Demonstration of a unified and flexible coupling environment for nonlinear fluid-structure interaction problems

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LIÈGE université

Motivations

Fluid-structure interaction

- Nonlinear behavior
- Large range of physics
- High fidelity models
- Development of a computational environment for research and design

Primary target application : aeroelasticity

Computational approach

Monolithic

- One single framework to solve the coupled problem

Partitioned

- Coupling of independent codes
- Each code is optimized for a particular physics

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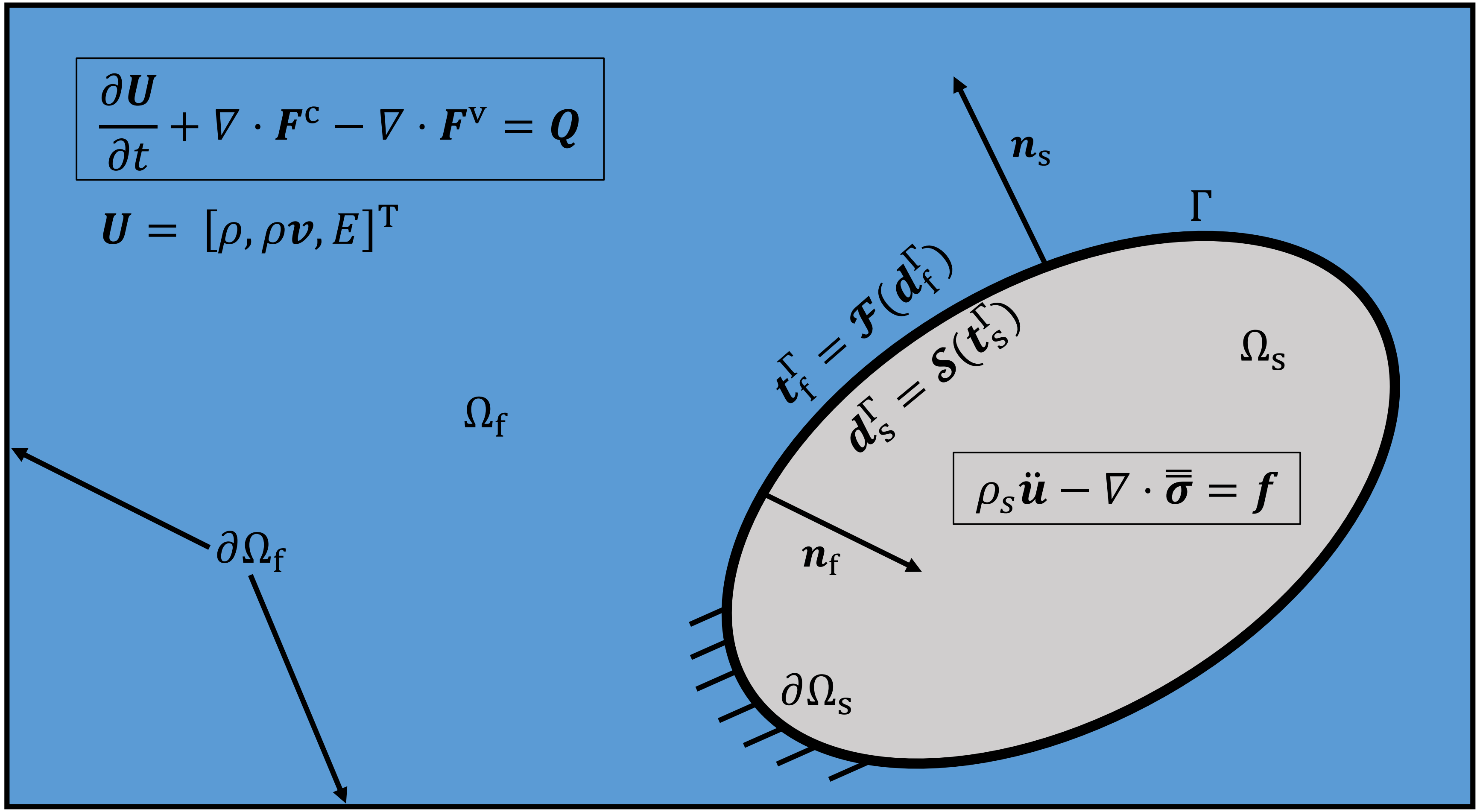
➔ Need an interfacing tool { flexible, performant }

FSI : governing physics & formulation



Interface loads : $\boldsymbol{t}_{\mathrm{f}}^{\Gamma} = -p\boldsymbol{n}_{\mathrm{f}} + \bar{\bar{\boldsymbol{\tau}}}\boldsymbol{n}_{\mathrm{f}}$
$\boldsymbol{t}_{\mathrm{s}}^{\Gamma} = \bar{\bar{\boldsymbol{\sigma}}}\boldsymbol{n}_{\mathrm{s}}$

Governing equations

$\mathcal{F} \leftrightarrow$ Fluid operator
$\mathcal{S} \leftrightarrow$ Solid operator

