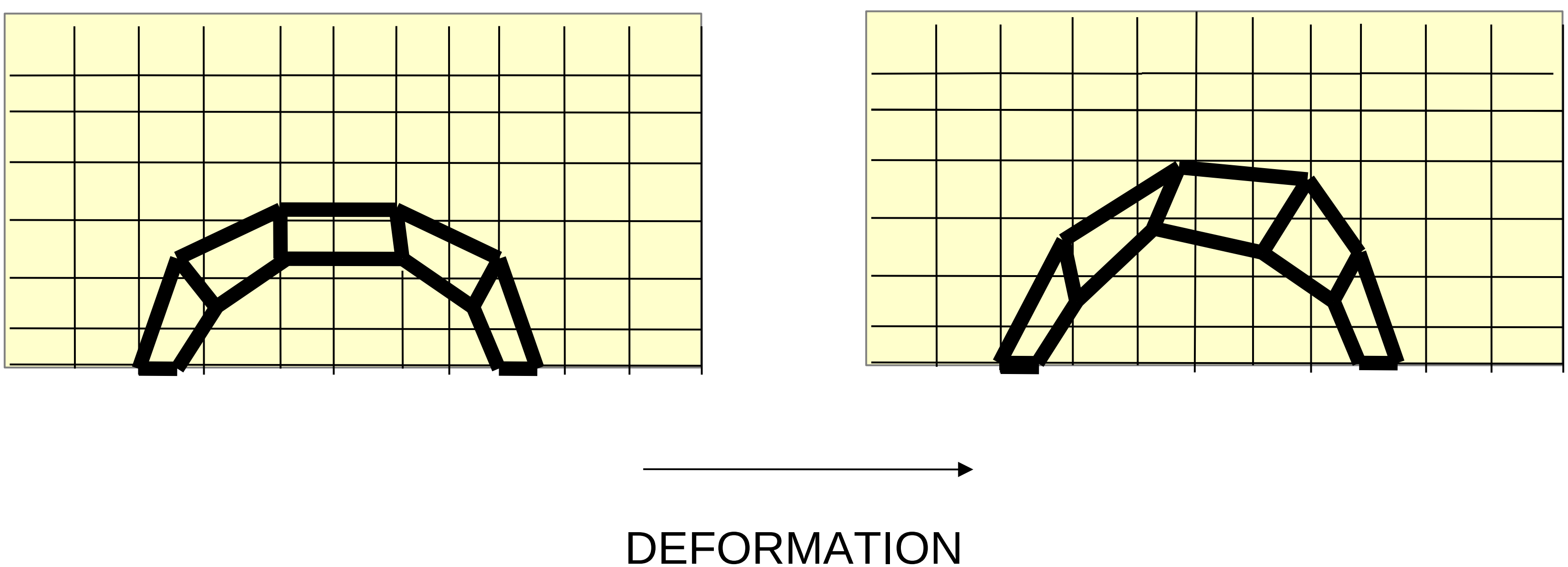
2. State-of-the-art

- Embedded approaches: **Eulerian** fluid, **Lagrangian** structure. <u>Fixed fluid mesh</u>

  +No restrictions for the structural motion

  +Different meshes can be used for both domains

  \- Necessity to locate the position of the structure within the fixed Eulerian mesh



Taking into account the problem of interest

- We need to handle problems where large deformations are expected
- Of industrial interest: millions DOFs
- Re-meshing is highly undesirable

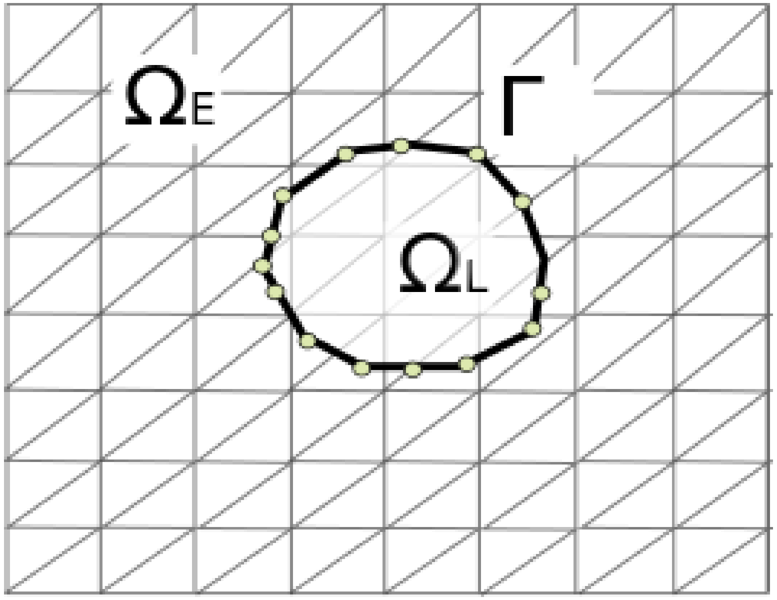
embedded approach

(also known as “immersed boundary”)

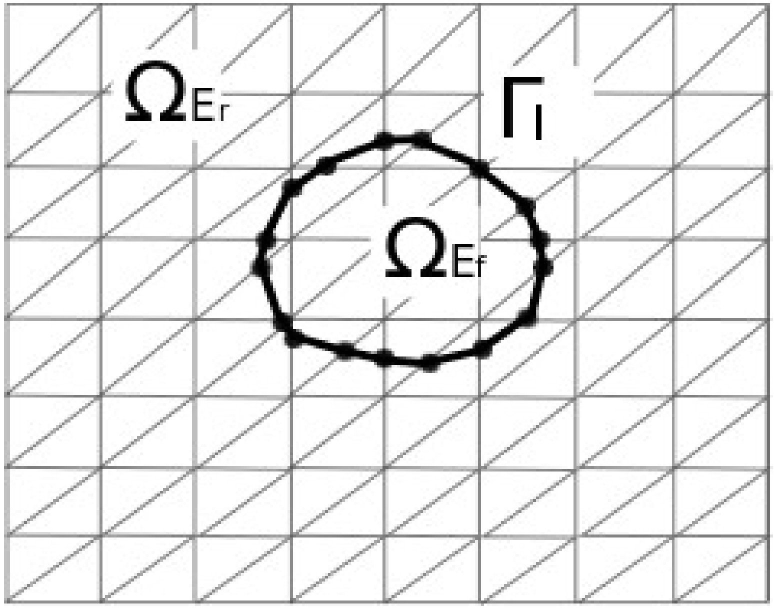
Gerstenberger A. and Wall W. *CMAME*, 197, 2008
Codina R. and Baiges J. *INJME*, 80, 2009

3 Embedded approach

- Eulerian fluid and Lagrangian structure
- Solved in a partitioned way
- Coupled using an iterative Dirichlet-Neumann algorithm
- Stability of the coupling => Interface Laplacian technique



