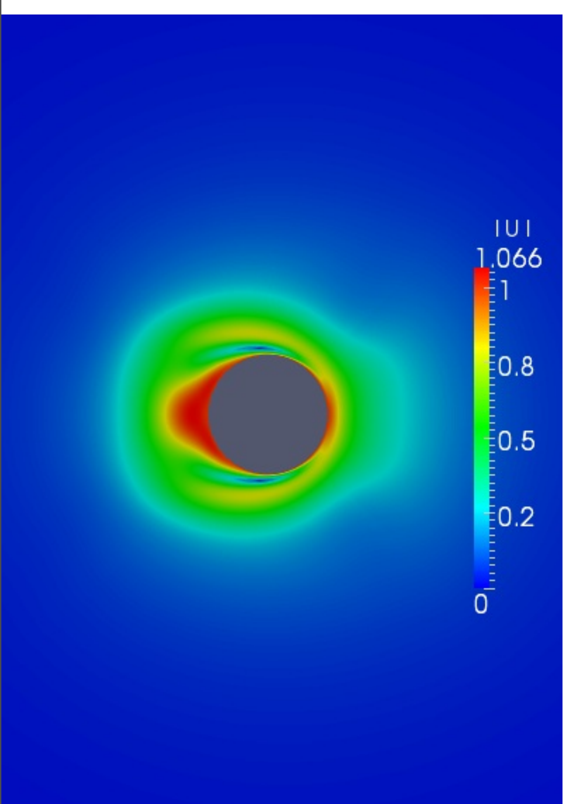
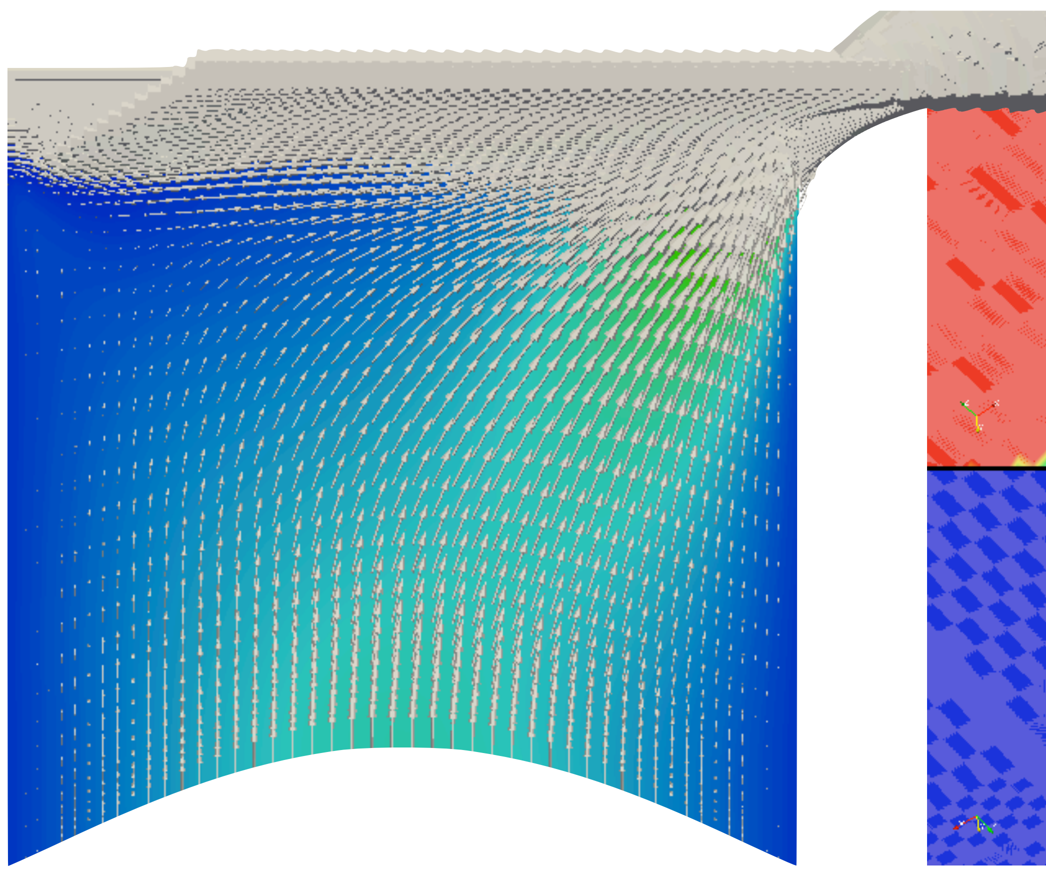
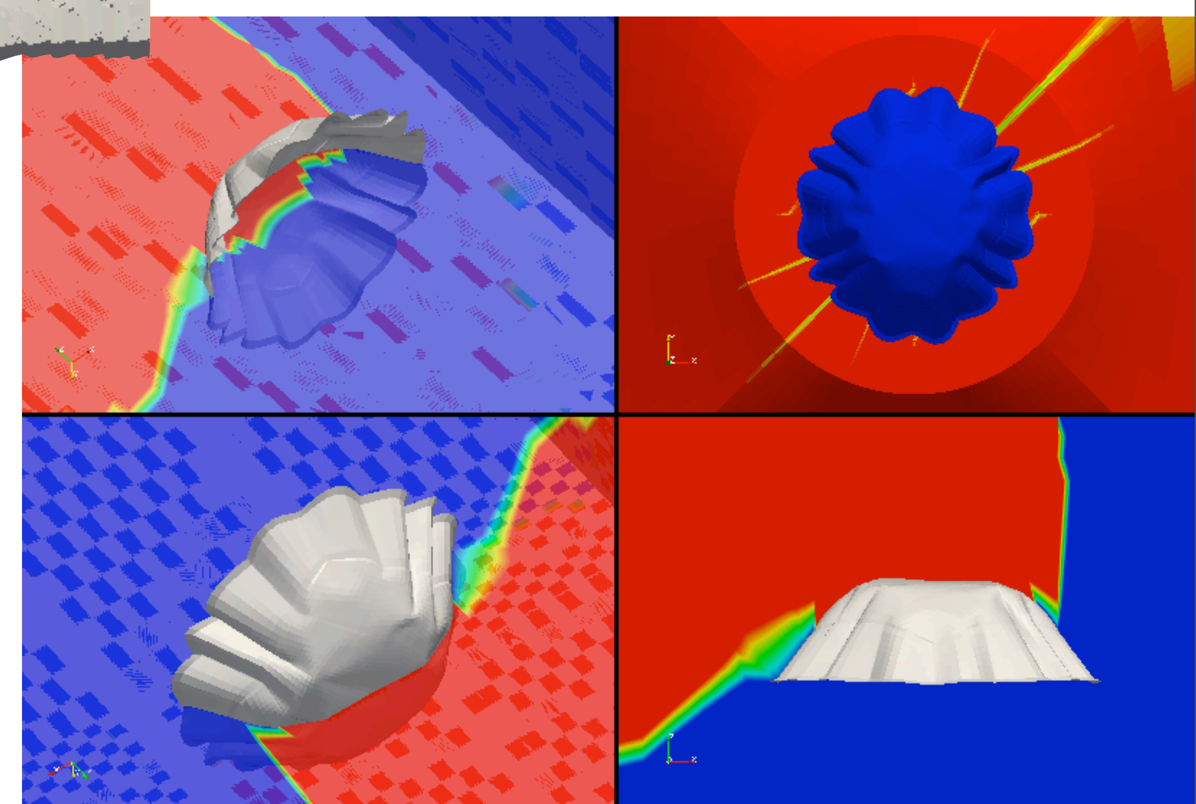
UNIVERSITY OF Southampton
School of Engineering Sciences