+

Coupling conditions

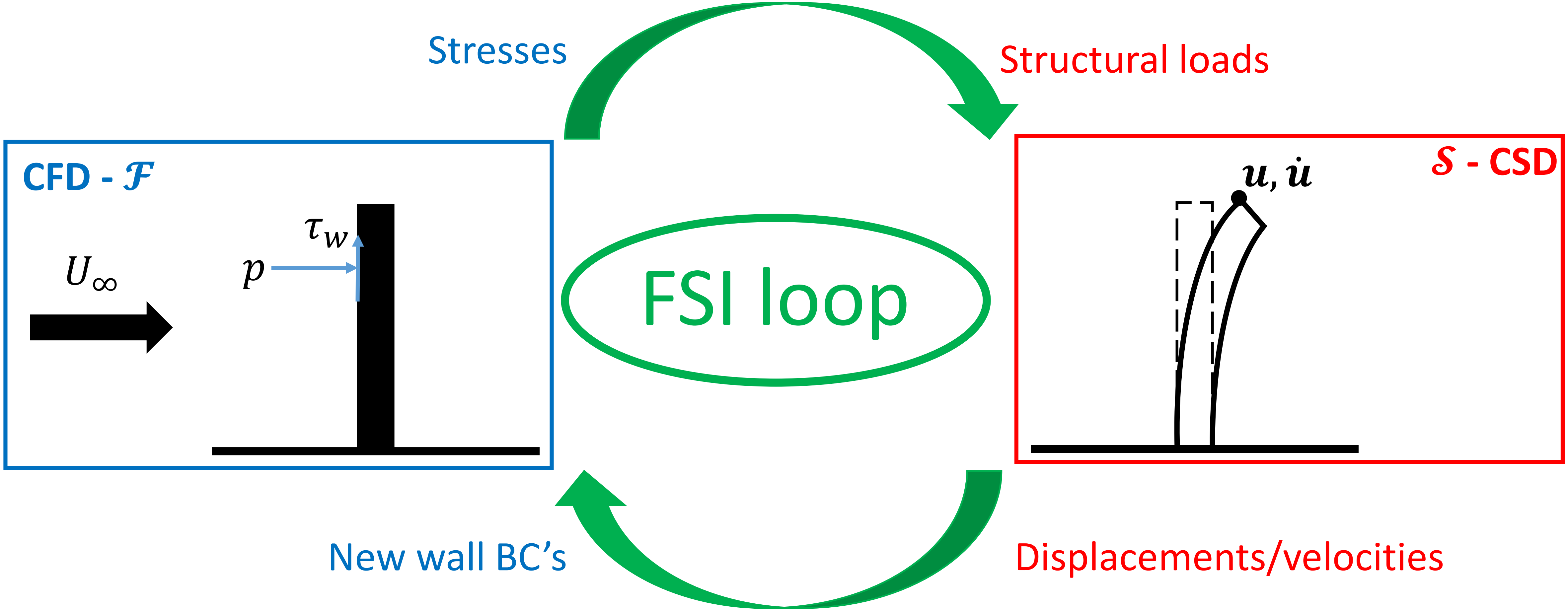
$$\boldsymbol{d}_{\mathrm{f}}^{\Gamma} = \boldsymbol{d}_{\mathrm{s}}^{\Gamma} = \boldsymbol{d}^{\Gamma}$$
$$\boldsymbol{t}_{\mathrm{f}}^{\Gamma} + \boldsymbol{t}_{\mathrm{s}}^{\Gamma} = \boldsymbol{0}$$

=

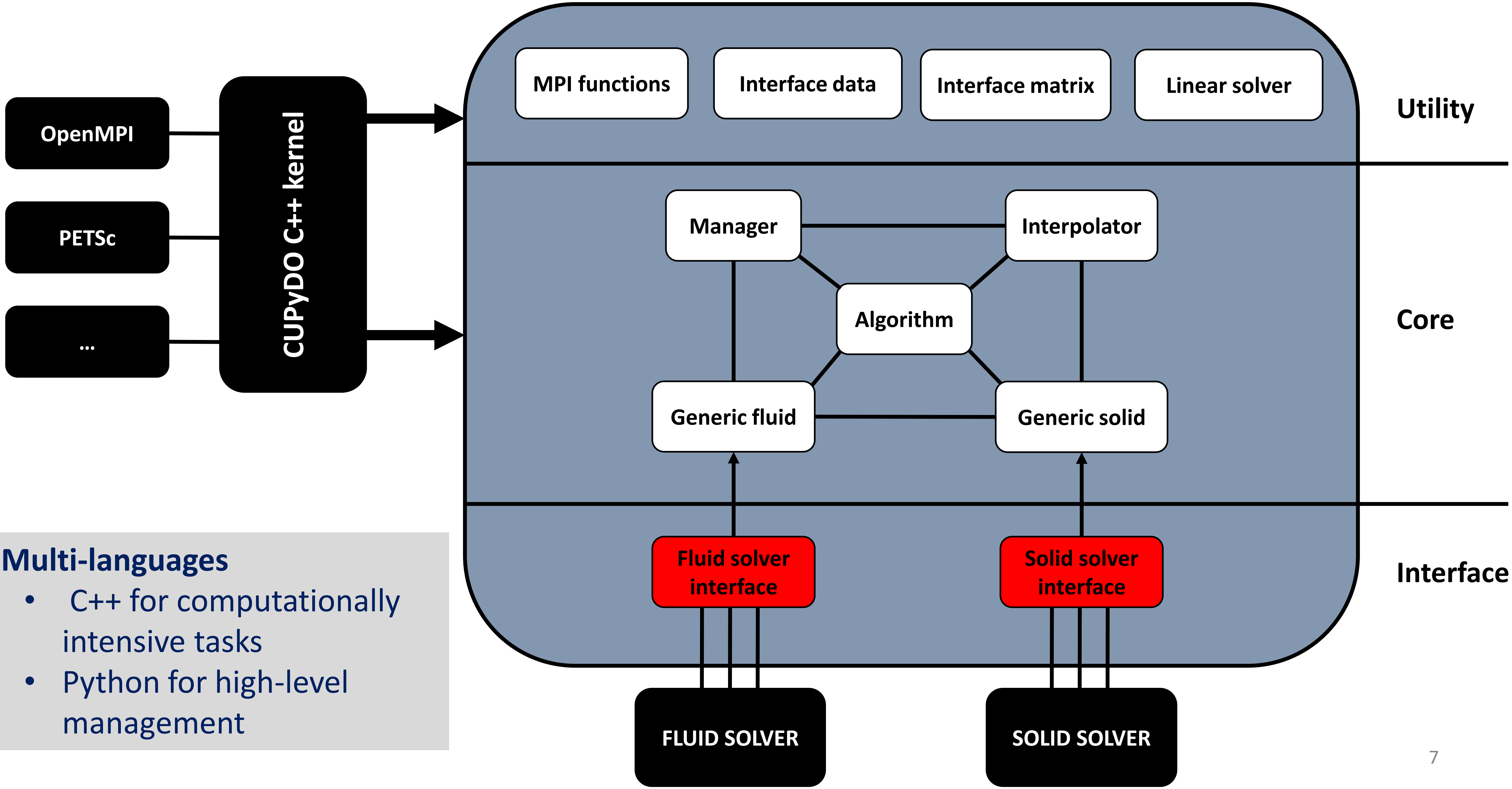
Fixed-point formulation

$$\boldsymbol{d}^{\Gamma} = \mathcal{S}\left(-\mathcal{F}(\boldsymbol{d}^{\Gamma})\right)$$

Coupling simulations – strong coupling



Multi-codes coupling technology : CUPyDO



- **Multi-languages**
  - C++ for computationally intensive tasks
  - Python for high-level management