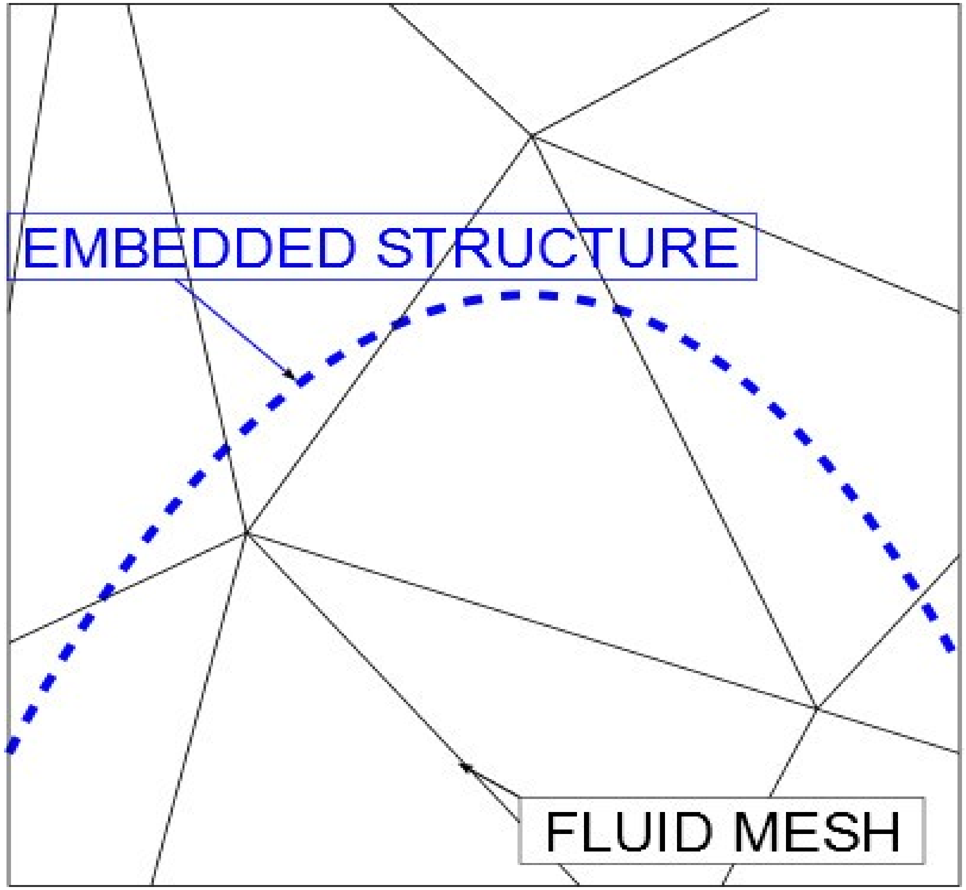
Lagrangian structure: superimposed over Eulerian mesh