Inria informatiques mathématiques

Fluid Structure Interactions in OpenFOAM







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University of Southampton

OpenFOAM workshop
Gothenburg, Sweden, 16/11/2011

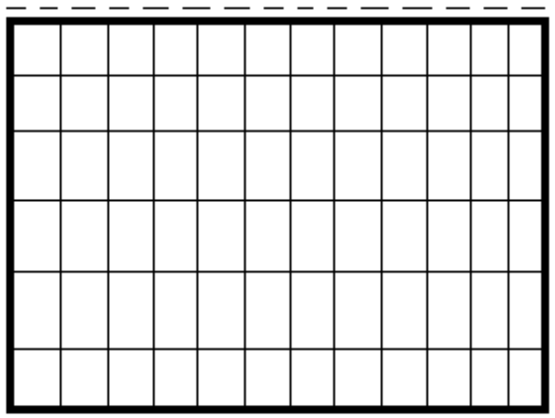
Presentation overview

- FSI: **A**rbitrary **L**agrangian **E**ulerian approach
- implicit scheme with Aitken relaxation factor
- Overview of the FSInterface class
- Lidden flow cavity validation test case
- Note on the convergence criterion and communications issues
- Limitations: singularities arising when folds occurs
- Further development and open questions

ALE approach

Fluid equations:

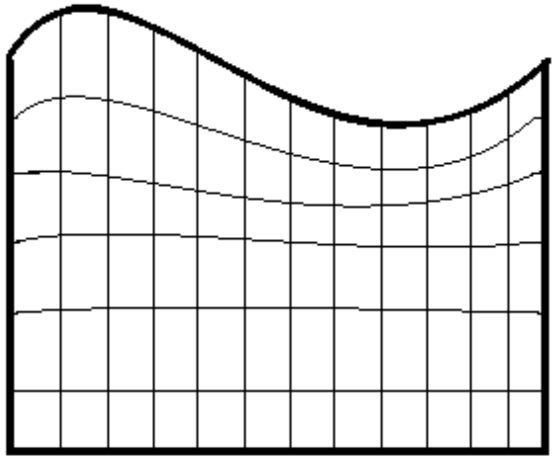
$$\begin{cases} \left.\frac{\partial u}{\partial t}\right|_{x_0} + c \cdot \nabla u - 2\nu \nabla^2 u + \nabla p = b^F \quad in\ \Omega^F \times (0,T) \\ \nabla \cdot u = 0 \quad in\ \Omega^F \times (0,T) \end{cases}$$



Structural equations:

$$\rho^s \frac{d^2 d}{dt^2} = \nabla \cdot (F \cdot S) + \rho^s b^s \quad \Omega^s \times (0,T)$$

Coupling conditions to be met at the F/S interface:



$u_\Gamma^{n+1} = \frac{d_\Gamma^{n+1} - d_\Gamma^n}{\Delta t}$ Continuity of the velocity

$f_\Gamma^{F,n+1} = -f_\Gamma^{S,n+1}$ Conservation of the forces

$d_\Gamma^{G,n+1} = d_\Gamma^{n+1}$ Continuity of the displacements

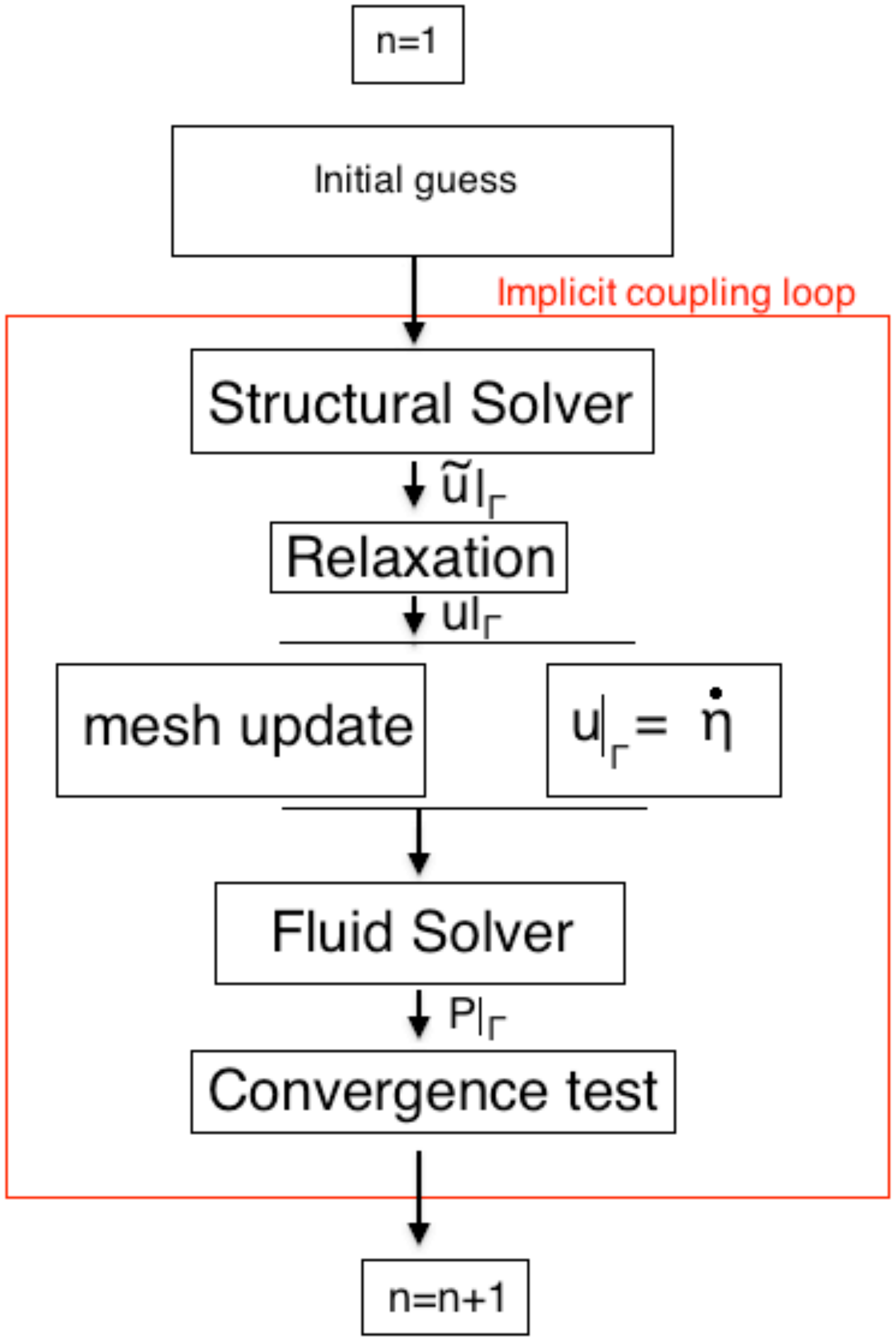
The mesh deforms as the structure on the structural interface, it remains undeformed on the rigid boundaries and the movement is arbitrarily (laplacian) spread into the domain