Examples of coupled solver

Fluid solvers

- SU2 – FV unstructured (Stanford)
- PFEM – particle FE (ULiège)

Structural solvers

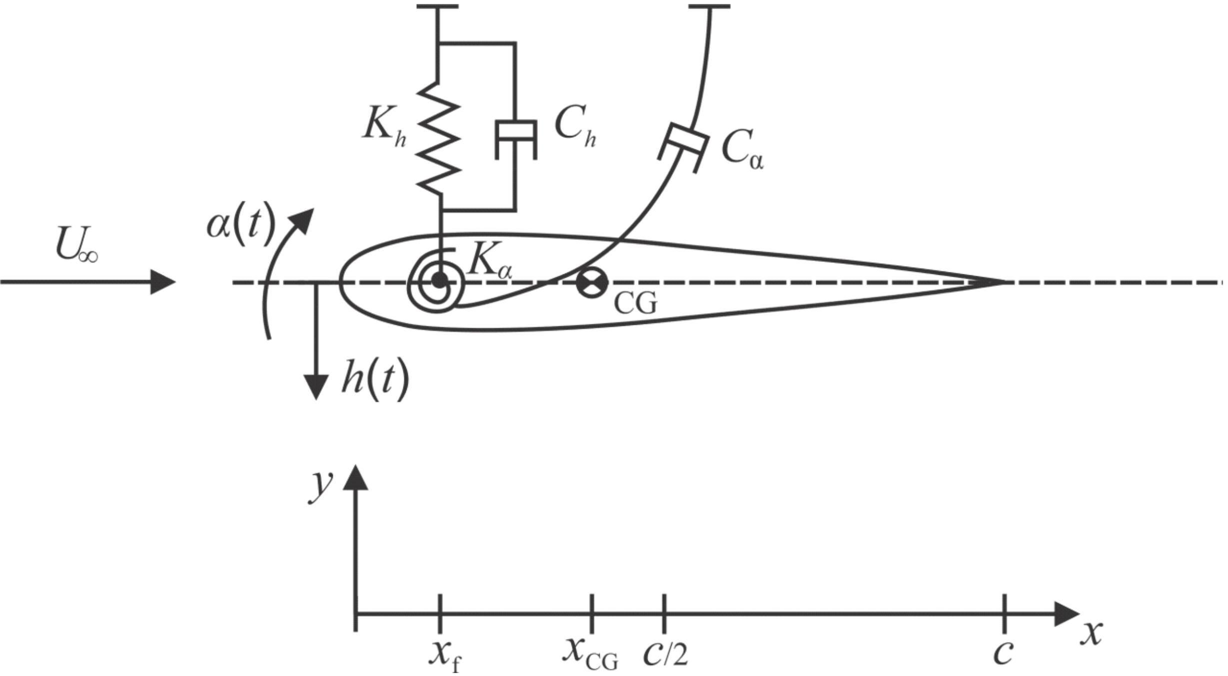
- Metafor – NLFEM (ULiège)
- GetDP – LFEM (ULiège)
- RBM integrator (ULiège)

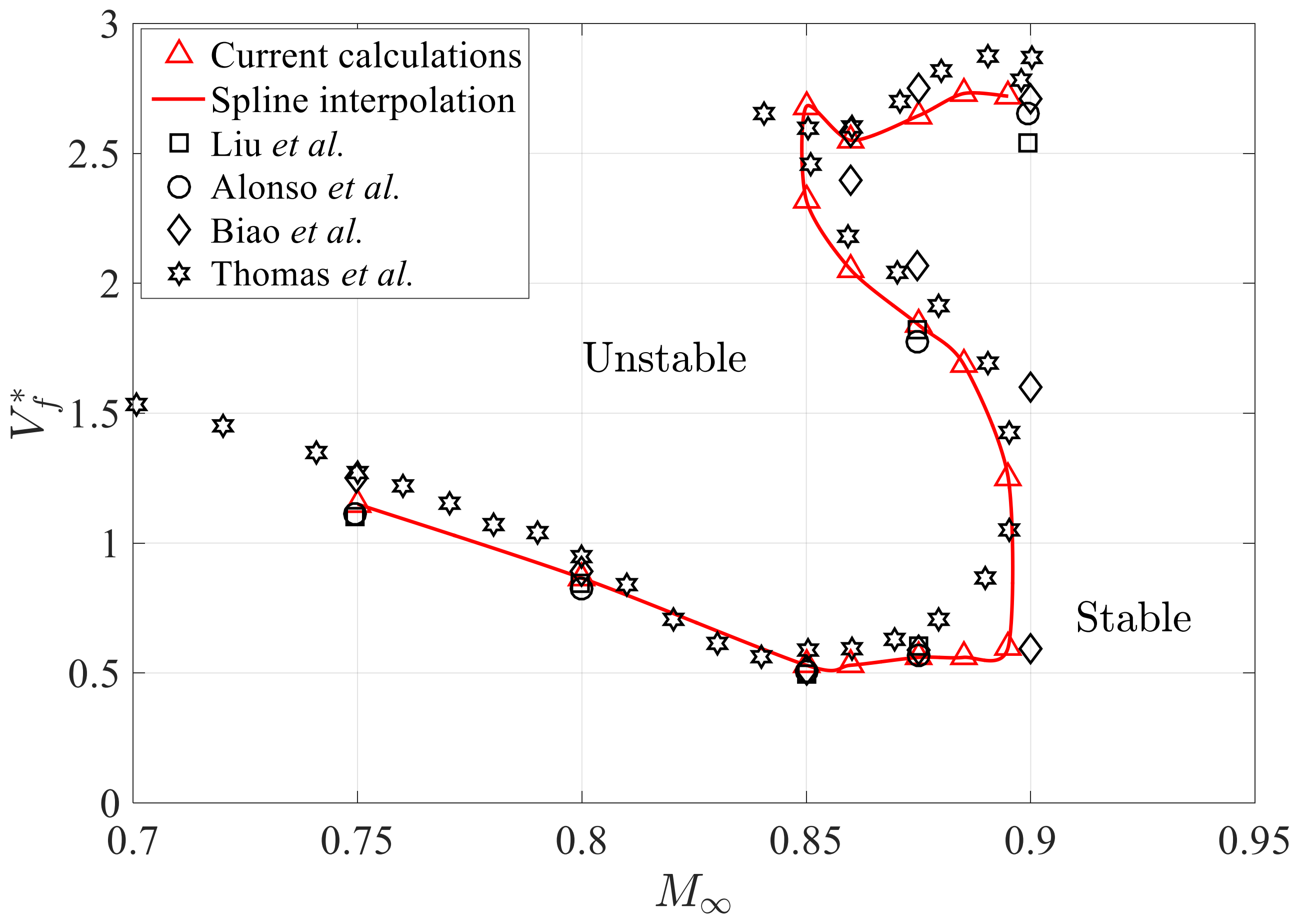
- Ready-to-use interfaces
- No technical restriction for coupling other software, even commercial packages