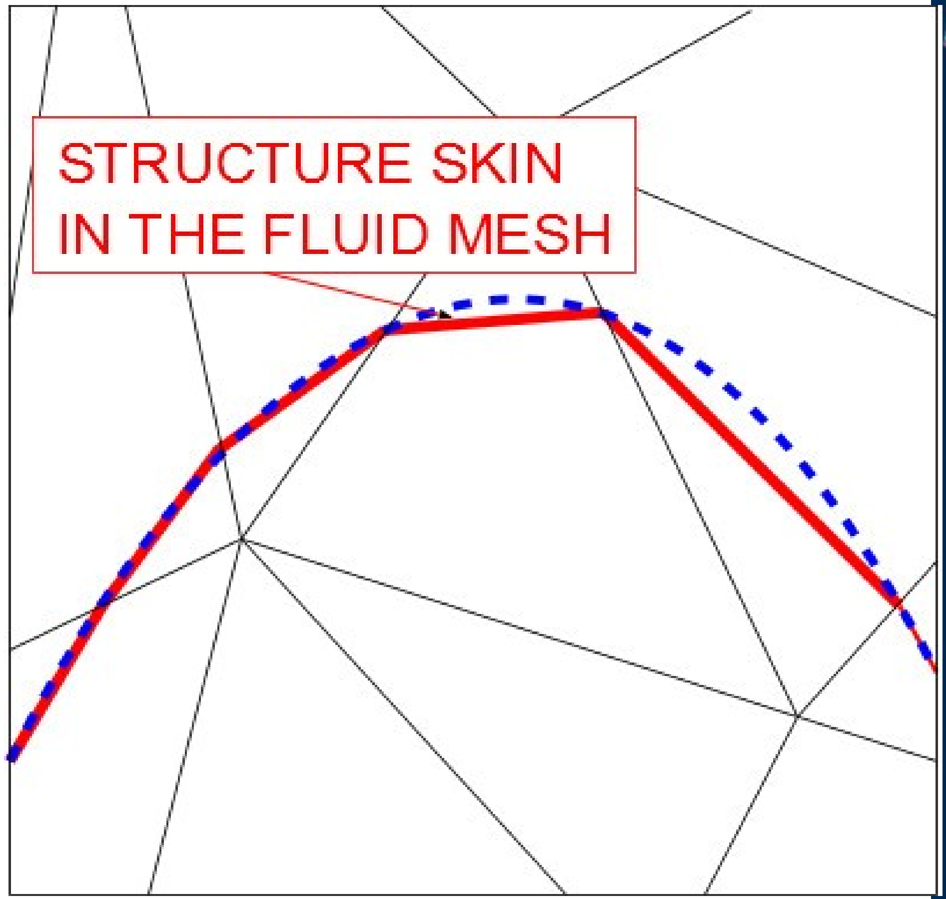


Lagrangian image: intersections of Lagrangian boundary with the Eulerian mesh

Lagrangian image: close-up

Quality of the Lagrangian image depends upon the resolution of the Eulerian mesh



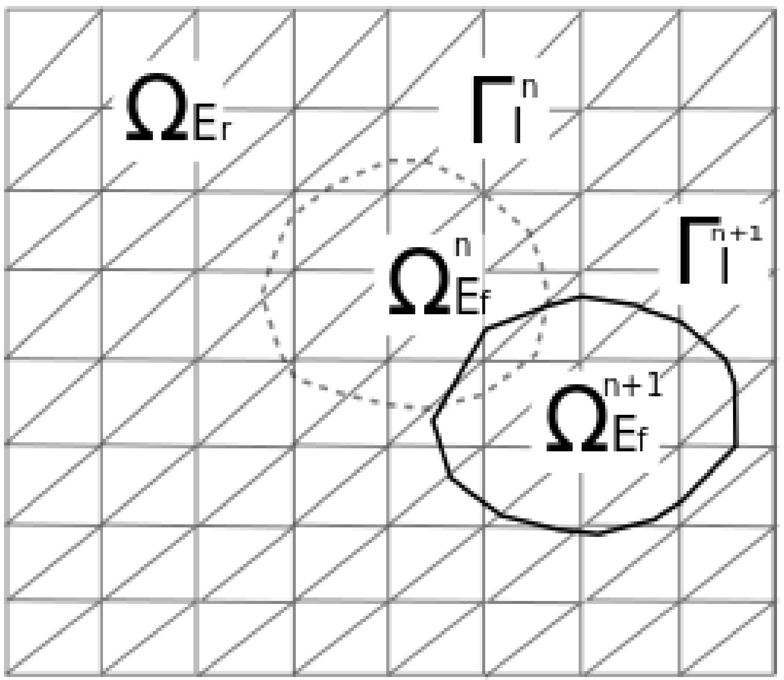


Courtesy: A. Larese

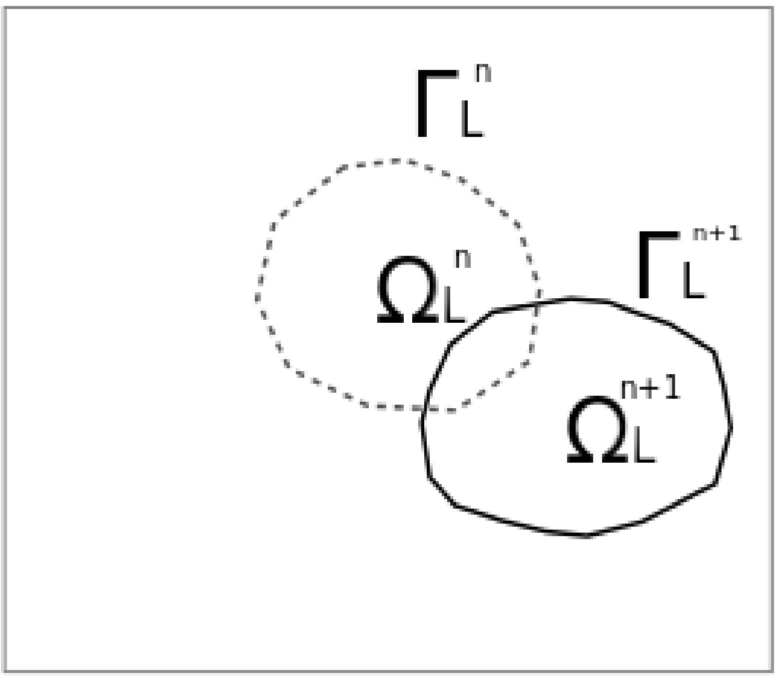
Embedded approach

$$\begin{pmatrix} \frac{\mathbf{M}}{\Delta t} + \rho\bar{\mathbf{K}}\left(\bar{\mathbf{v}}_{n+1}\right) + \mu\mathbf{L} + \mathbf{S}_K & \mathbf{G} + \mathbf{S}_G \\ \mathbf{D} + \mathbf{S}_D & \tau\mathbf{L} \end{pmatrix} \begin{pmatrix} d\bar{\mathbf{v}} \\ d\bar{p} \end{pmatrix} = \begin{pmatrix} \bar{\mathbf{r}}_m \\ \bar{\mathbf{r}}_c \end{pmatrix}$$

$$\rho\mathbf{M}\bar{\mathbf{a}}_{n+1} + \mathbf{K}\bar{\mathbf{u}}_{n+1} = \mathbf{F}_{n+1}$$



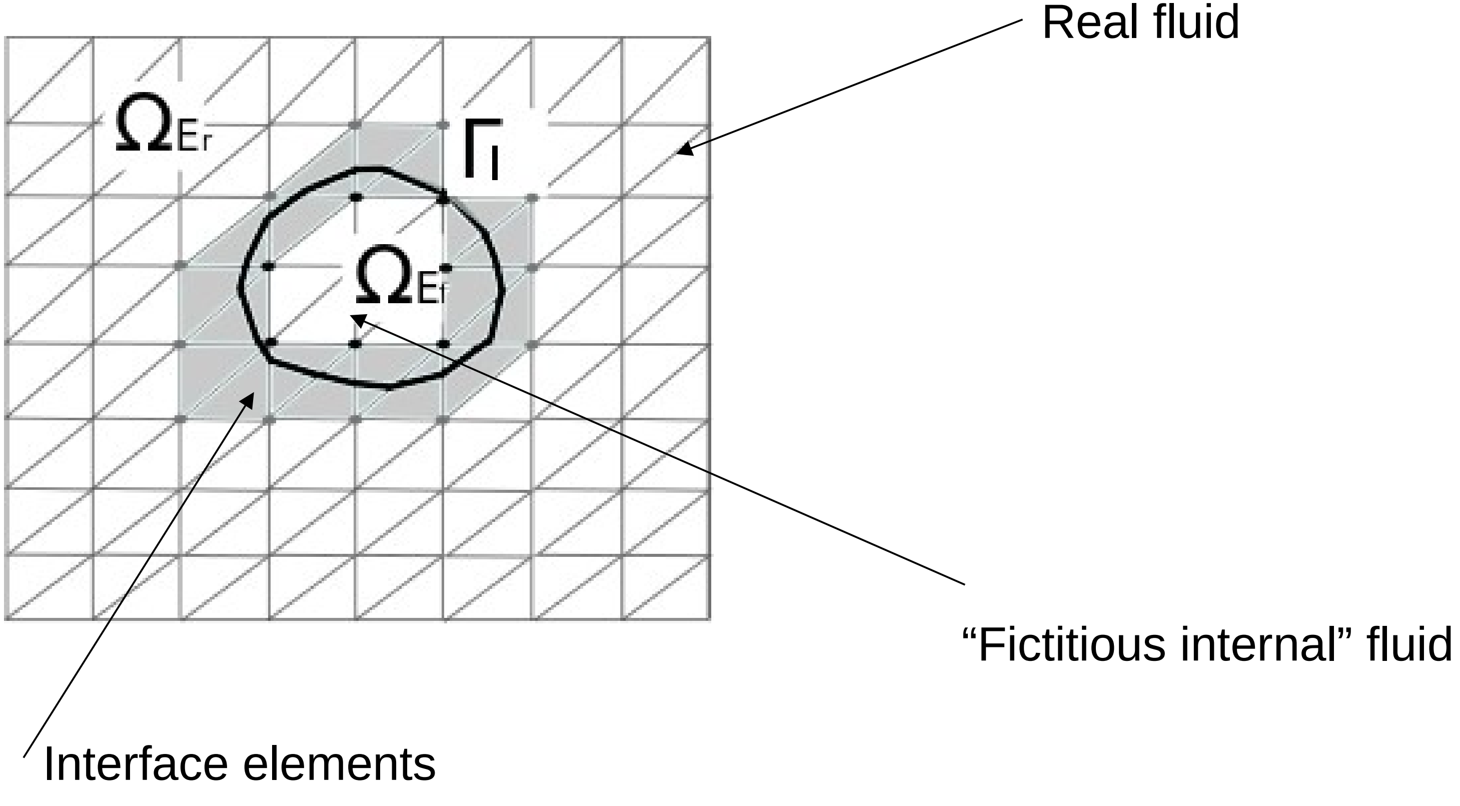
Eulerian domain: fluid with the embedded Lagrangian image



