Development of wrinkles and their influence or not on sail performance

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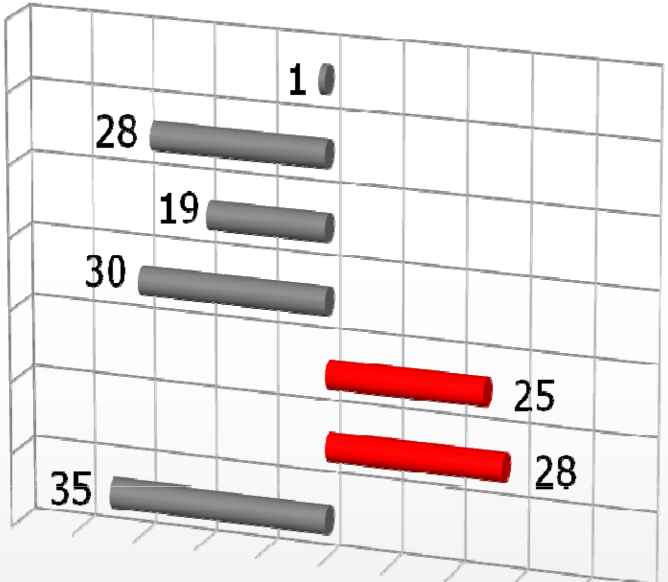
School of Engineering Sciences

Stephen Turnock,
Daniele Trimarchi,
Dominique Chappelle(INRIA),
Dominic Taunton

Performance Sports Engineering Lab./
Fluid structure interactions
Faculty of Engineering and Environment
University of Southampton
srt@soton.ac.uk

32nd America's Cup, Valencia, 2007: 7 Races
Average racing time 1h 32m 38s



Winning deltas (sec)

Need experimental techniques, equipment and instrumentation that can collectively resolve to <0.5%, supported by whole race simulation, computational fluid dynamics and effective athlete feedback/buy-in

Yacht sails: fluid structure interactions


a


b

c

Aims and objectives:

- Simulate with sufficient accuracy the phenomena involved in fluid and the structural dynamics of sails
- Couple the models and perform fully unsteady Fluid Structure Interactions
- Once a validated calculation has been established, this can be used by sailmakers as a design tool
- Optimised sails for specified conditions of sail

What is the influence of wrinkles?

Why do sails wrinkle?

- It is a buckling phenomenon eg fabric cannot sustain compression
- Flown shape captures force from wind and transmits as thrust and heeling moment to yacht.
- Dynamic nature of yacht motion and turbulent wind results in a complex stress path
- Challenge from a structural perspective is that sail thickness is very small compared to other dimensions
- Conventional analysis uses a net of 1D tension elements (CST) but cannot deal directly with compression effects

Fluid Model:

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- The fluid is described using the Reynolds Averaged Navier-Stokes equations,
- The turbulence is closed with a turbulence model (SST)
- Equations are solved through the Finite Volume method, implemented in the Open Source C++ finite Volume library

OpenFOAM

Fluid solver	Fluid solver, dynamic mesh	Fluid solver, FSI, MPI comm
pisoFOAM	pimpleDyMFOAM	FSIFluidFOAM

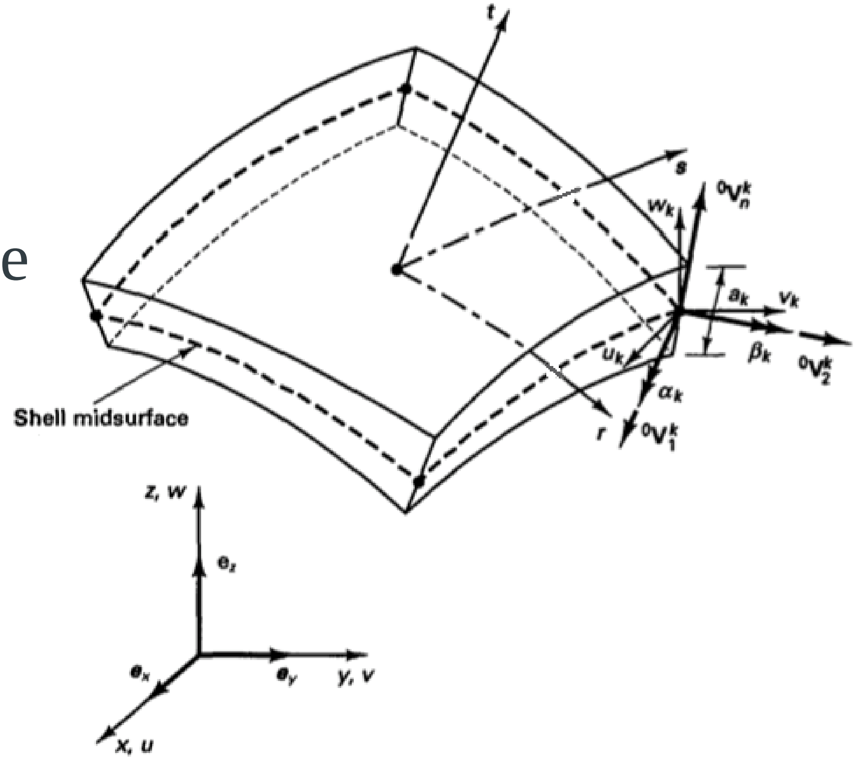
Structural Model:

- The equilibrium of the internal/external energy

$$\int_V \sigma^{ij}(\vec{U})\,\delta\epsilon_{ij} = \int_V \vec{f}\,\delta\vec{V}\,dV$$

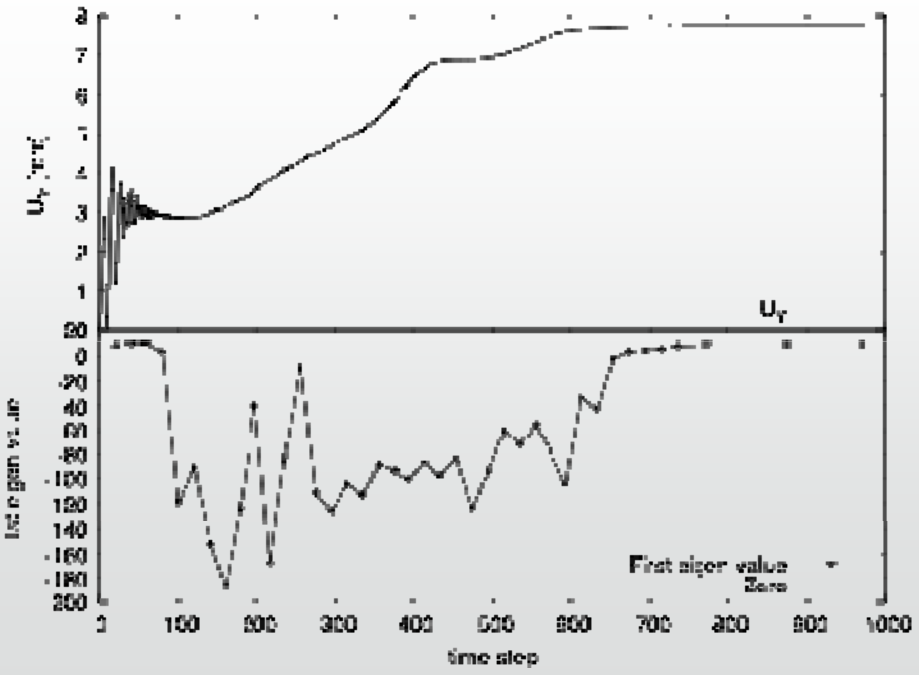
- From the continuous model, the above equation is discretized using the finite element (FE) method in order to be solved numerically