Isogai wing section

$$V^* = \frac{U_\infty}{b\omega_\alpha\sqrt{\mu}}$$

SU2+RBM

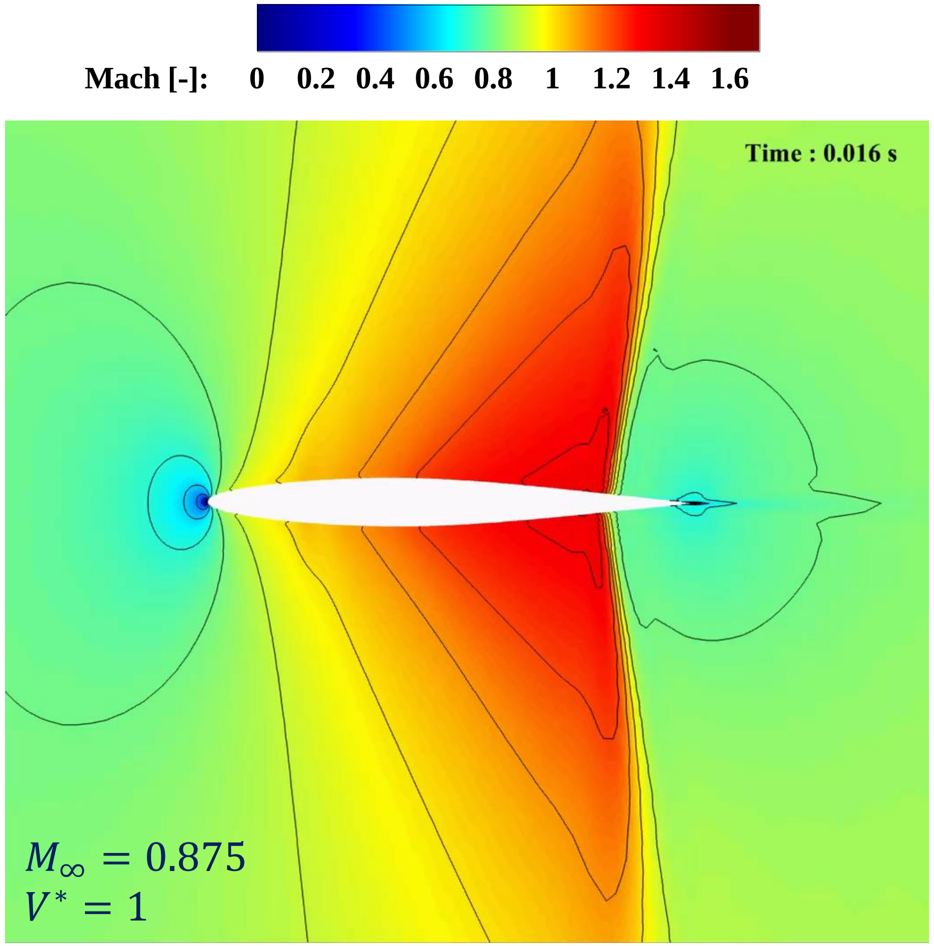


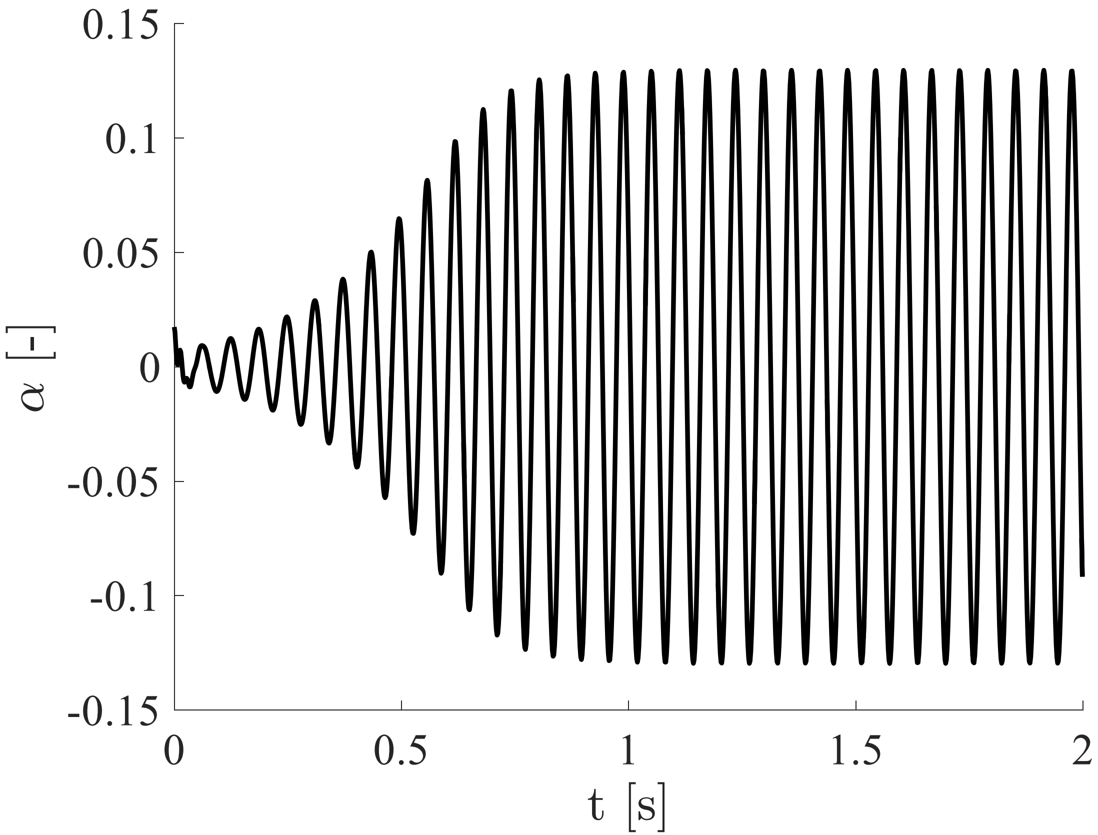


- Determine flutter conditions as a function of M_∞
- Transonic dip is captured
- S-shape curve is well recovered
- Inviscid fluid