Lagrangian domain: structure

Parts of the Eulerian domain

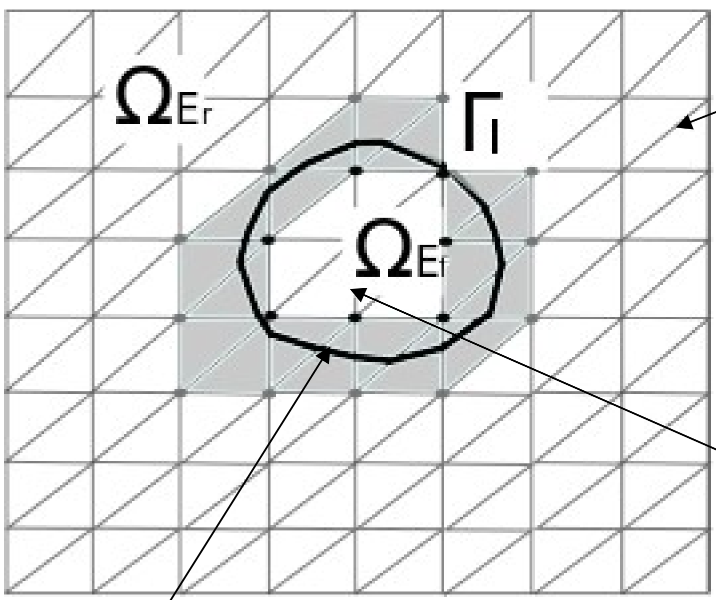
- Lagrangian image splits the Eulerian domain into: **real** and **fictitious** parts. We also distinguish the "**interface**" elements



Interface Dirichlet b.c.

- How to impose structural motion within an Eulerian mesh: velocity Dirichlet b.c. at the inteface

Real fluid: Navier-Stokes



$$\begin{pmatrix} \frac{\mathrm{M}}{\Delta t} + \rho \bar{\mathbf{K}}\left(\bar{\mathbf{v}}_{n+1}\right) + \mu \mathbf{L} + \mathbf{S}_K & \mathbf{G} + \mathbf{S}_G \\ \mathbf{D} + \mathbf{S}_D & \tau \mathbf{L} \end{pmatrix} \begin{pmatrix} d\bar{\mathbf{v}} \\ d\bar{p} \end{pmatrix} = \begin{pmatrix} \bar{\mathbf{r}}_m \\ \bar{\mathbf{r}}_c \end{pmatrix}$$

Fictitious fluid: only use the nodes of the interface elements for the b.c. imposition

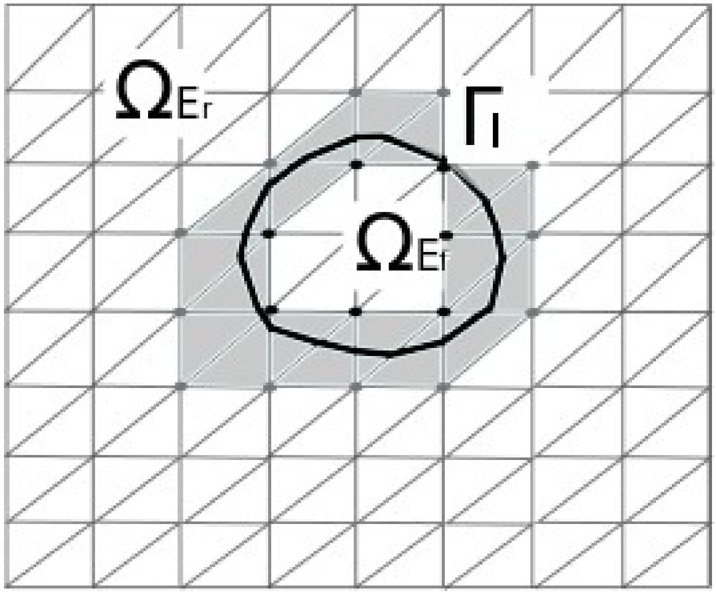
Interface: Dirichlet

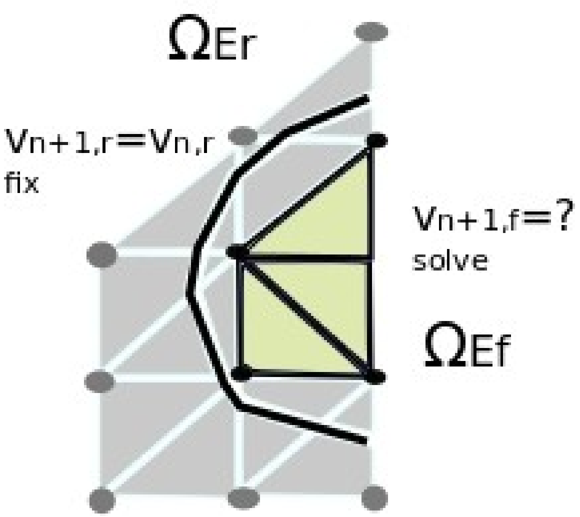
$$\int_{\Gamma_I} \omega(\mathbf{v}_{n+1} - \mathbf{v}_L) = 0$$

Codina R. and Baiges J. *INJME*, 80, 2009

Interface Dirichlet b.c.