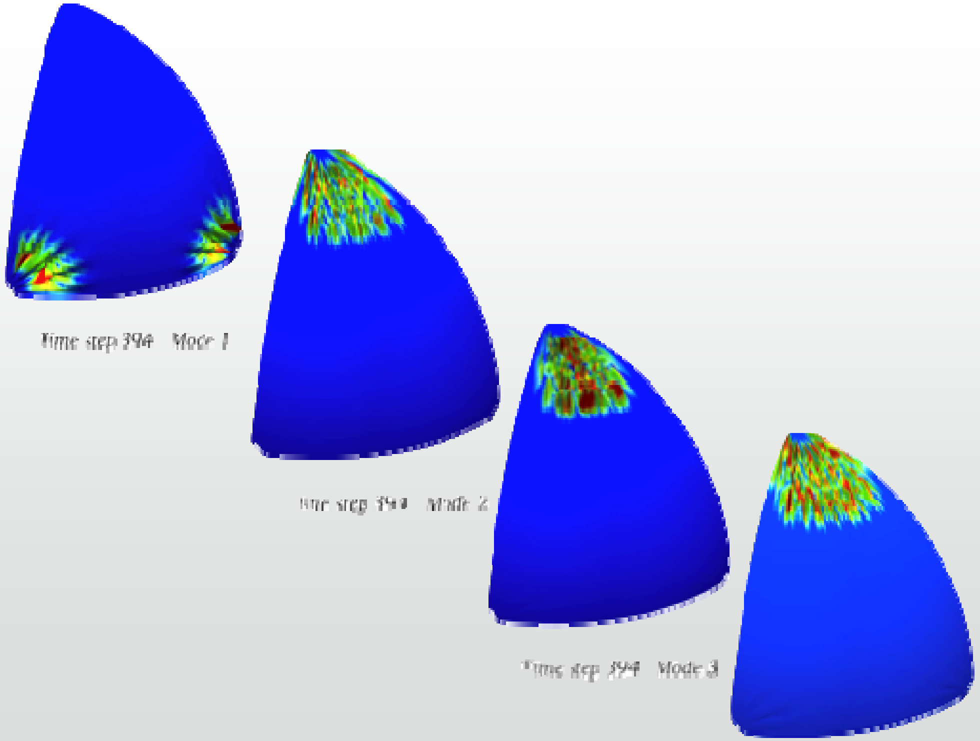
- The fabric is represented using thin non-linear shells MITC4. Nodes have 5 degrees of freedom: 3 translations (membrane energy) + 2 rotations (bending energy)

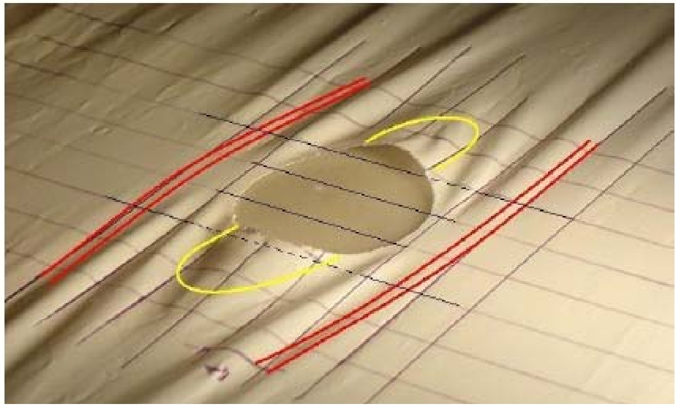


Structural Model:

- The Mixed Interpolation is necessary in order to prevent numerical locking. This arises when the thickness →0
- A dynamic routine with Rayleigh damping is used to ensure convergence of the results. The system is ill posed/unstable.







a b c

Figure 5.16: Different types of wrinkling arising on downwind sails. a: large amplitude wrinkles, b: singular wrinkle, producing a cusp; c: small amplitude wrinkles induced by the seams of the sail

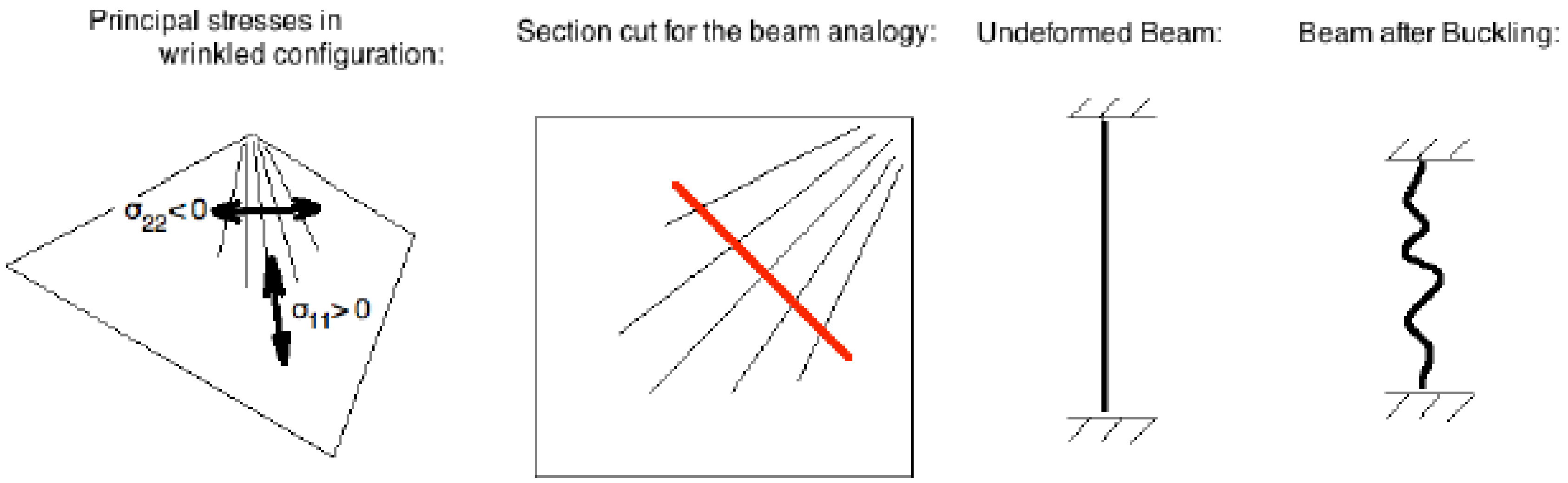
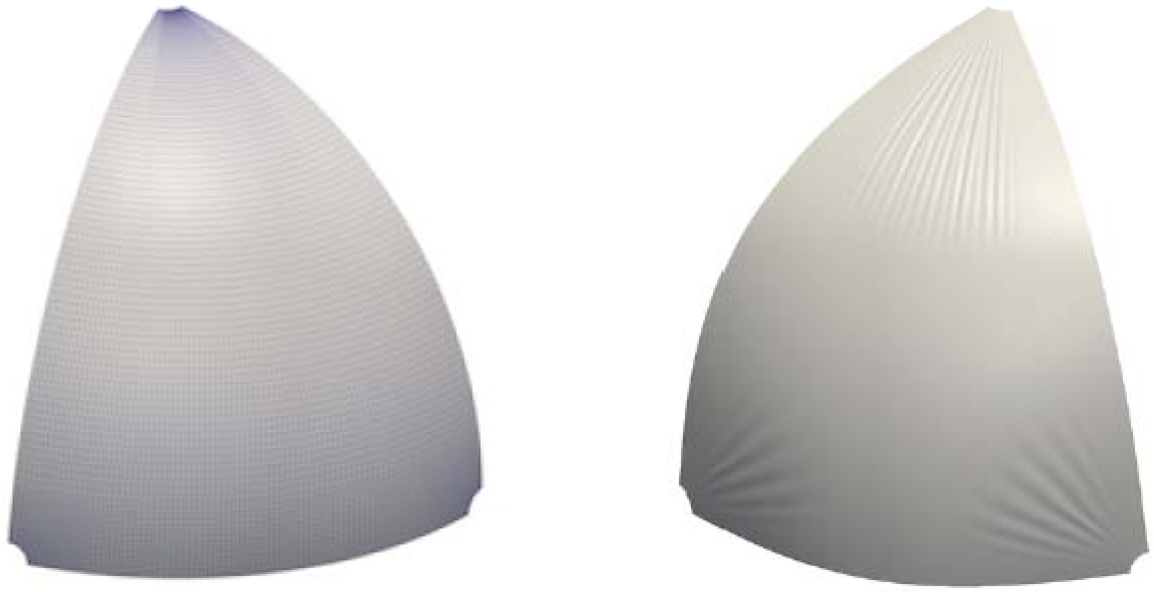
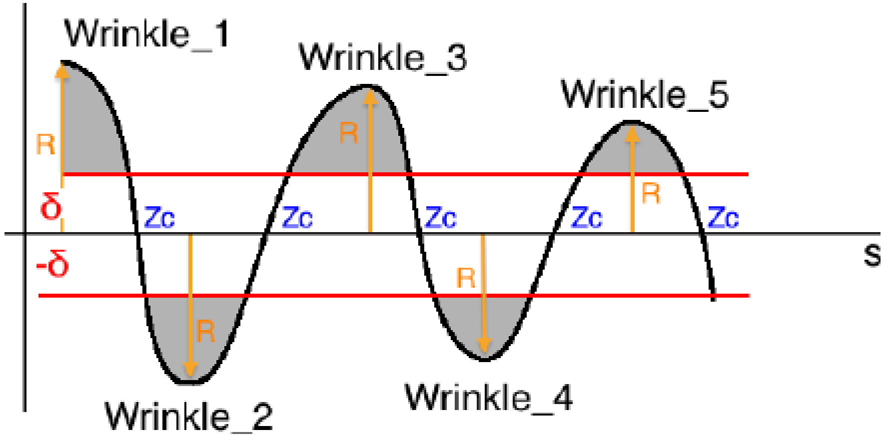