"K. Isogai. AIAA Journal, 17, 1979"

Isogai wing section

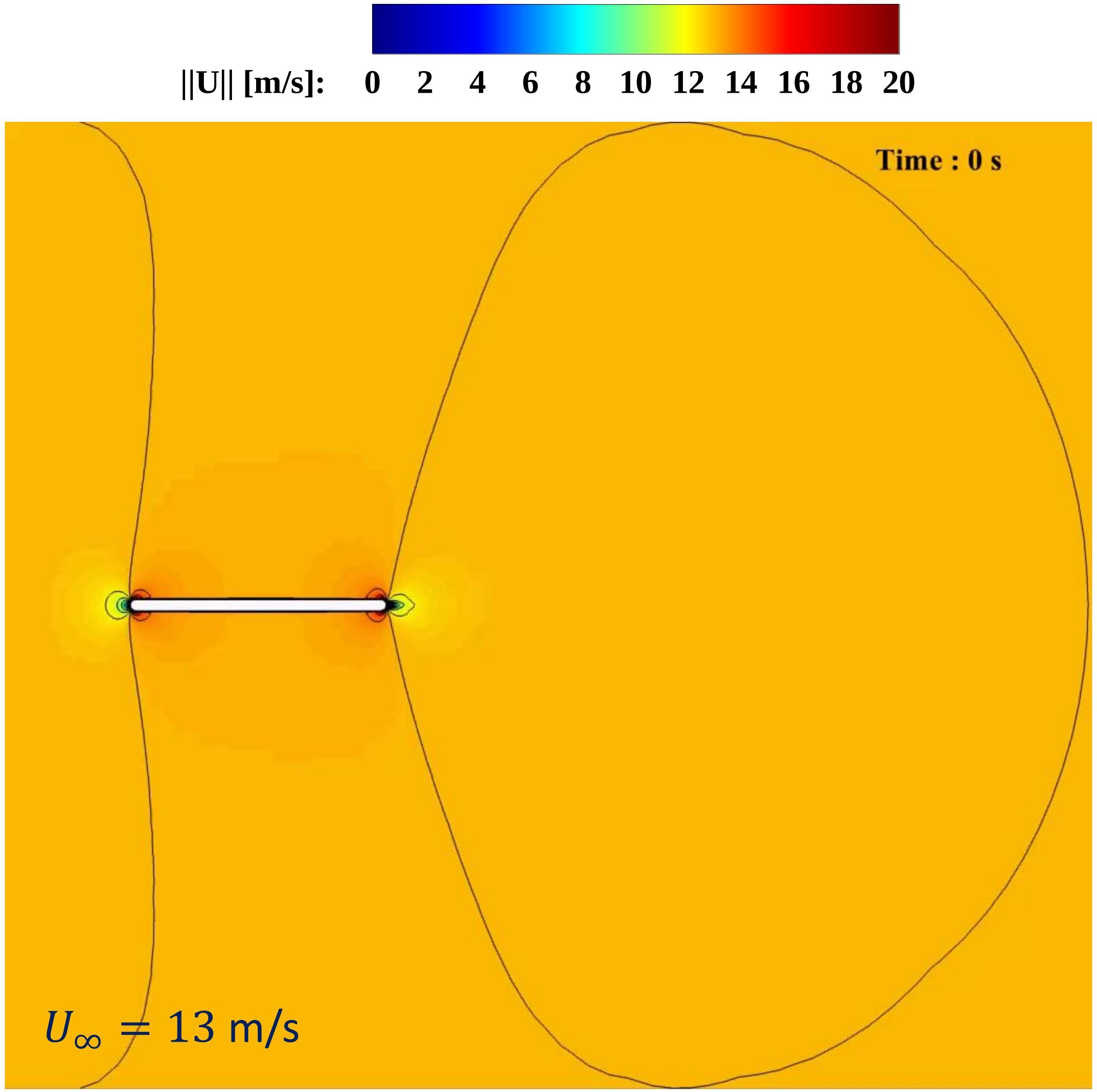




- Moving shock interacting with the motion of the airfoil
- Existence of a LCO due to nonlinear aerodynamics