- Interface Dirichlet b.c. explicit treatment





$$\mathbf{M}_{\Gamma_I}\bar{\mathbf{v}}_{n+1,\,r} + \mathbf{M}_{\Gamma_I}\bar{\mathbf{v}}_{n+1,\,f} = \mathbf{f}_{\Gamma_I} \longrightarrow \mathbf{M}_{\Gamma_I}\bar{\mathbf{v}}_{n+1,\,f} = \mathbf{f}_{\Gamma_I} - \mathbf{M}_{\Gamma_I}\bar{\mathbf{v}}_{n+1,\,r}$$

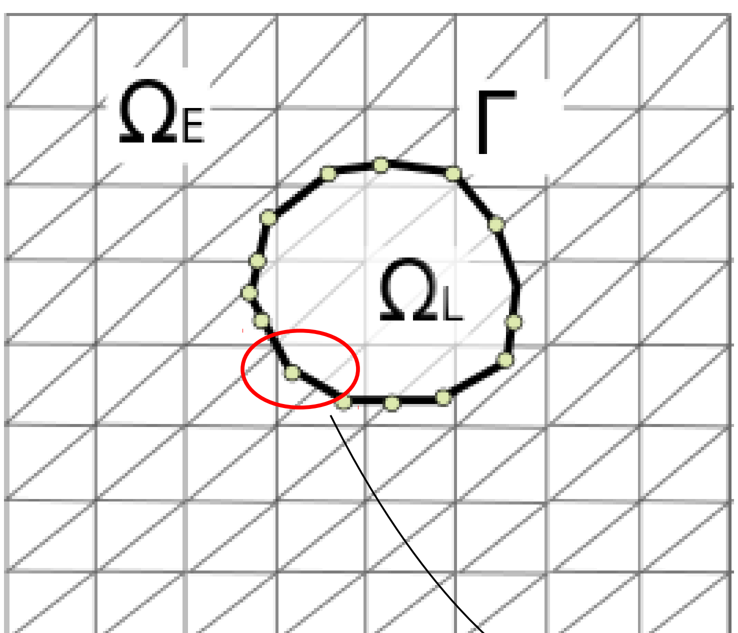
$$\bar{\mathbf{v}}_{n+1,\,r} \approx \bar{\mathbf{v}}_{n,\,r}$$

Ryzhakov P., *Computers and Fluids*, 2014, submitted

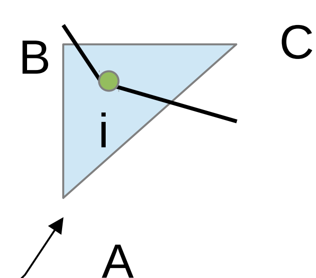
Neumann b.c.

- Project the pressure from the interface elements of the Eulerian domain onto the boundary of the Lagrangian domain
- Add the corresponding Neumann term to the momentum

equation of the structure: $$\mathbf{F}_N = \int_{\Gamma_L} \mathbf{N} p_E \cdot \mathbf{n} d\Gamma$$



$$p_E^i = N_A(x_i)p_A + N_B(x_i)p_B + N_C(x_i)p_C$$



Stabilization of the coupling

- In order to improve the coupling convergence (crucial when incompressible FSI with light-weight structure is considered), an **interface Laplacian technique** is used

Idelsohn et al., FSI problems with strong added-mass effect, *INJME*, **38**, 2009
Rossi R et al., *Met. Num. para Calculo y Diseño* en Ing. **27**, 2011

Overall strategy

Step 1: Solve structure

Step 2: Find Lagrangian image within the Eulerian mesh

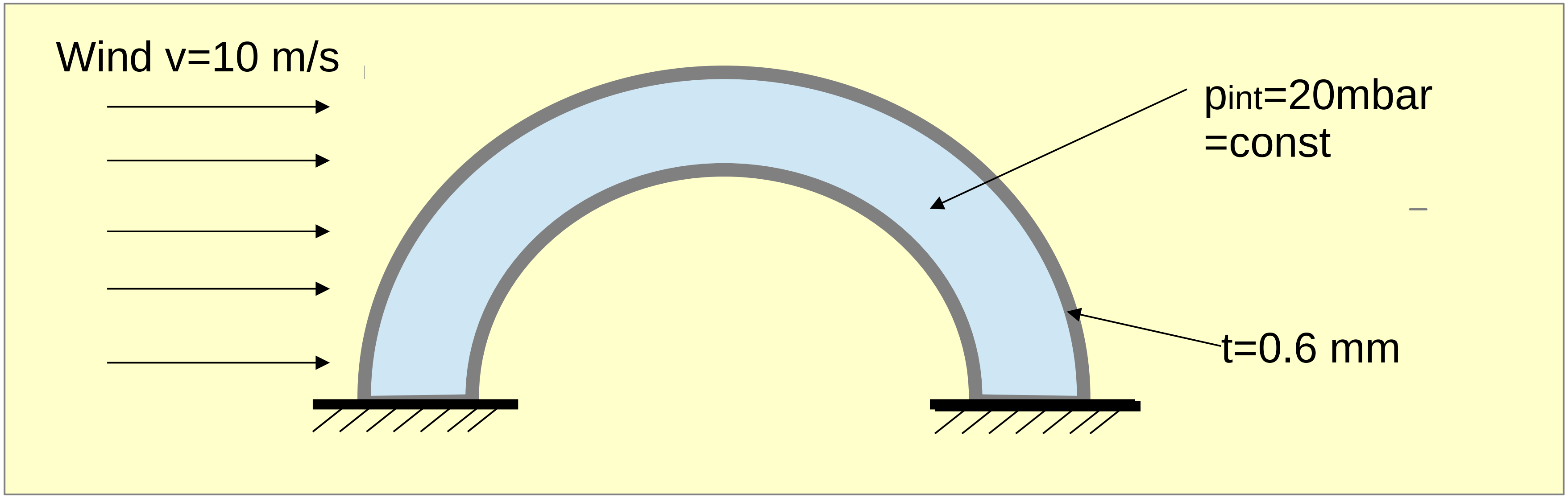
Step 3: Represent the velocity of the structure within the Eulerian mesh: interface Dirichlet b.c. using the fictitious nodes of the interface elements

Step 4: Solve the Eulerian fluid (fictitious elements are switched off)