Implicit coupling

Added mass effects affects the stability of the coupled solution, unless[1]:

$$\frac{\rho_s h_s}{\rho_f \mu_{max}} < 1$$

ρ_s density of the structure
h_s thickness of the strucutre
ρ_f density of the fluid
$\mu_{max} = \frac{L}{\pi\, htan(\frac{\pi R}{L})}$

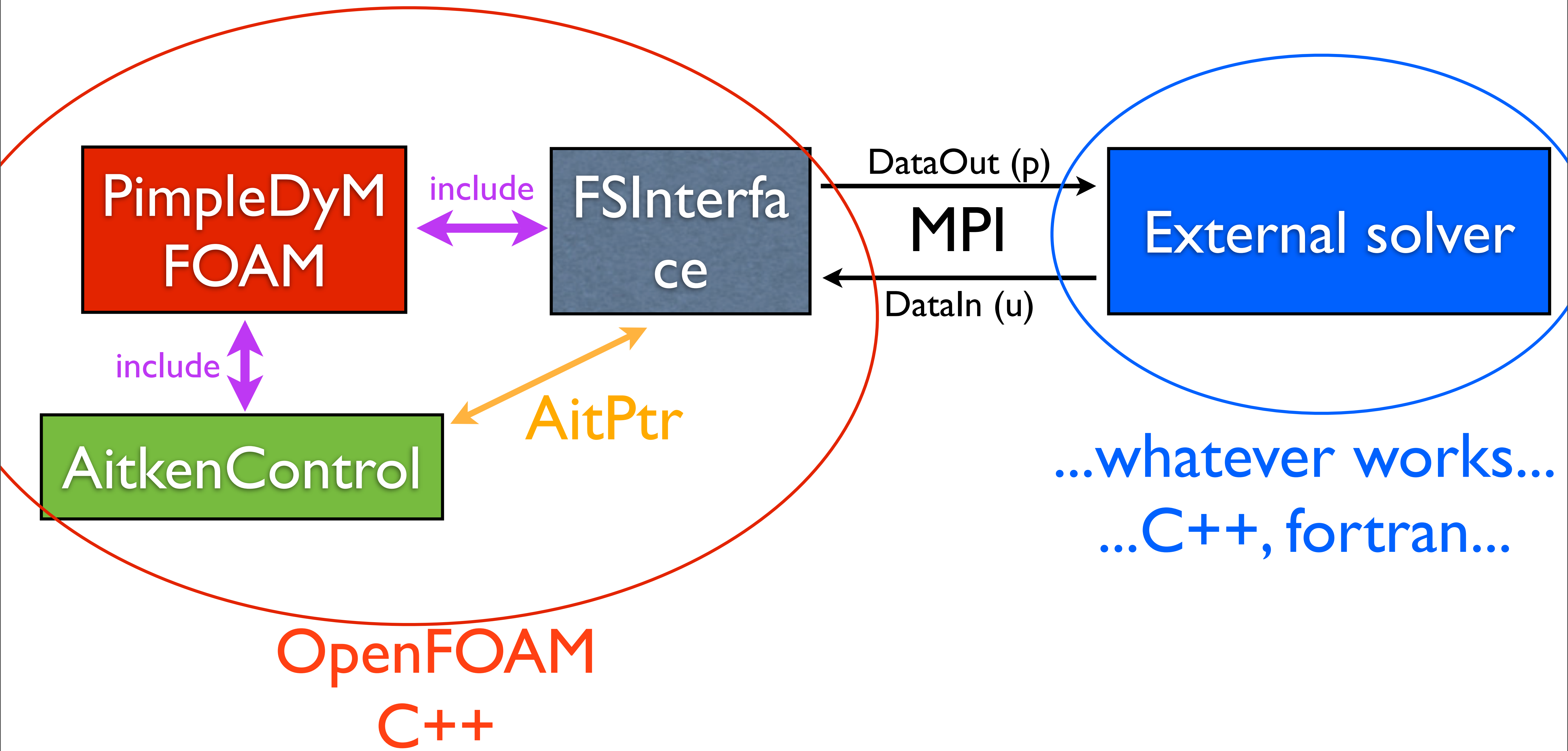


In the majority of cases the condition is not met, and the algorithm is unstable. The most easy (but computationally expensive) way is to perform fixed point iterations between the fluid and the structure

[1]: Causin, P., J.-F. Gerbeau, et al. (2004). Added mass effect in the design of partitioned algorithms for fluid-structure problems. INRIA - Res. Rep. **5084**.

FSInterface class

Multiple Program Multiple Data type environment, the external solver is "spawned" during the execution time. This generates a communicator we can use for exchanging data (black arrows)



Iteration scheme

if(k==1)

$\gamma_{k+1}^{Predicted} = 2 * \gamma_{k+1} - \gamma_{old};$

if(k==2)