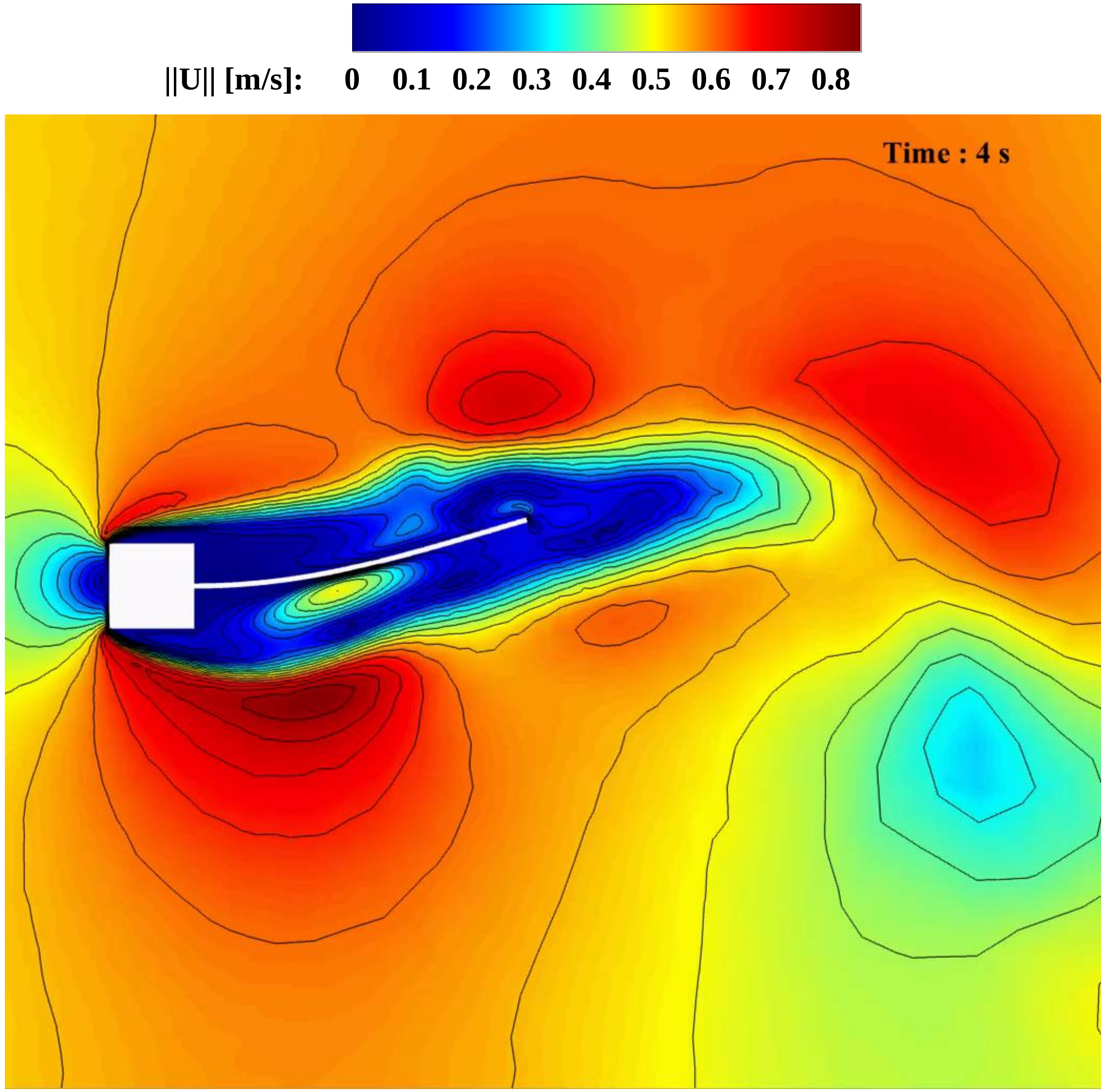
Stall flutter of a flat plate

- Airfoil motion rapidly turns into stall flutter
- Induced by dynamic flow separation
- Nonlinearities lead to LCO



"X. Amandolese *et al.*, *Journal of Fluids and Structures, 43*, 2013."

VIV of a flexible cantilever

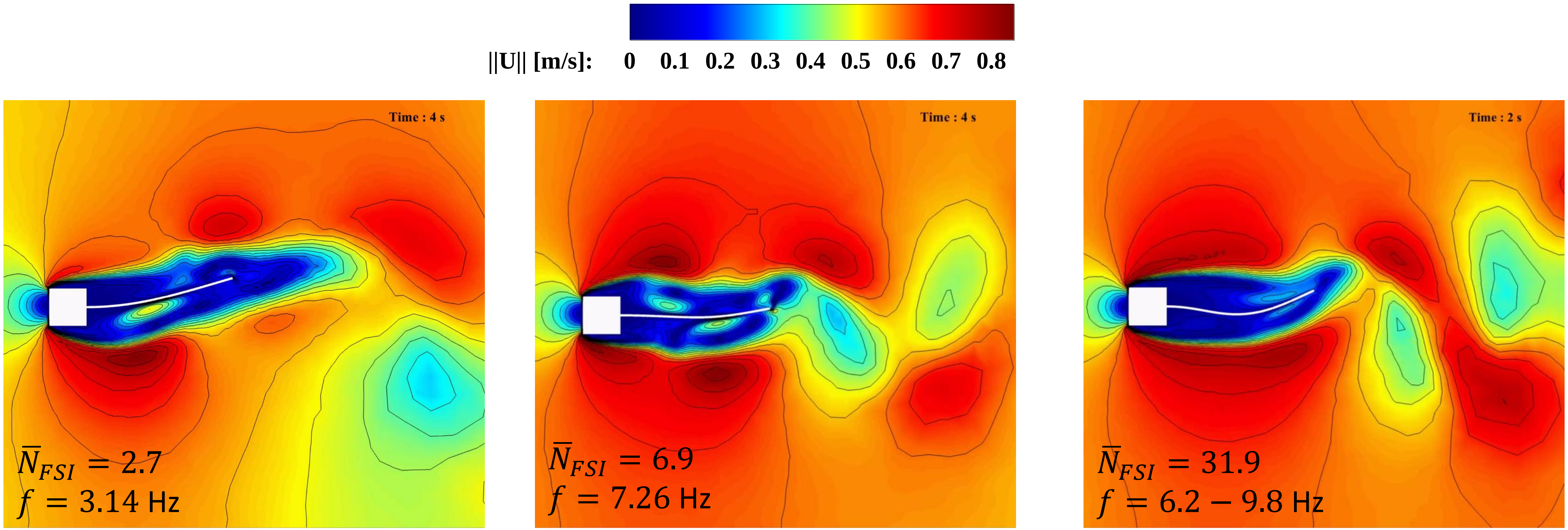


- Solid motion is generated by vortex shedding
- Large displacement amplitude (nonlinear)
- Laminar flow at Re = 333

"C. Habchi *et al.* , *Computer & Fluids, 71*, 2013."

SU2+Metafor

VIV of a flexible cantilever



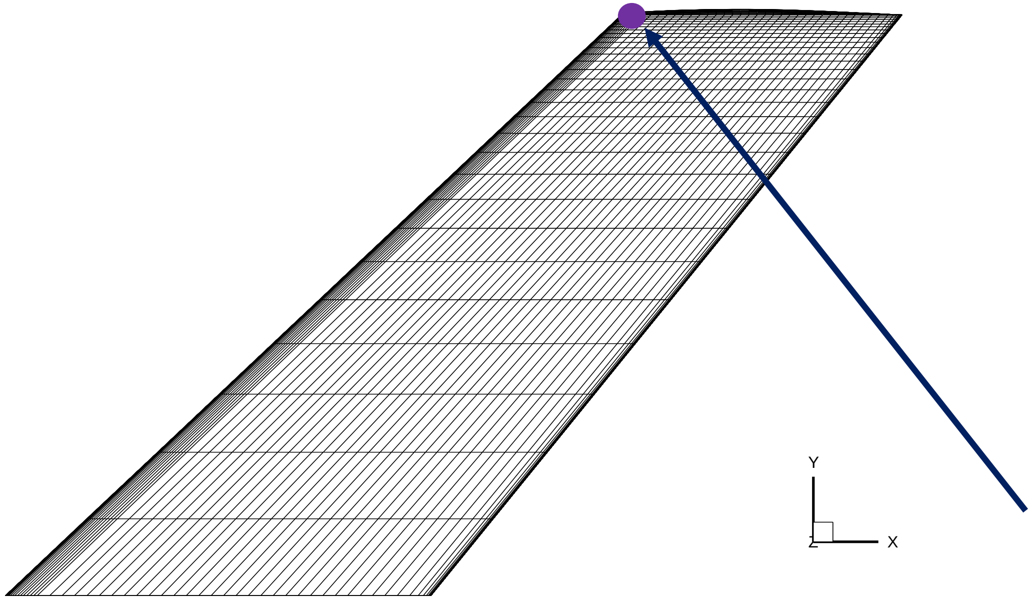
$\frac{\rho_s}{\rho_f} \approx 100$ $\frac{\rho_s}{\rho_f} \approx 10$ $\frac{\rho_s}{\rho_f} \approx 1$