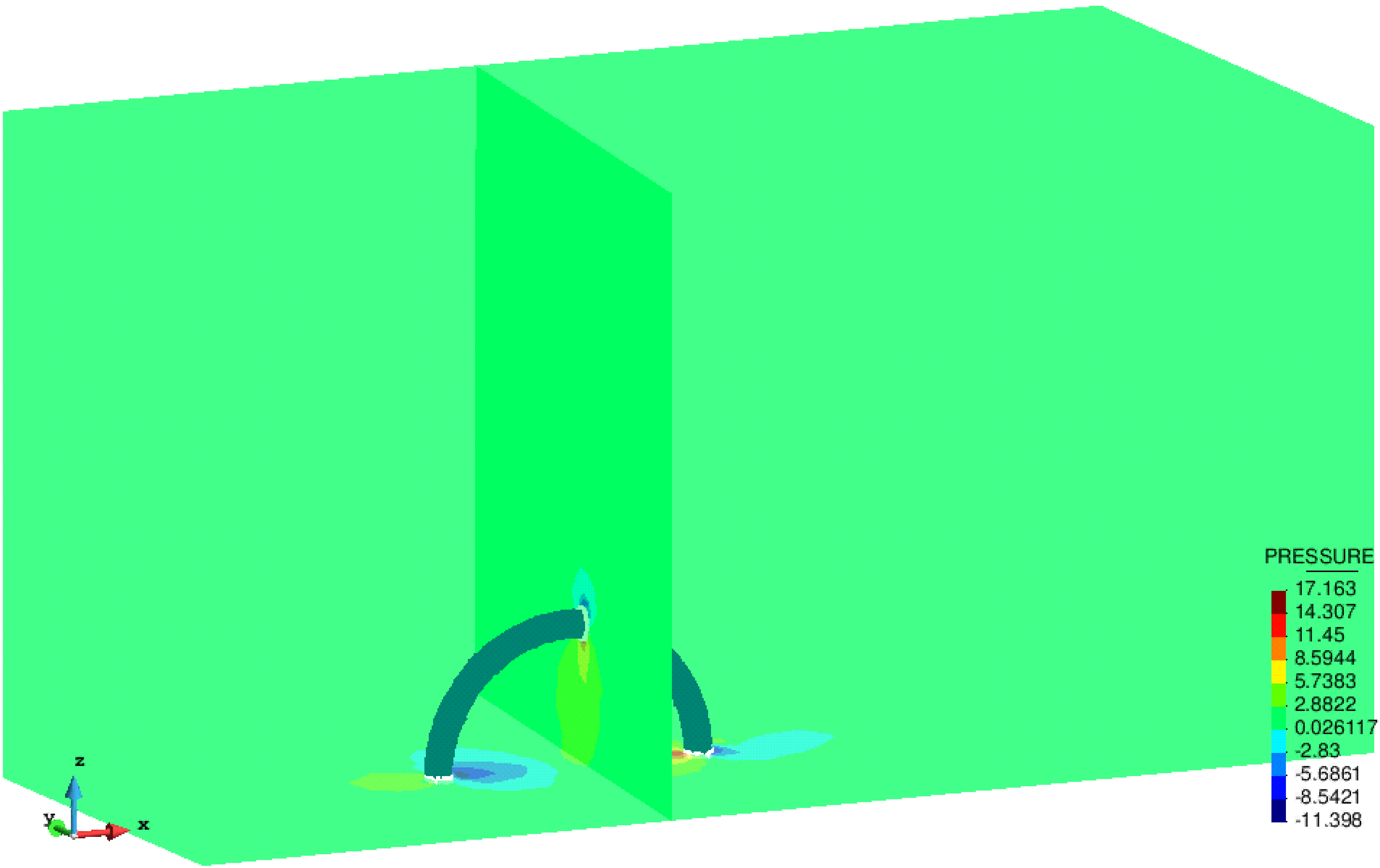
Step 5: Map the fluid pressure to the surface of the structure, apply interface Neumann b.c.