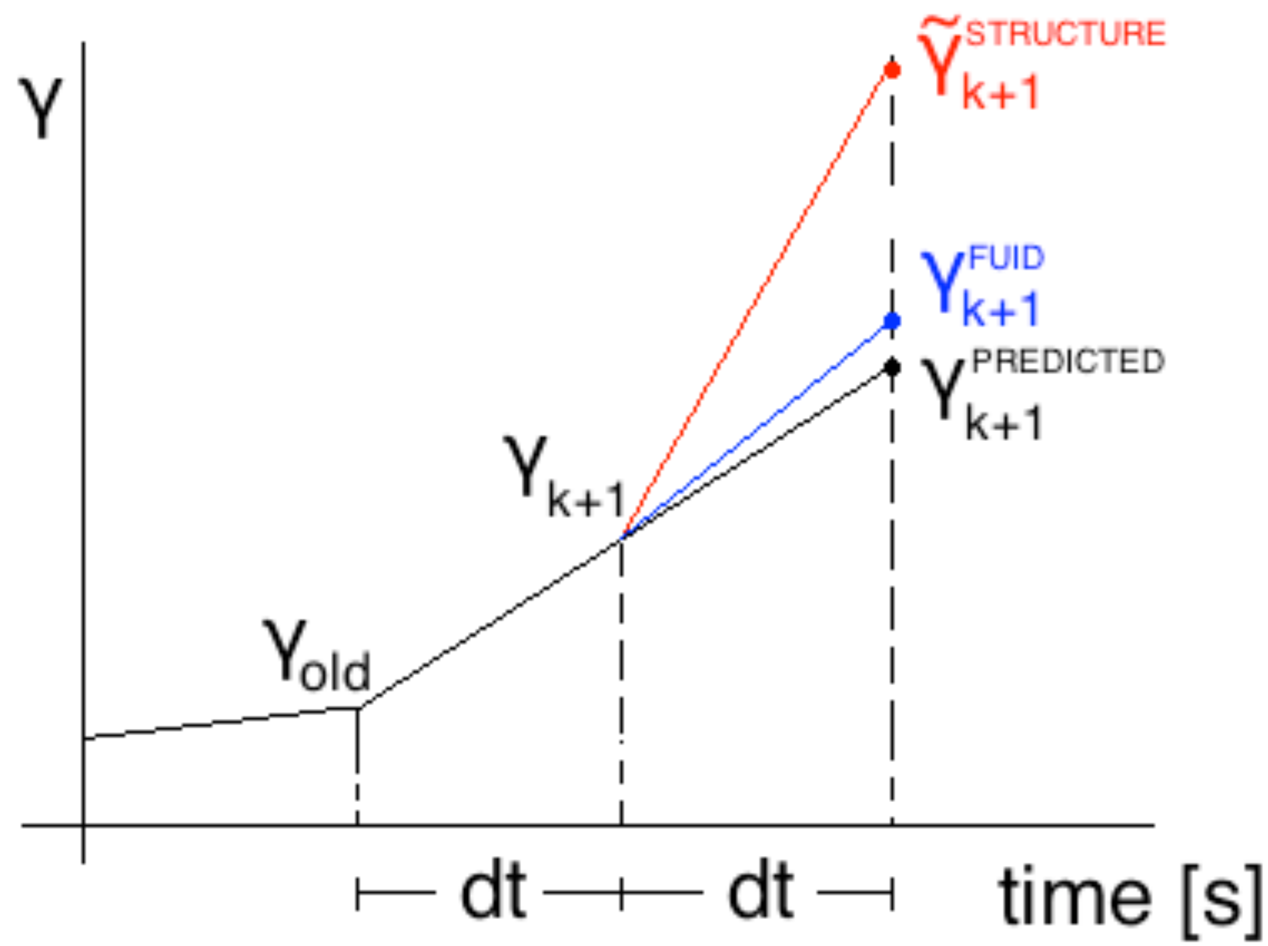
$\omega_k = 0.01;$

$\gamma_{k+1}^F = \omega_k \tilde{\gamma}_{k+1}^S + (1 - \omega_k)\gamma_{k+1}^F;$

if($k > 2$)

Calculate ω_k;

$\gamma_{k+1}^F = \omega_k \tilde{\gamma}_{k+1}^S + (1 - \omega_k)\gamma_{k+1}^F;$



Aitken dynamic relaxation factor[2]:

$$\omega_k = \frac{(\gamma_k - \gamma_{k-1}) \cdot (\gamma_k \tilde{+} 1 - \gamma_k + \gamma_k \tilde{+} 1 - \gamma_{k-1})}{\|\gamma_k \tilde{+} 1 - \gamma_k + \gamma_k \tilde{+} 1 - \gamma_{k-1}\|^2}$$

Note: linear predicting do not introduce discontinuities of the velocity at the interface

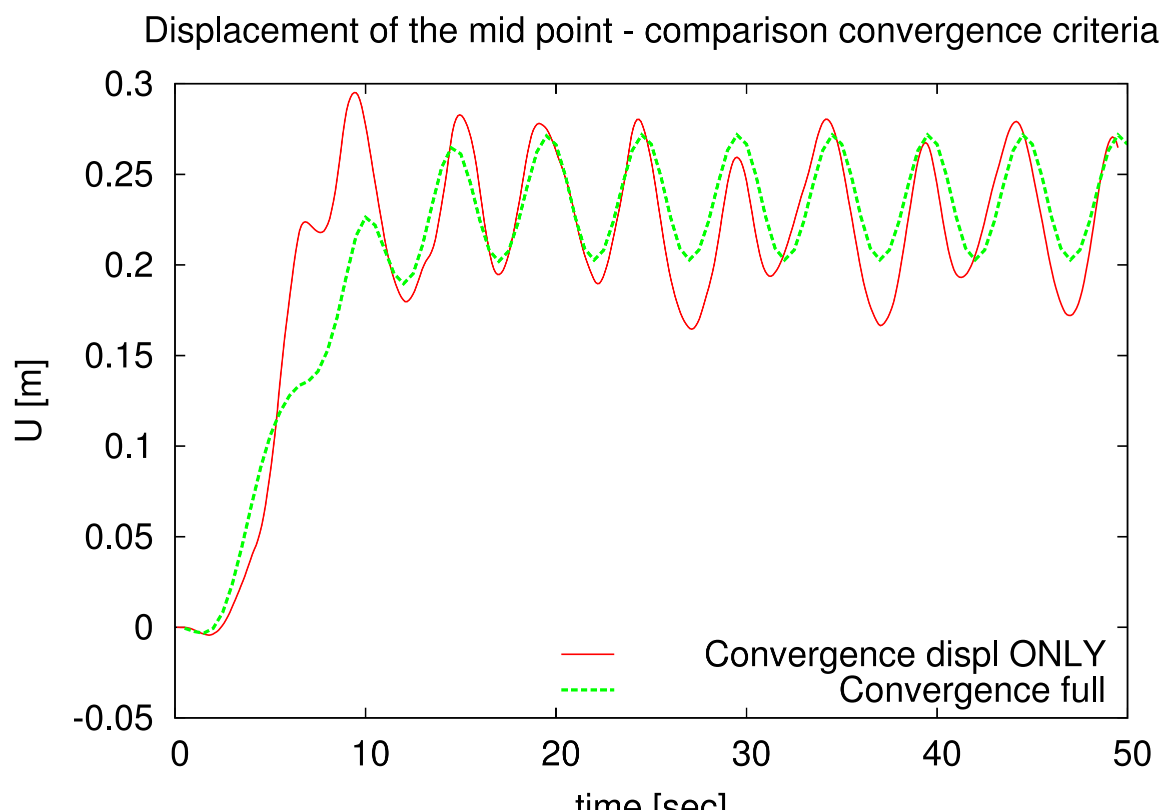
[2]: M. Fernandez (2011) Coupling schemes for incompressible fluid-structure interaction:implicit, semi-implicit and explicit. Bol. Soc. Esp. Mat. Apl. no0 (0000), 1–52