Figure 5.17: Different types of wrinkling arising on downwind sails

Table 5.4: Equilibrium and eigenvalues of the tangent stiffness matrix

Matrix property	Eigenvalues	Equilibrium
Positive definite	$\lambda_i > 0 \ \forall i = 1, ndof$	Stable
Non-positive definite	$\lambda_j < 0$ for some j	Unstable
Semi-Positive	$\lambda_i \geqslant 0 \ \forall i$ and $\lambda_j = 0$ for some j	Critical





Ts.50 Ts.100 Ts.150

Ts.200 Ts.250 Ts.300

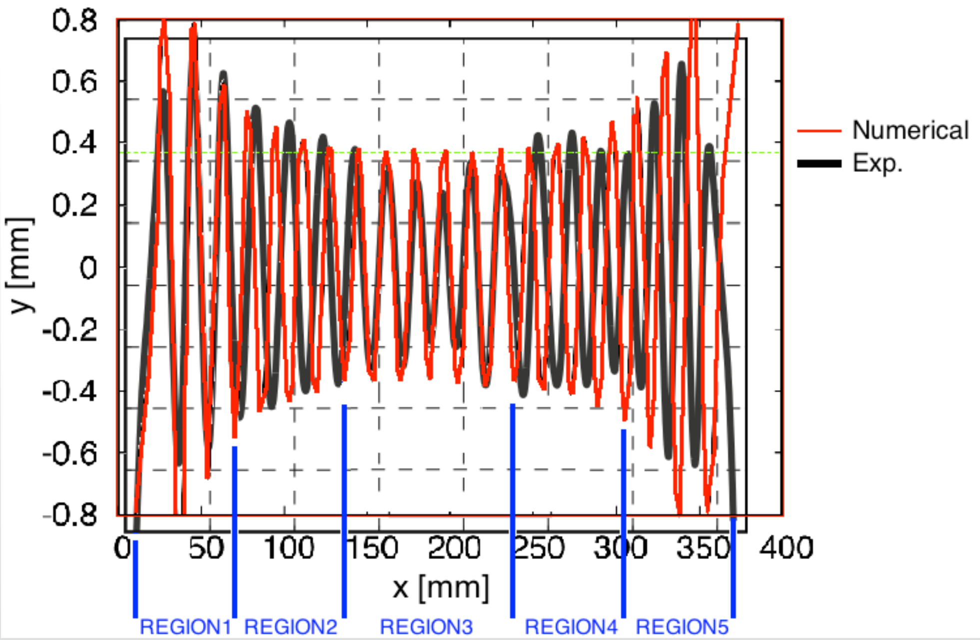
Figure 5.39: Deformation path for the fabric with constant (not following) applied load

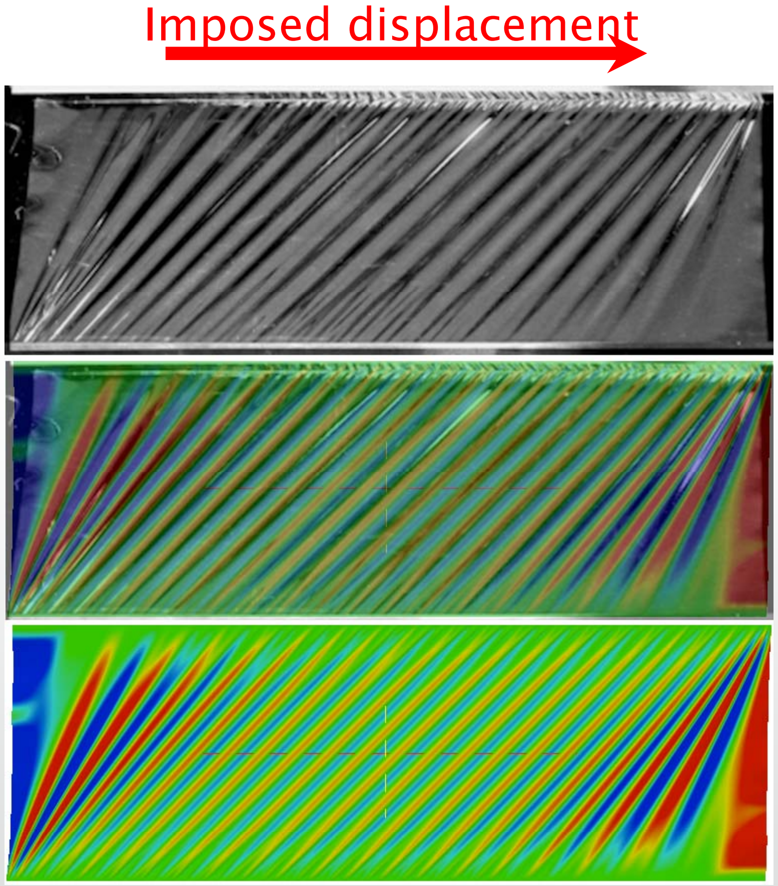
Wrinkling simulation:

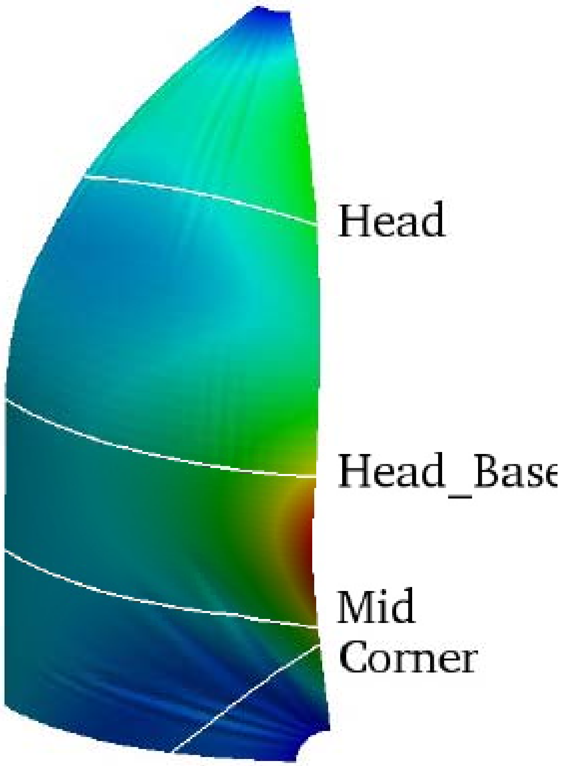
- Experiments by Wong, Pellegrino (2006)