Step 6: Go To next time step

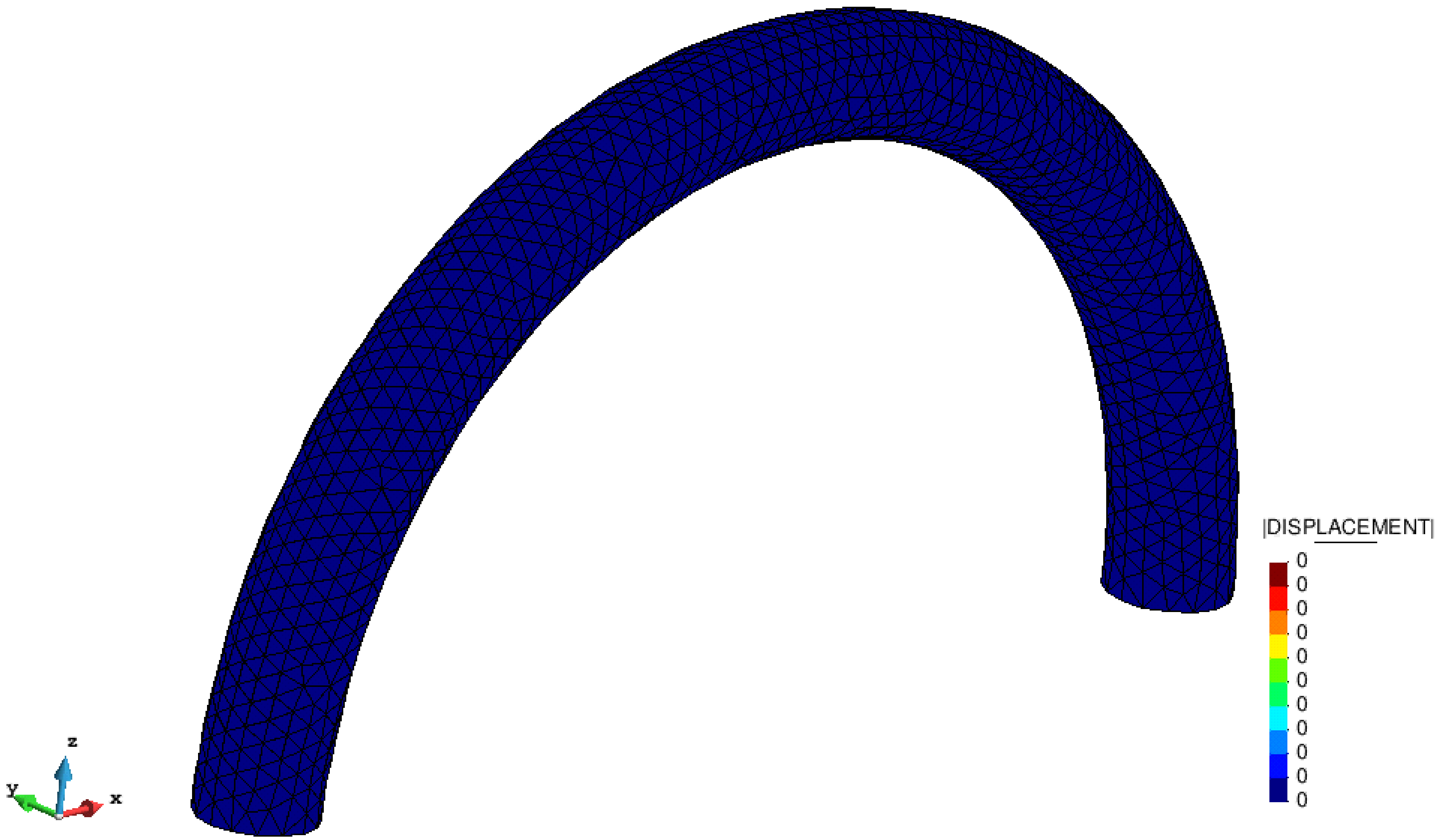
Example 1: FP7 project uLites



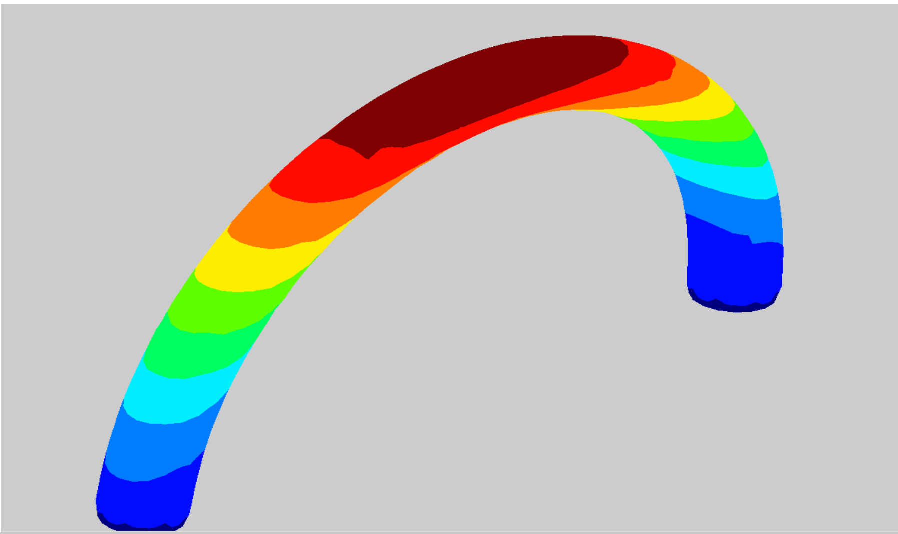
Eulerian domain + Lagrangian image



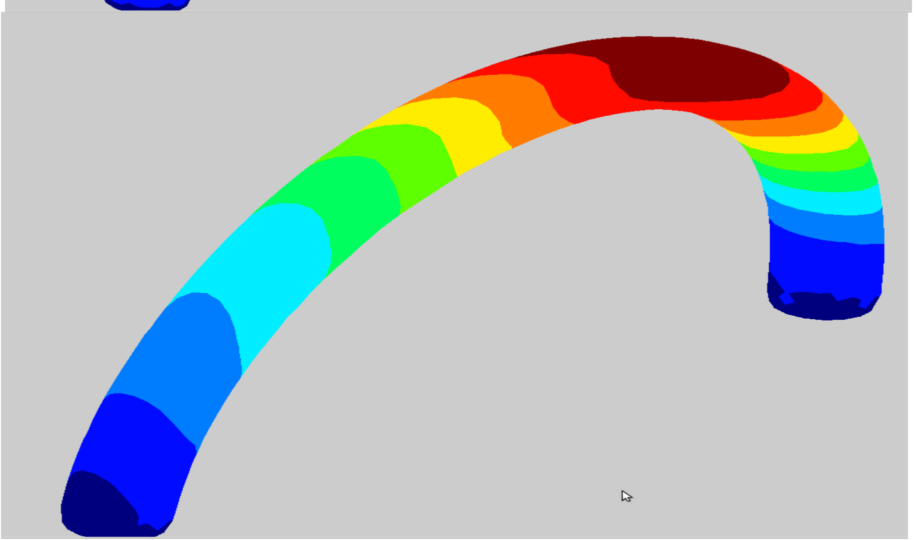
Lagrangian domain



Example 1: quantitative results



Membrane under internal pressure and self-weight



Membrane deformed due to external flow

Max. disp. = 0.62 m at wind velocity of v=10 m/s
Span of the structure: 20 m

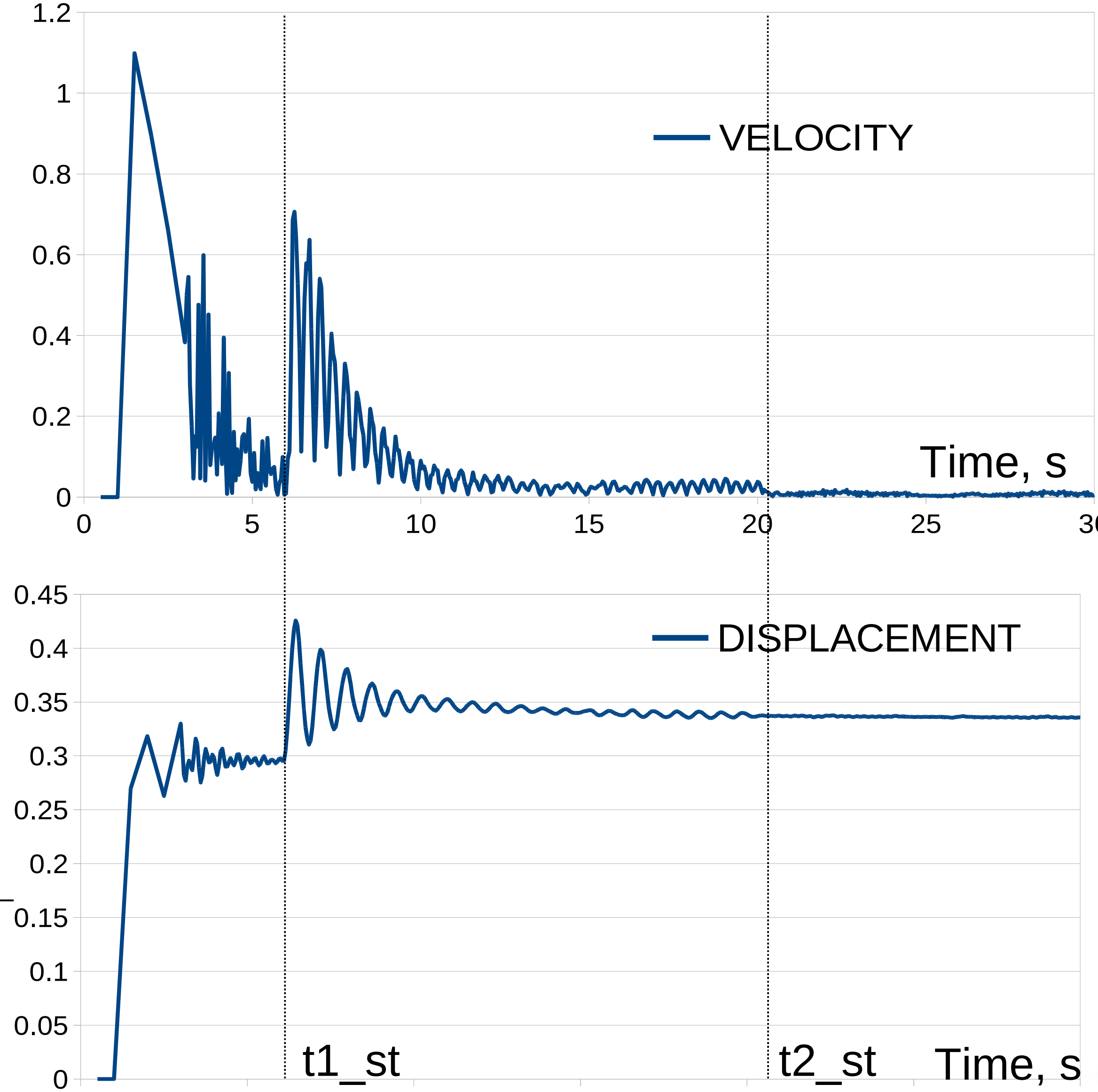
Practical considerations for the FSI with membranes

t1_st: t<t1_st stabilization time of the structure: when the “static” solution due to the internal pressure and the self-weight is obtained. FSI coupling is off