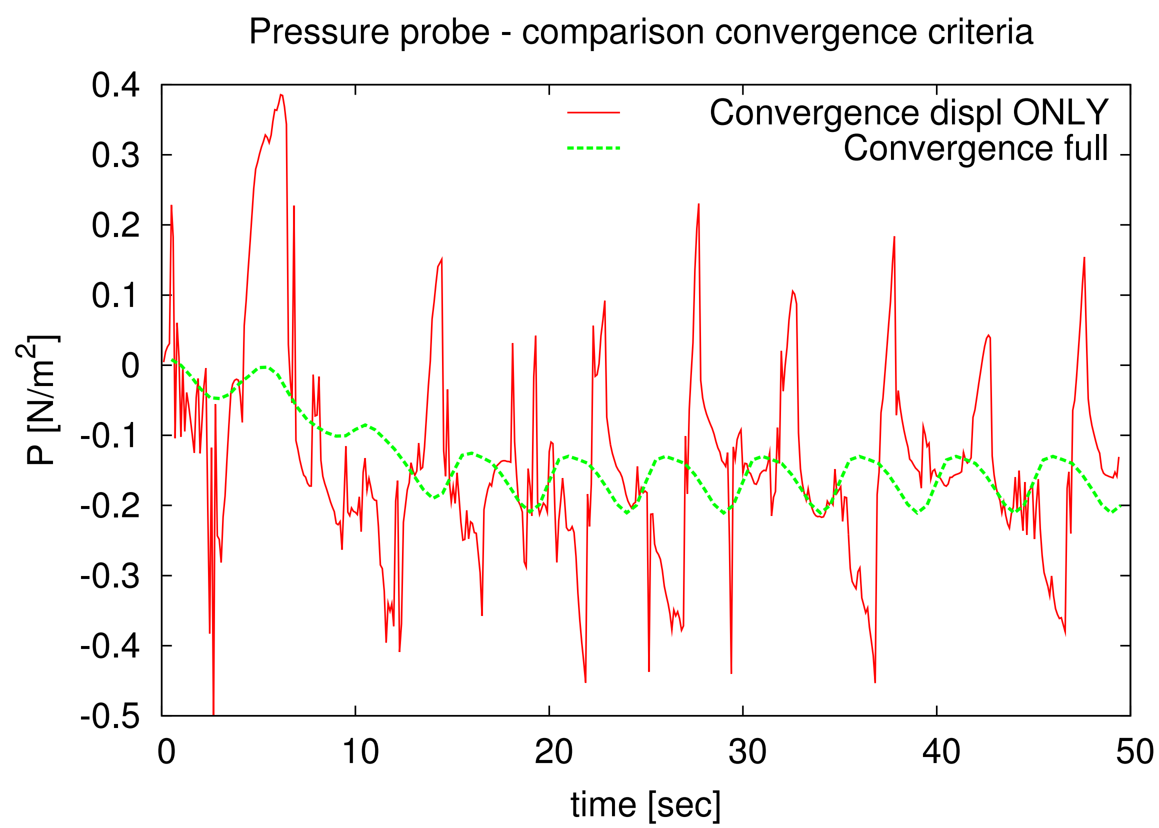
Convergence criterion

Since the fixed point is performed on the pressure, we need a convergence criterion on the pressure. Otherwise, very bad things are likely to happen...

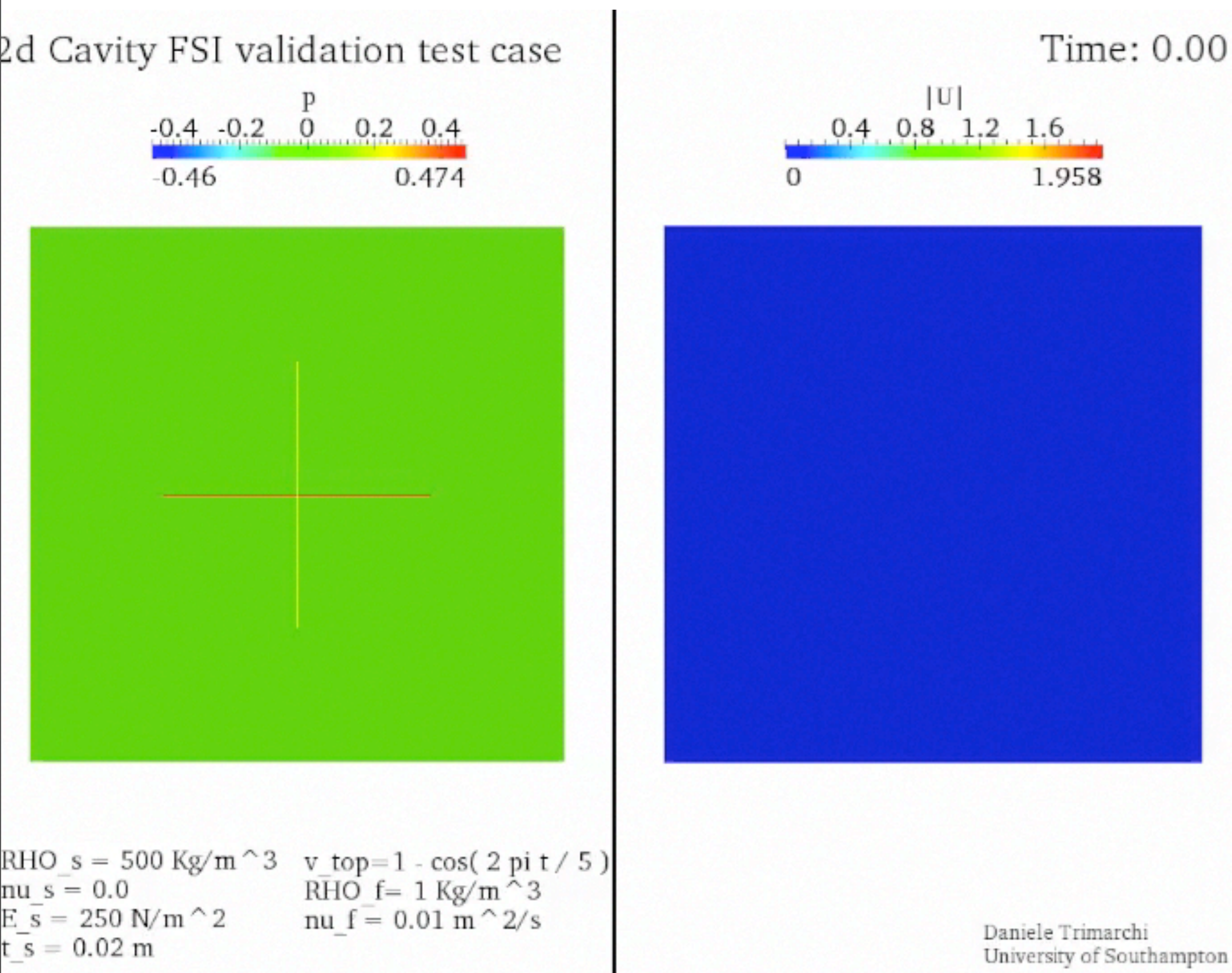
Table 1: Relaxed Dirichlet-Neumann fixed-point iterations