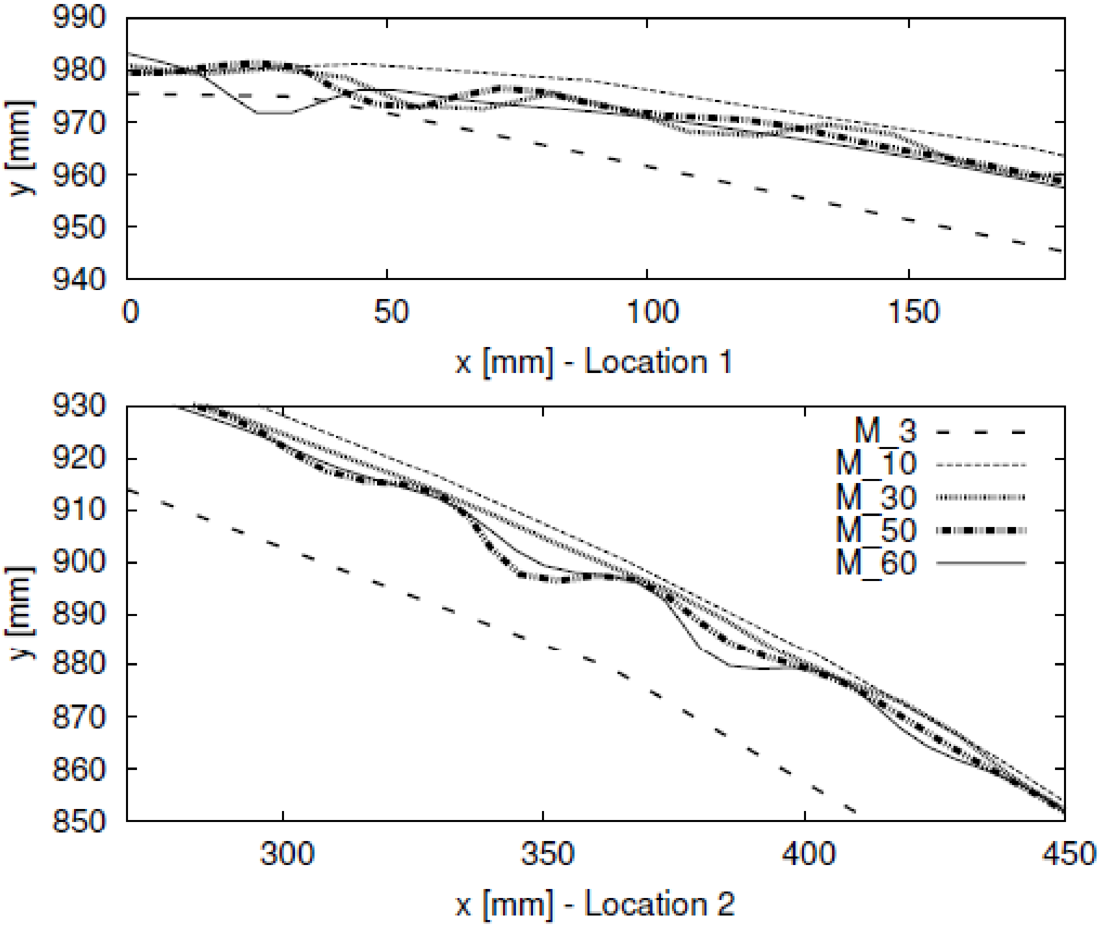
- Square membrane in shear

t [mm]	E [N/mm^2]	v [-]	t/L [-]
0.025	3500	0.31	1.9 10^{-4}



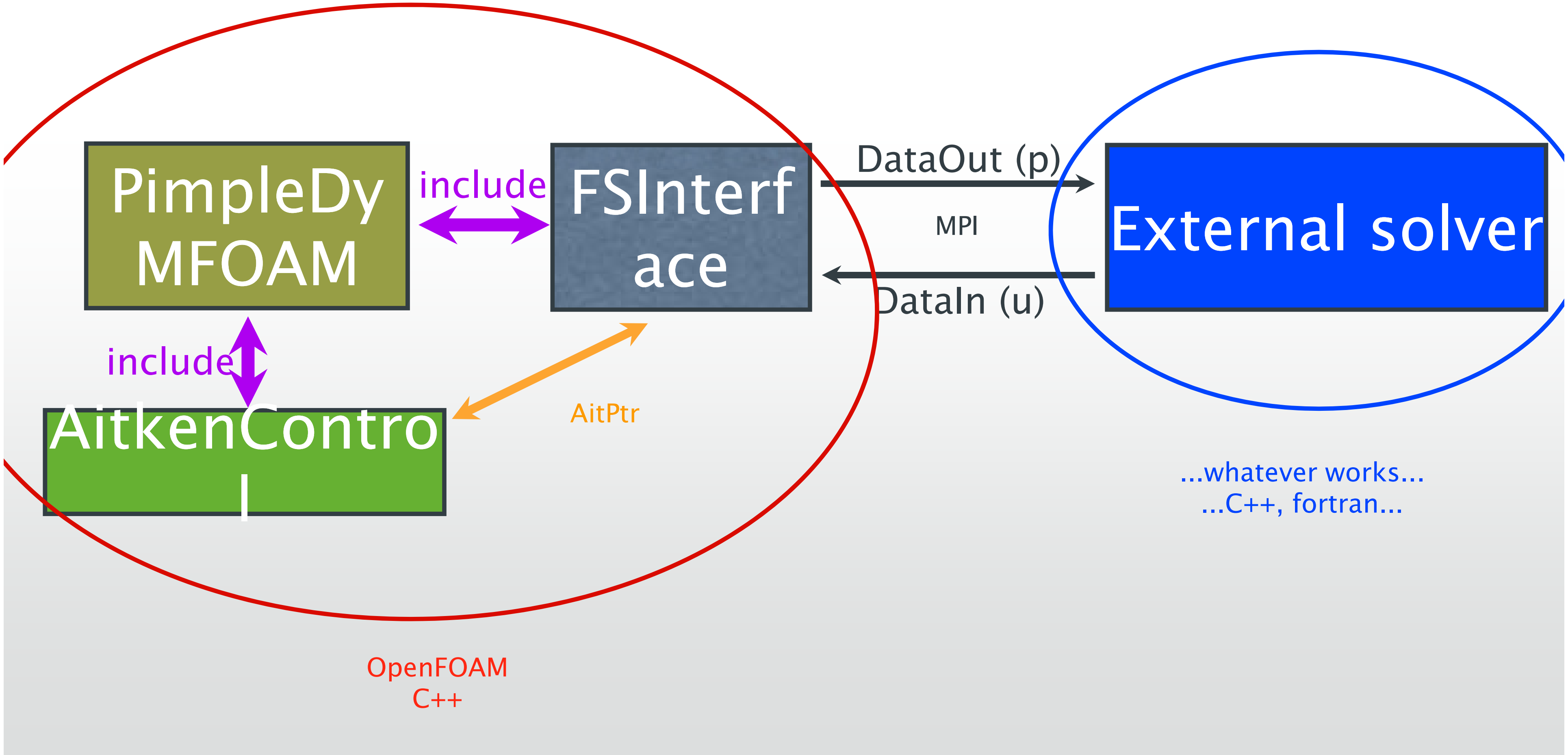



Head
Head_Base
Mid
Corner


y [mm]
990
980
970
960
950
940
0
50
100
150
x [mm] - Location 1
y [mm]
930
920
910
900
890
880
870
860
850
300
350
400
450
x [mm] - Location 2
M_3
M_10
M_30
M_50
M_60