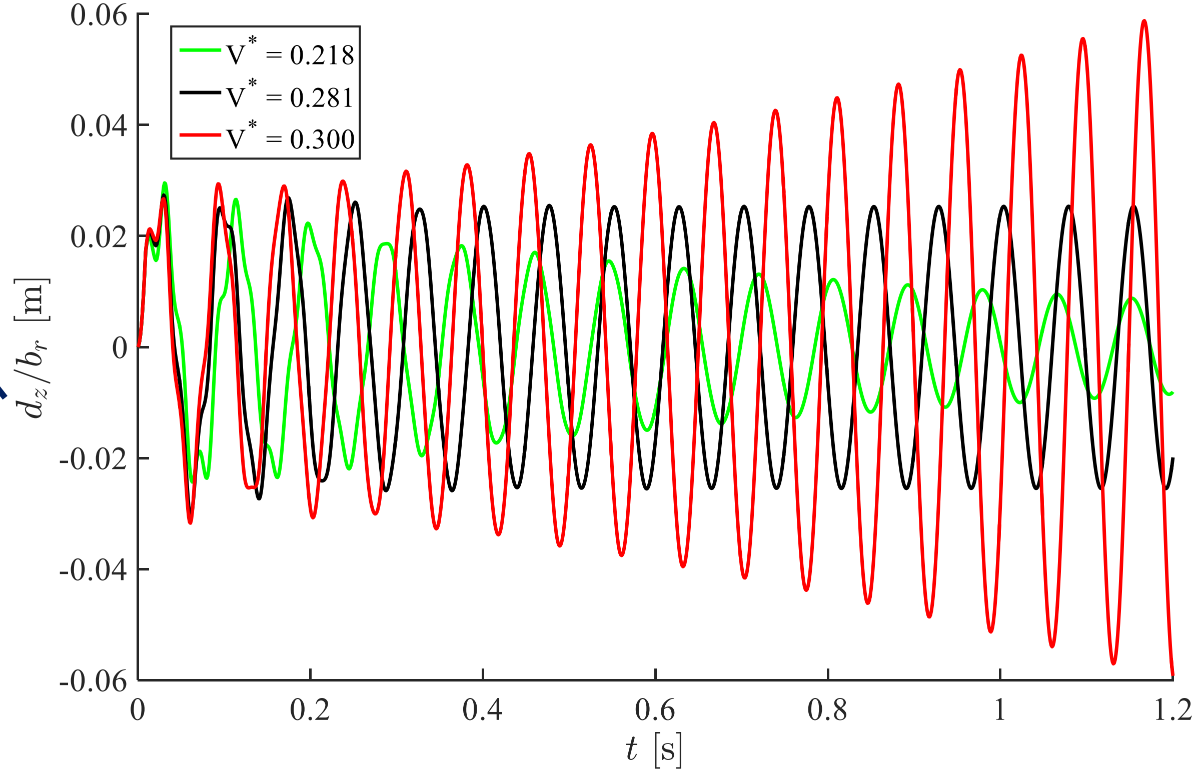
- From dense to light material
- Low mass ratios = numerical coupling instabilities ➔ relaxation needed in coupling
- Number of coupling iterations per time step increases