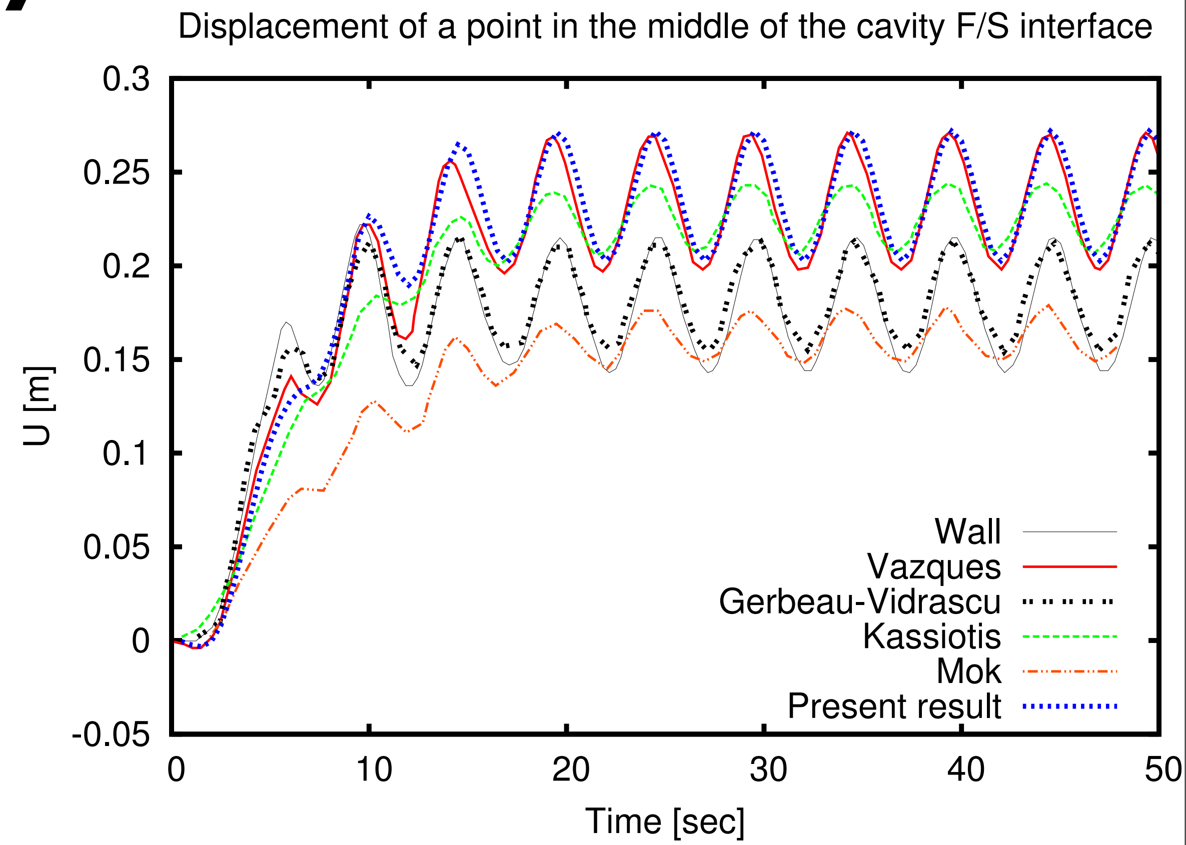
normal setting	setting adopted in openFOAM
solve fluid: $p_k = S^f(\gamma_k)$	solve solid: $\tilde{\gamma}_{k+1} = S^s(p_k)$
solve solid: $\gamma_{\tilde{k+1}} = S^s(p_k)$	apply relaxation: $\gamma_{k+1} = \omega_k \gamma_{\tilde{k+1}} + (1-\omega_k)\gamma_k$
apply relaxation: $\gamma_{k+1} = \omega_k \tilde{\gamma}_{k+1} + (1-\omega_k)\gamma_k$	solve fluid: $p_{k+1} = S^f(\gamma_{k+1})$
$\gamma_k = S^s(S^f(\gamma_k))$	$p_k = S^f(S^s(p_k))$