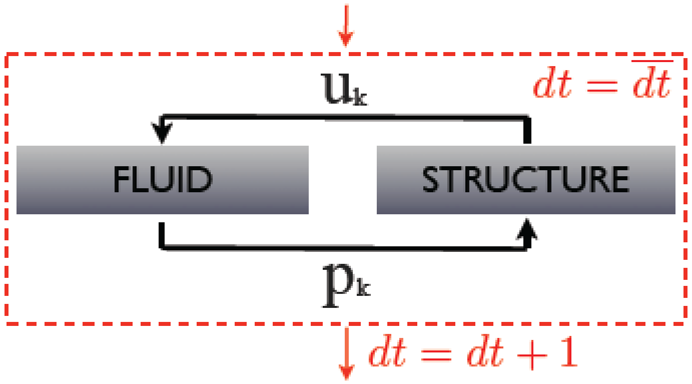
FSInterface class

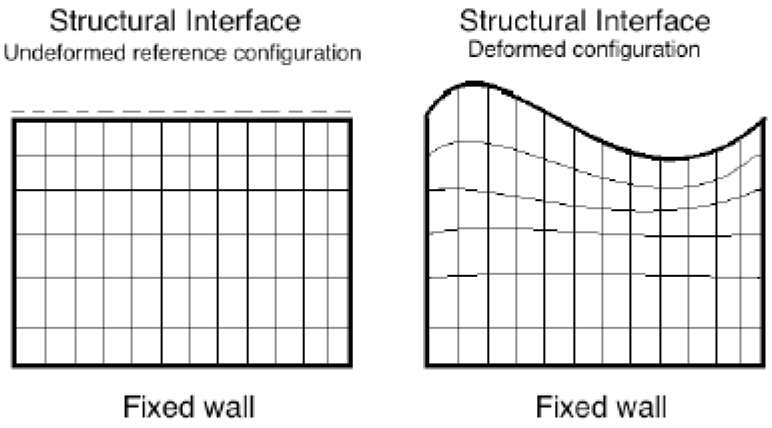
Multiple Program Multiple Data type environment, the external solver is “spawned” during the execution time. This generates a communicator we can use for exchanging data (black arrows)



Fluid Structure Interactions: ALE

- Implicit coupling algorithm with Aitken dynamic relaxation
- The fluid mesh deforms as the structure on the interface, remain fixed on the other boundaries. The mesh motion is spread in the internal domain (Laplacian)
- The case is particularly difficult: small t and high E => high added mass!





Fluid validation test cases:

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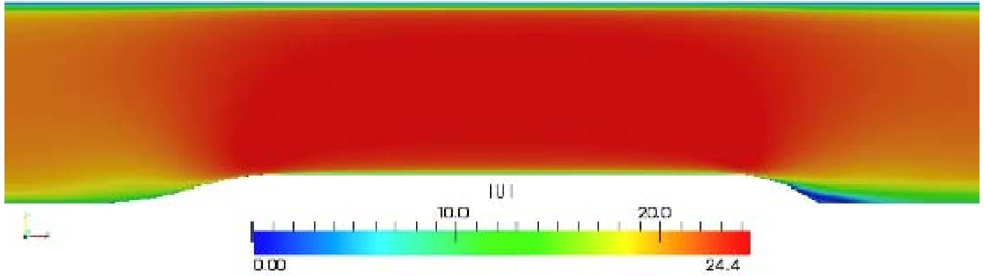
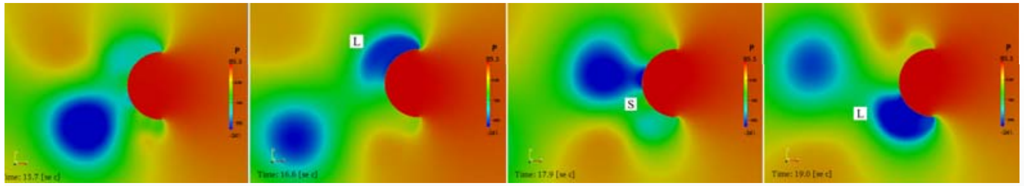
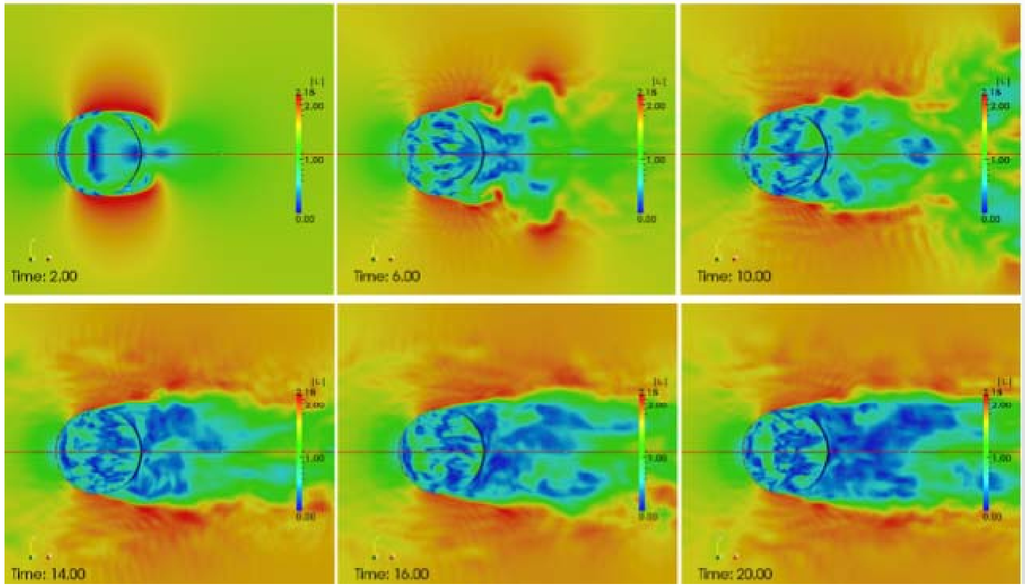
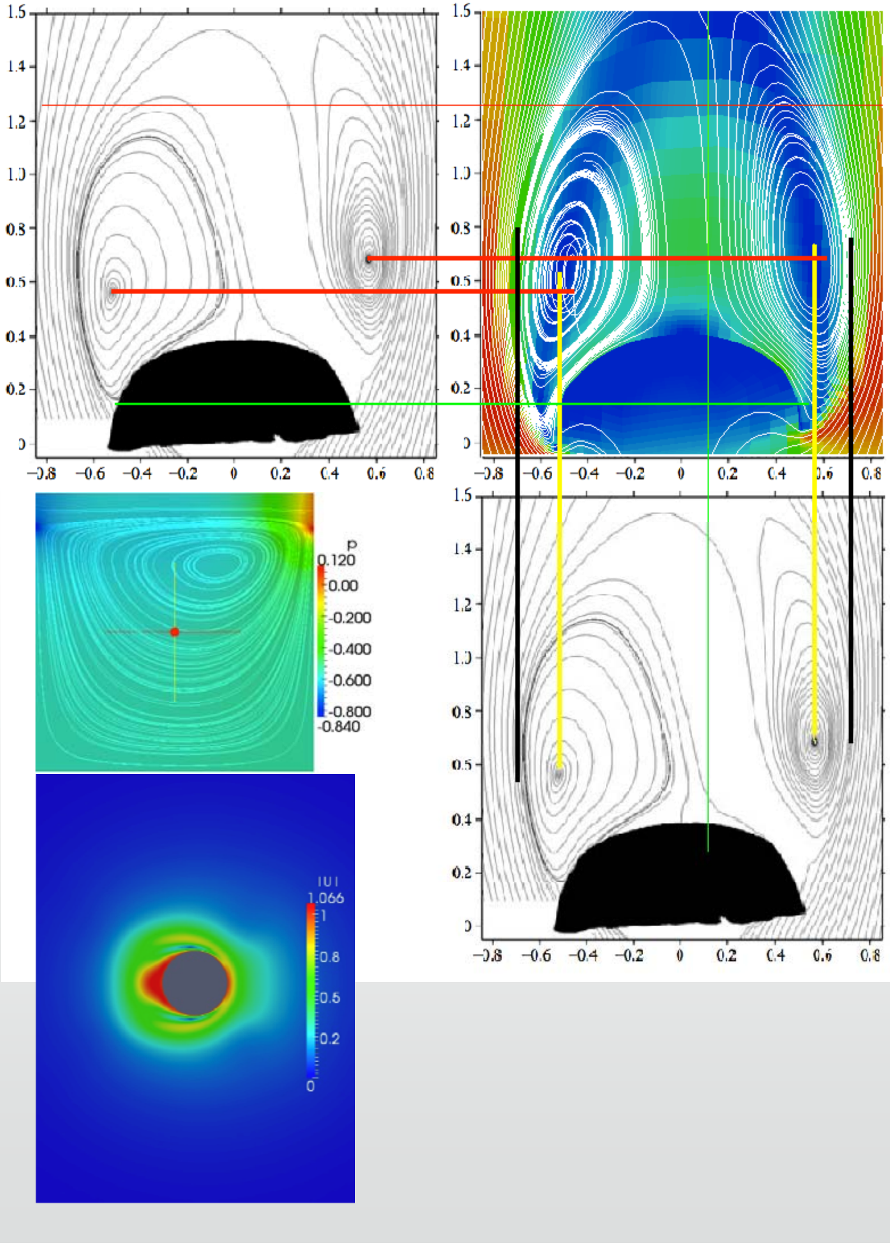