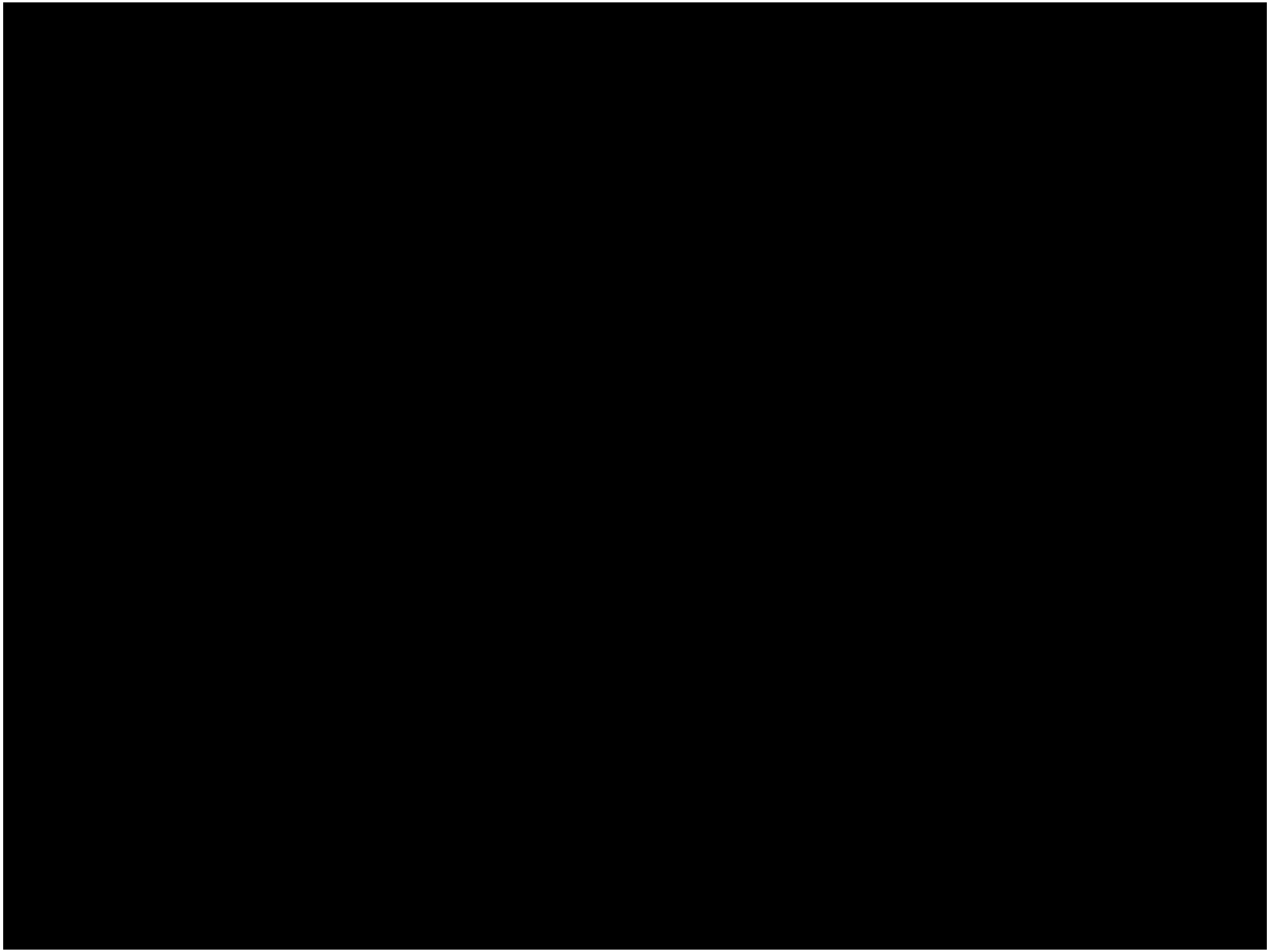
t2_st: t1_st<t<t2_st stabilization time of the structure due to the fluid pressure. Only 1-way coupling is on (membrane velocity is “assumed” to be zero in the interface Dirichlet b.c.

t>t2_st: iterative two way coupling

Also: t<t1_st fluid is solved with a Stokes solver, to “start” the coupling with a “good” solution



Example 2

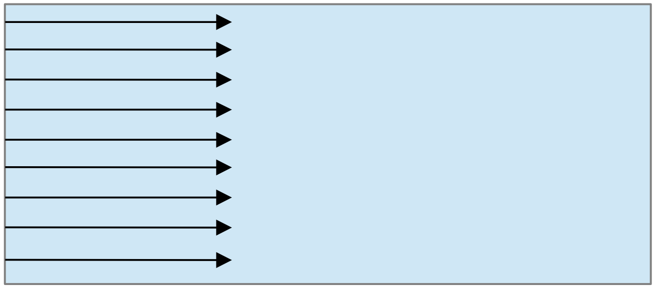


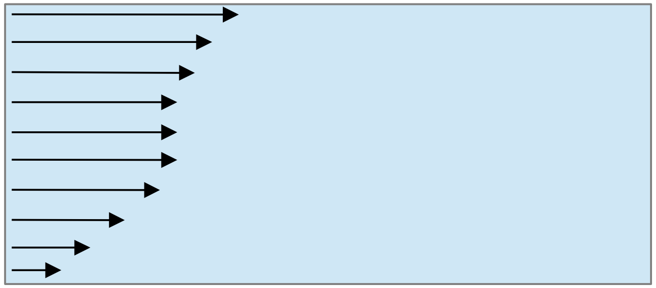
Summary and conclusions

- Embedded, partitioned
- Coupling: Dirichlet-Neumann+interface Laplacian technique
- Arbitrary meshes, arbitrarily structural deformations can be handled
- The proposed explicit coupling using fictitious nodes works only when the structure is “closed”, i.e. the fluid inside the structure does not need to be solved

Future work

- Realistic wind profiles





- Multi-compartment structures (real tents)

- Testing and comparison with experiments

Acknowledgements

uLites: *Ultra-lightweight structures with integrated photovoltaic solar cells: design, analysis, testing and application to an emergency shelter prototype*

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CAPACITIES