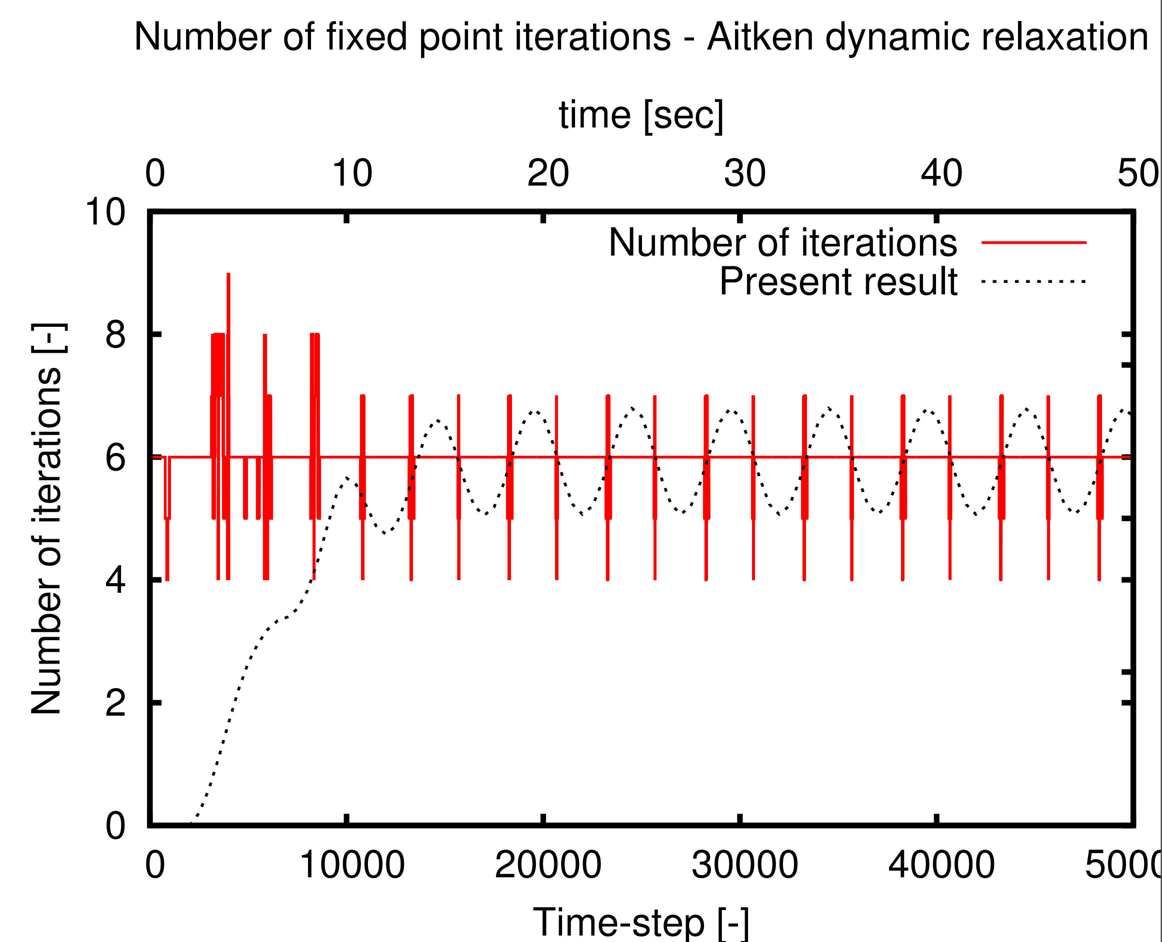




Lidden flow cavity validation





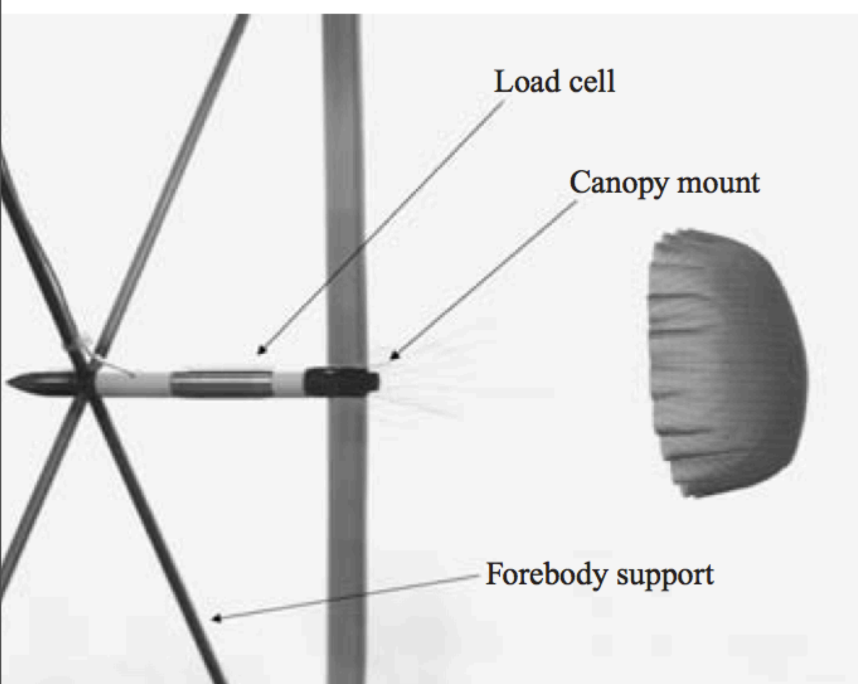


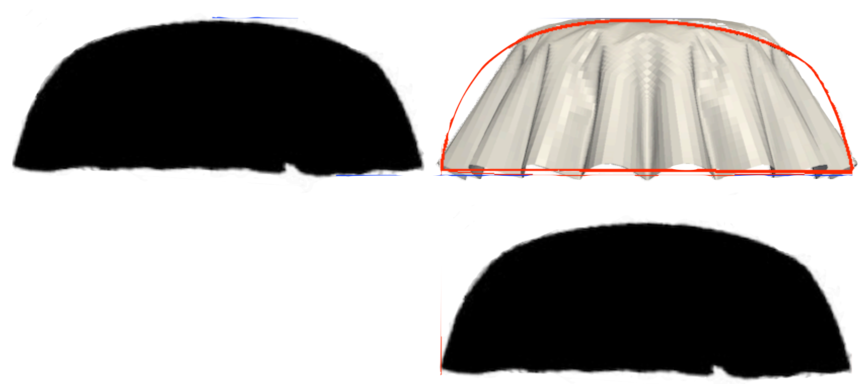
Limitations: parachute canopy

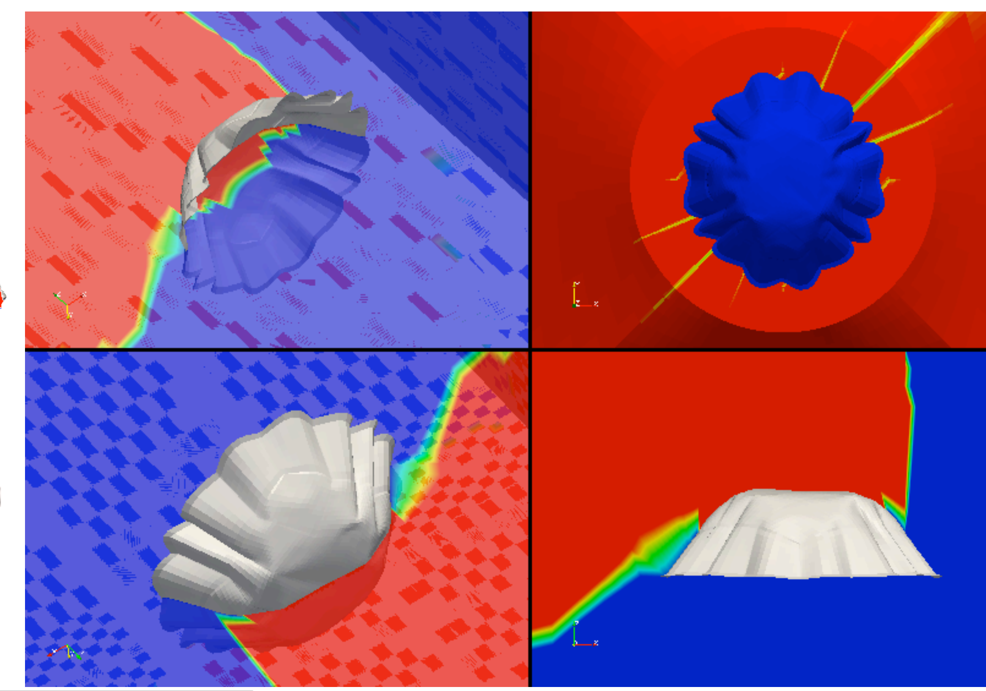
Experiments flying an initially flat membrane held with cables in the cavitation tunnel

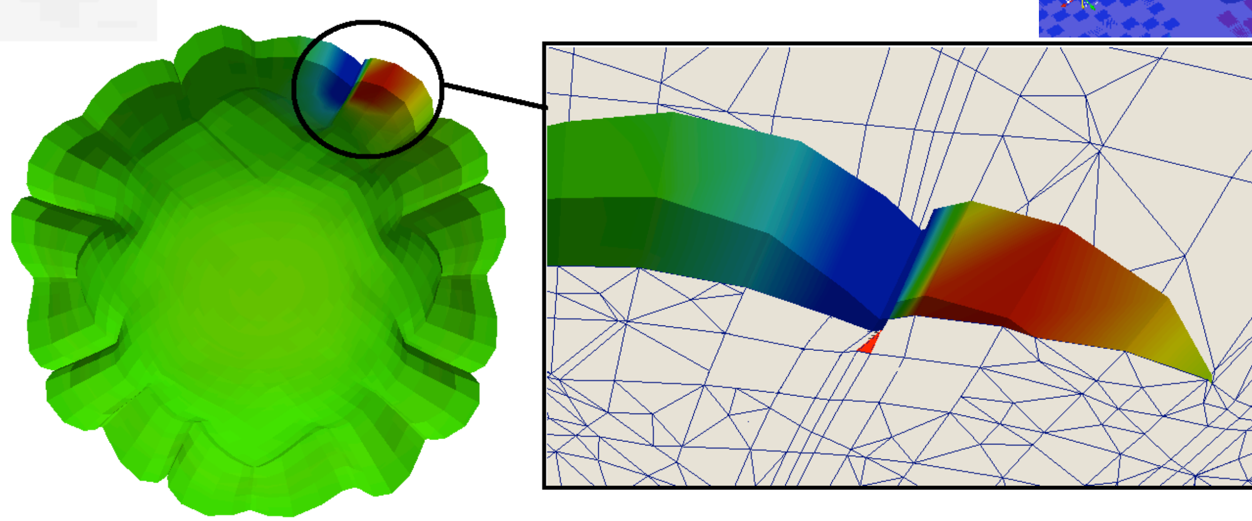
During its deformation, large folds are generated on the device