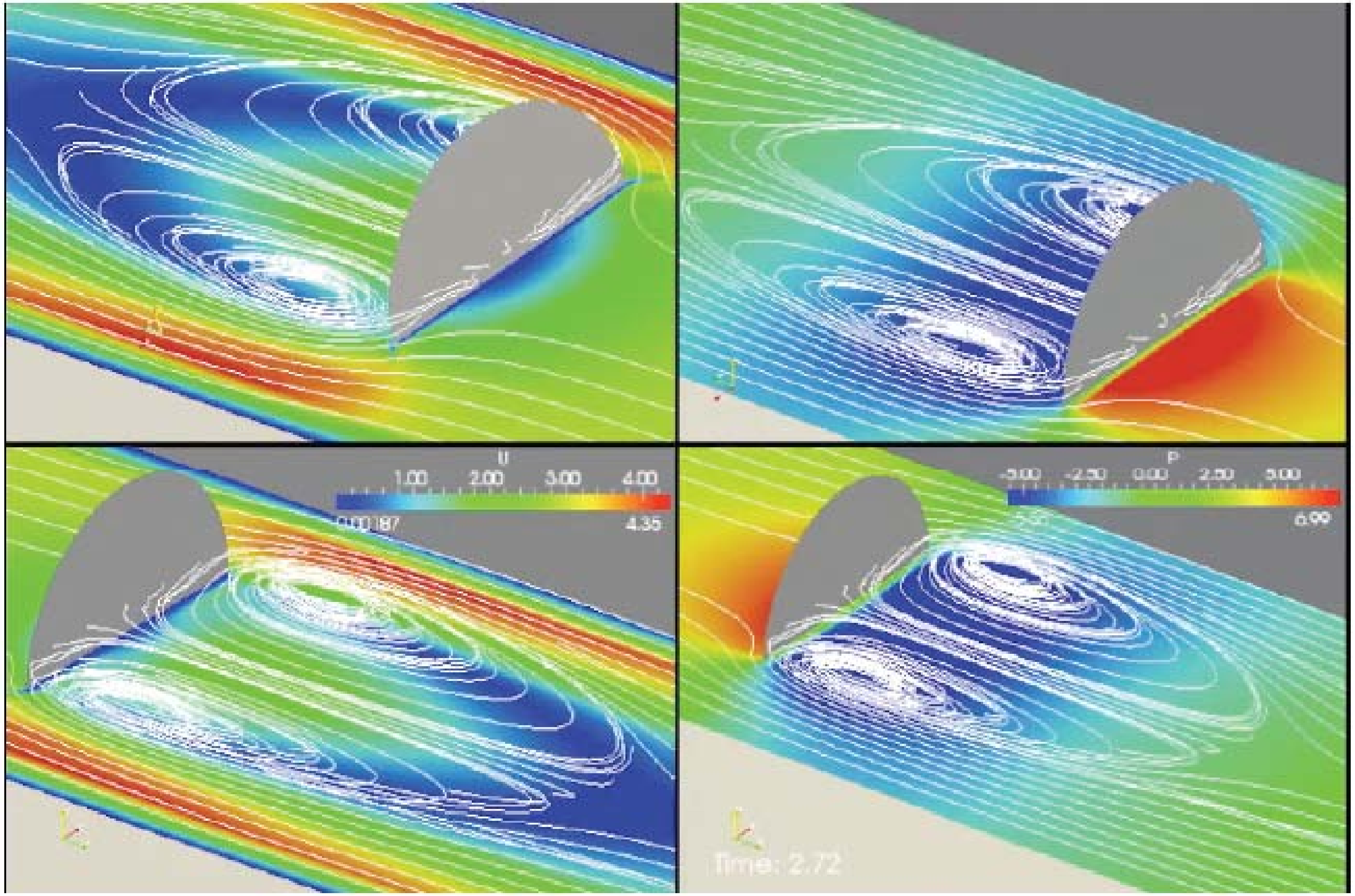






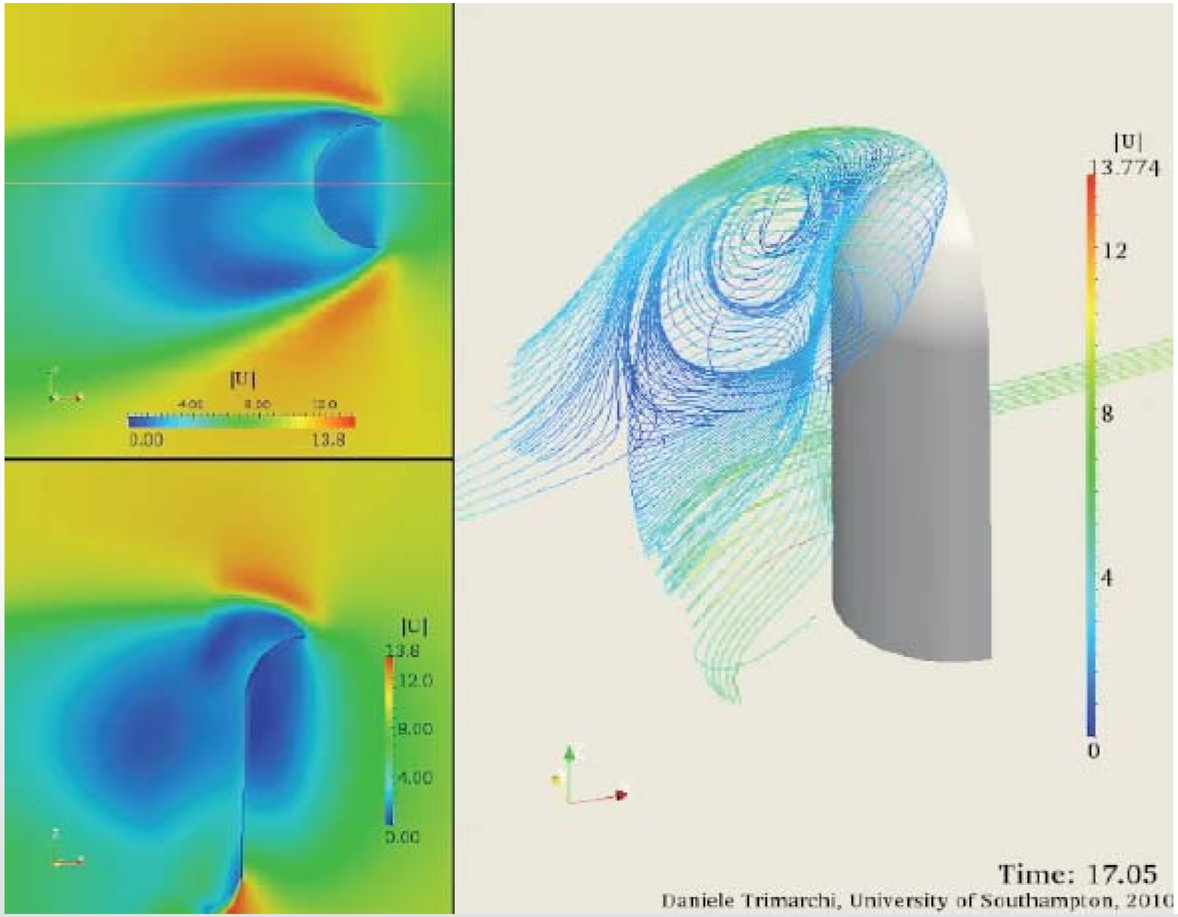
Limitations: large mesh distortions

- Case of the canopy: quasi-static FSI
- The analysis starts, but after 2.9 sec (physical time) it crashes…



Unsteady flow on a spinnaker:

- Uniform velocity
- sinusoidal direction: $\alpha = \pm 10°$



Time: 17.05

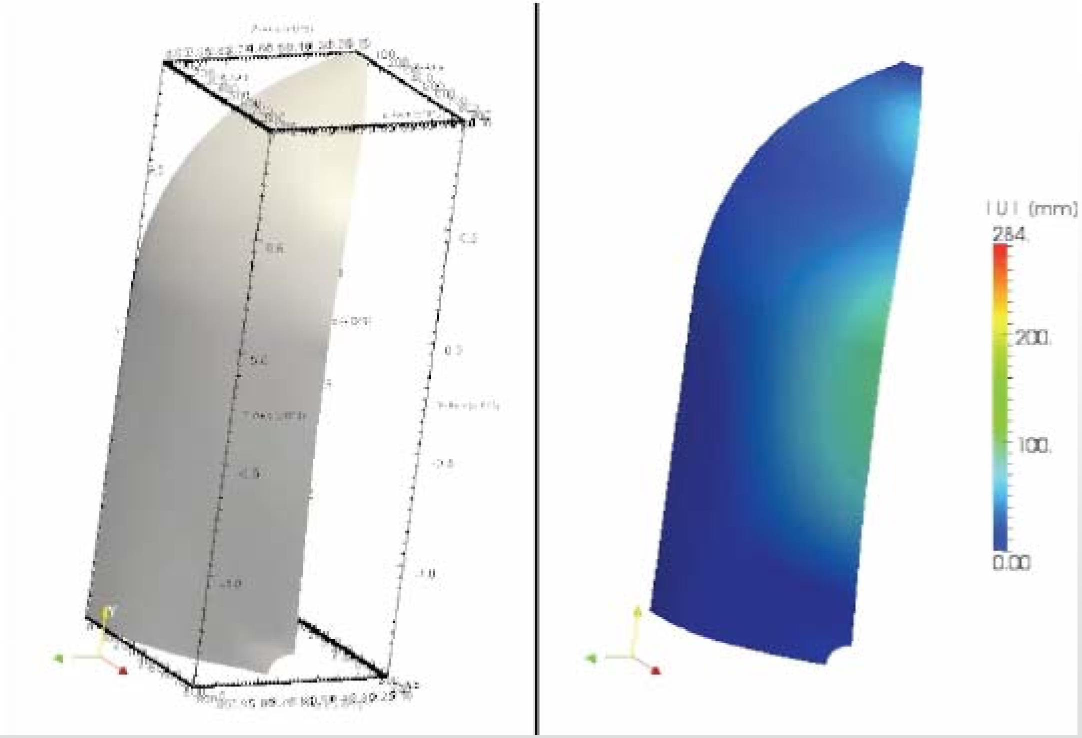
Daniele Trimarchi, University of Southampton, 2010

Spinnaker deformation example:

- Spinnaker type geometry

- Uniform material, no reinforcements

P [N/mm^2]	H [m]	t [mm]	E [N/mm^2]	v [-]
10^{-4}	2.5	0.1	376	0.4



Conclusions

- Simulations have been carried out in the fluid, the structural and the Fluid Structure Interactions domains
- Validations examples confirm the good accuracy of the methods. Excellent agreement was found when simulating details such as the wrinkles
- With the techniques available it is possible to perform simulations of industrial interest, able to support the design decision making process
- Identified limitations: accuracy of the U-RANSE simulations, ALE approach when analysing large folds, an isotropic constitutive relationship was employed; seams and multi-layer materials were not taken into account

And do wrinkles matter?

- This depends on the relative direction of wind and wrinkles
  - Transverse flow certainly thickens boundary layer, like roughness elements
- Collapse of local area will influence the capture area for downwind drag
- Dynamic flutter, sails flogging is generally not good and can induce failure
- Likely influence on design is to better capture the necessary thickness distribution to maintain shape across wide range of wind speeds

Thank you for your attention,
Any questions?

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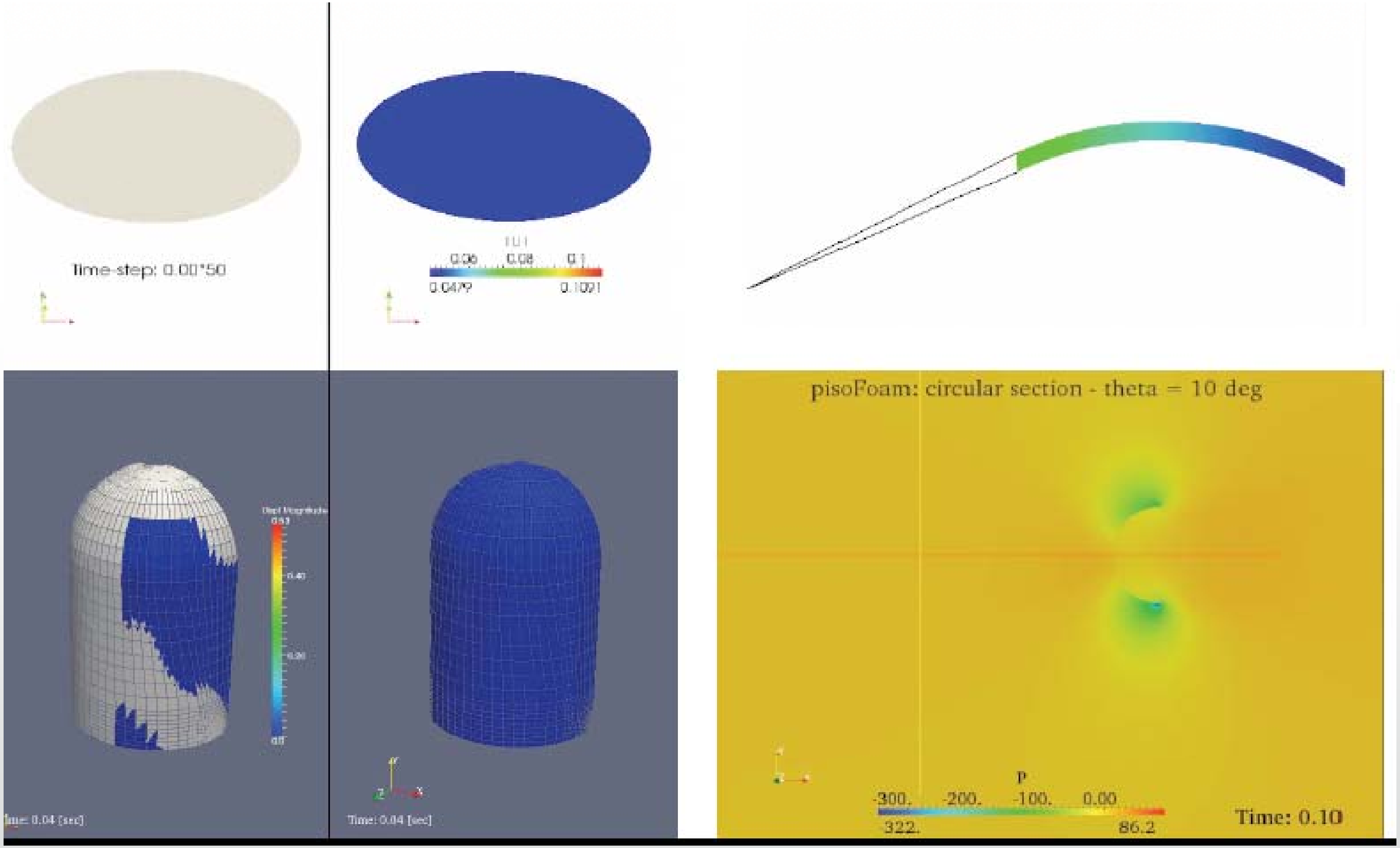
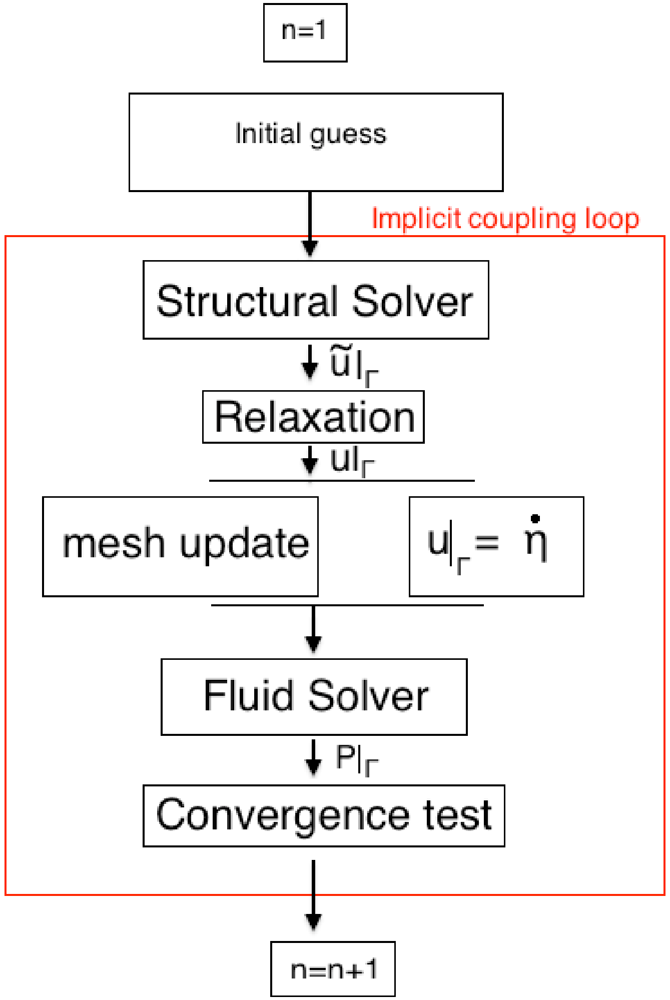