When repeating such experiments with ALE techniques, fall over is experienced due to the inversion of volume cells









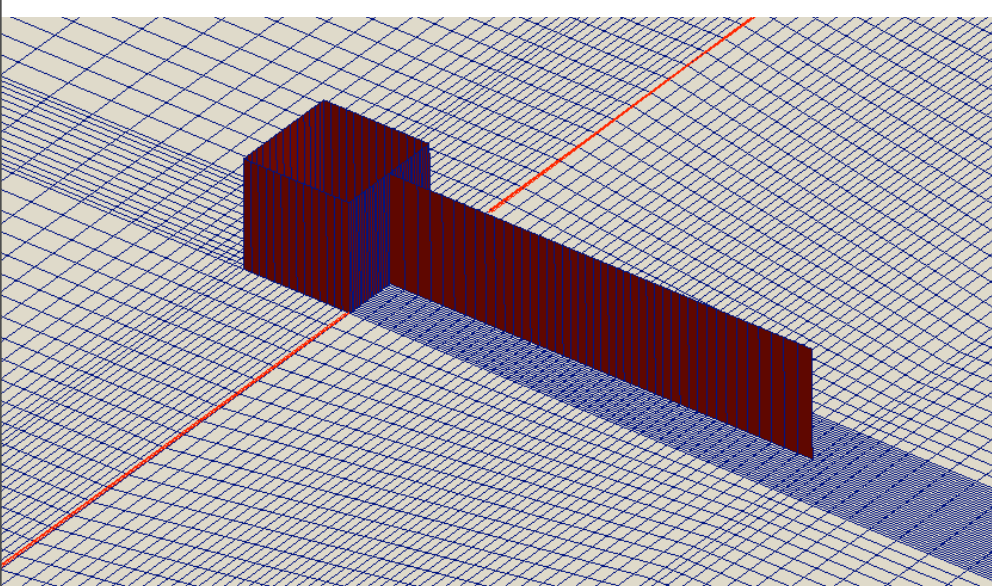
Further development and open questions

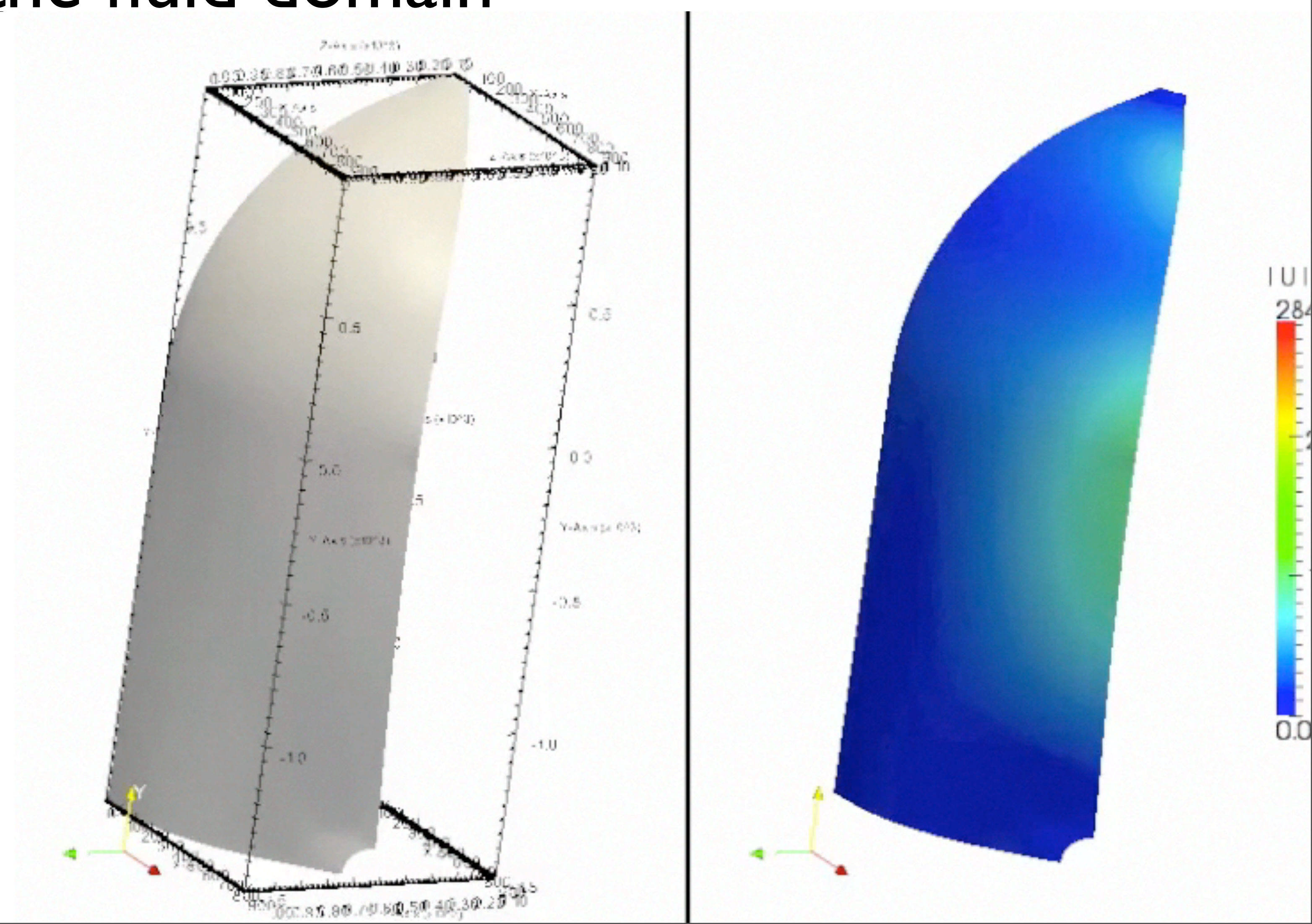
- How to treat extreme mesh deformations, such as displacements field coming from fabric wrinkling?

- Parallel computing in segregated environment: use of **PETSc**?

- New validations on external flows (flag test case[3])

- How to fix cell regions in the fluid domain





[3]: Kassiotis, C., A. Ibrahimbegovic, et al. (2011). "Nonlinear fluid-structure interaction problem. Part I: implicit partitioned algorithm, nonlinear stability proof and validation examples." Computational Mechanics **47**: 305-323.