Implicit coupling

dded mass effects affects the stability
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
$\mu_{max} = \frac{L}{\pi \, htan(\frac{\pi R}{L})}$



n=1
Initial guess
Implicit coupling loop
Structural Solver
$\tilde{u}|_\Gamma$
Relaxation
$u|_\Gamma$
mesh update
$u|_\Gamma = \dot{\eta}$
Fluid Solver
$P|_\Gamma$
Convergence test
n=n+1

the majority of cases the condition is t met, and the algorithm is unstable. e most easy (but computationally pensive) way is to perform fixed int iterations between the fluid and e structure

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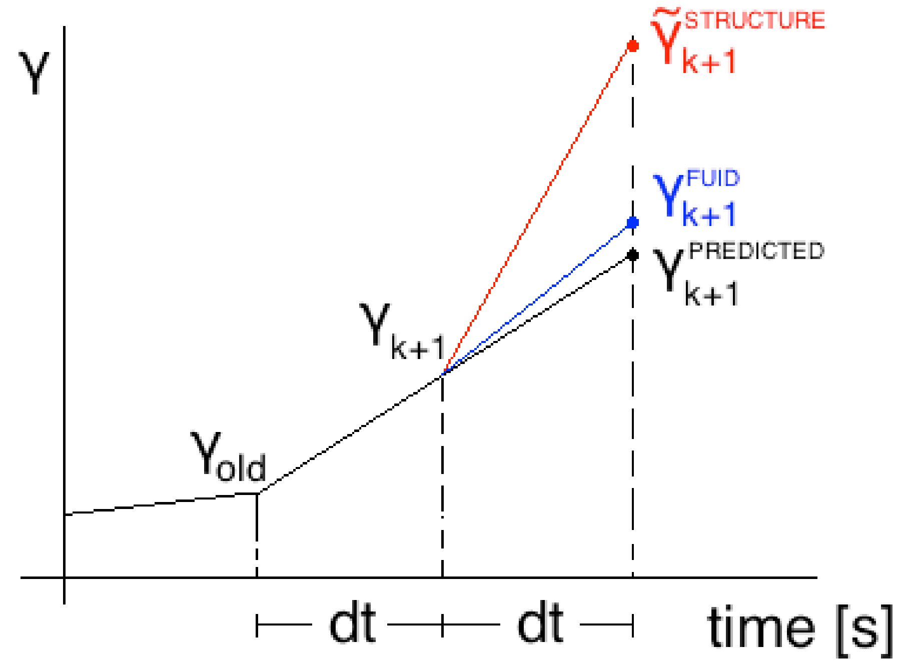
Causin, P., J.-F. Gerbeau, et al. (2004). Added mass effect in the design of titioned algorithms for fluid-structure problems. INRIA - Res. Rep. **5084**.

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



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

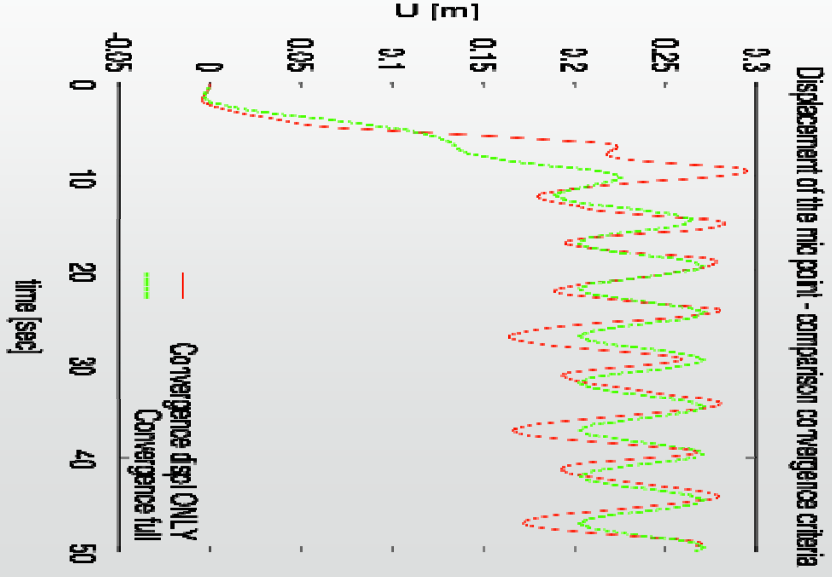
M. Fernandez (2011) Coupling schemes for incompressible fluid-structure
eraction:implicit, semi-implicit and explicit. Bol. Soc. Esp. Mat. Apl. no0
000), 1-52

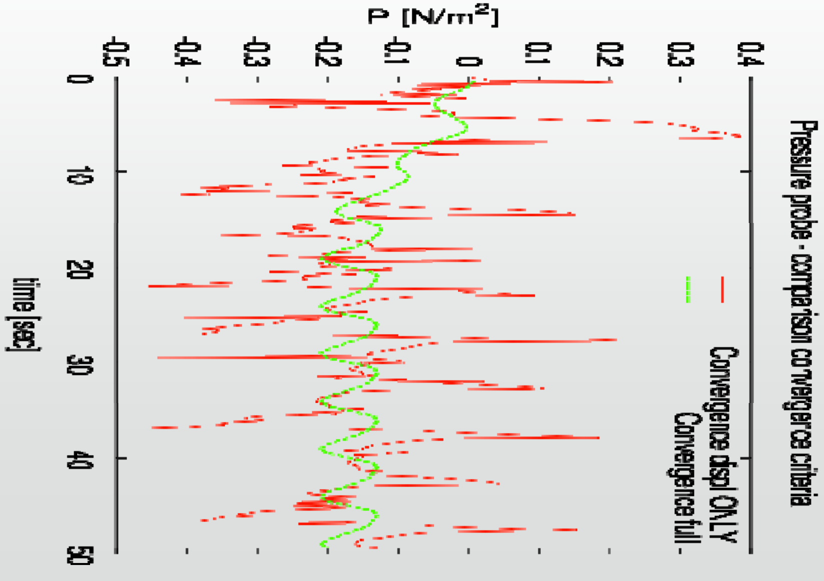
Convergence criterion

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





Lidded flow cavity validation

QuickTime™ and a
decompressor
are needed to see this picture.