AGARD 445.6 wing

SU2+Metafor

$$V^* = \frac{U_\infty}{b_r \omega_2 \sqrt{\mu}}$$

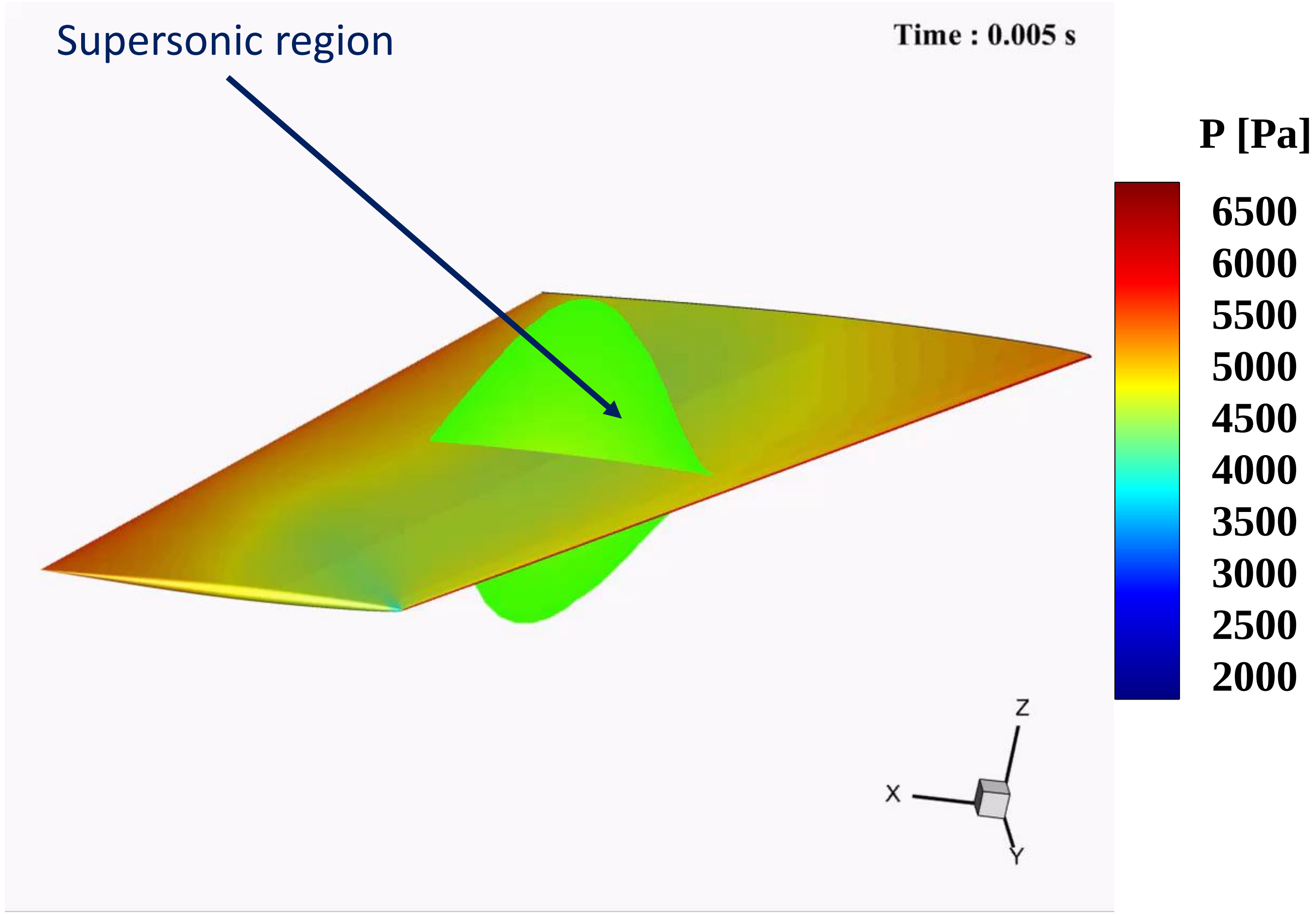




- Determine flutter conditions at $M_\infty = 0.96$
- Consider inviscid fluid
- Literature : $V_f^* = 0.243 - 0.327$
- Computed : $V_f^* = 0.281$

“E.C. Yates, *AGARD Report 765*, 1988.”

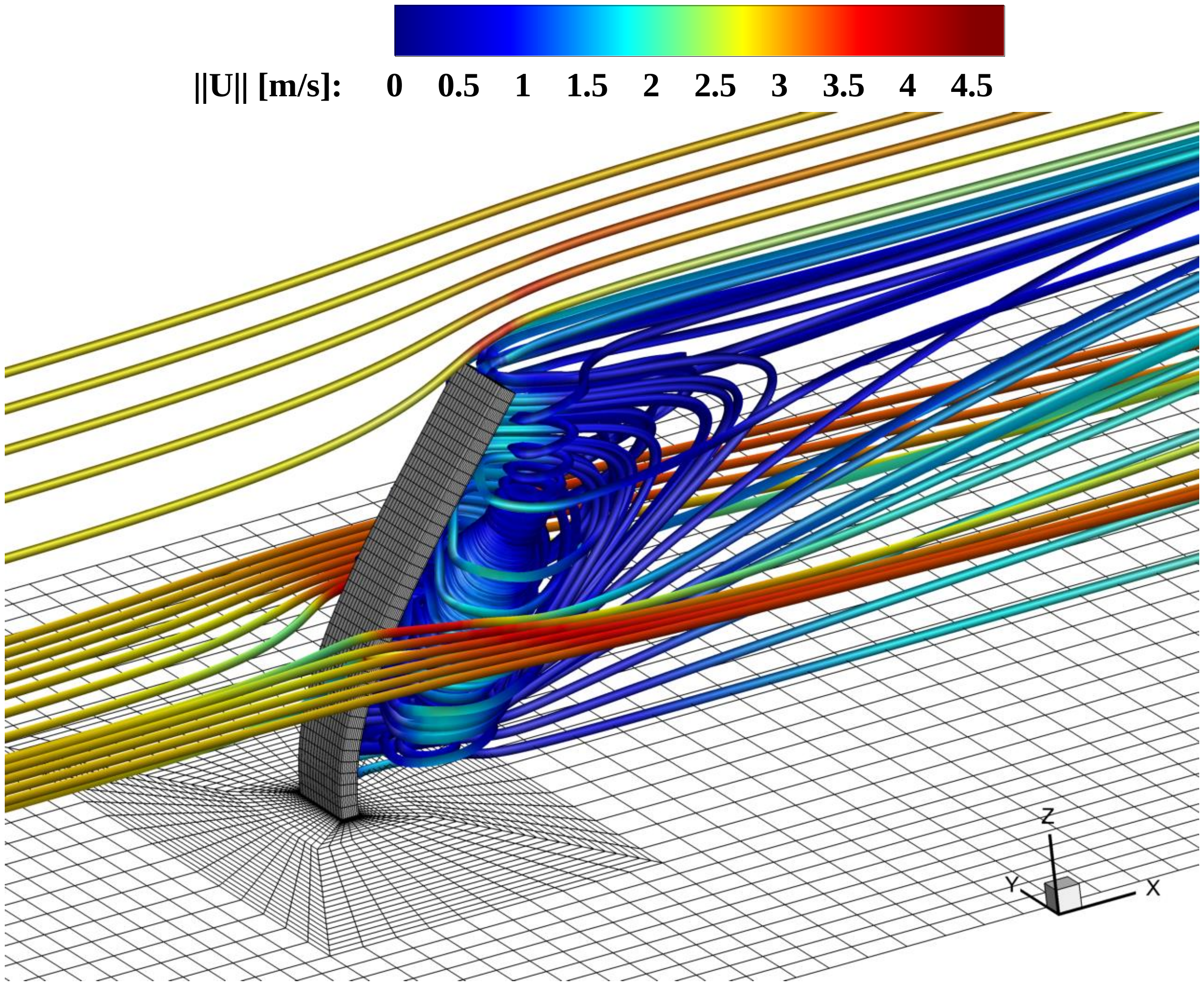
AGARD 445.6 wing



- Post-critical conditions at $M_{\infty} = 0.96$ and $V^* = 0.300$
- Significant motion of the supersonic region

"E.C. Yates, *AGARD Report 765*, 1988."

Bending of a flat plate submitted to cross flow



- Inspired from drag reconfiguration of aquatics plants
- Laminar flow at Re = 1600
- Relatively soft and light solid material :

$$\frac{\rho_s}{\rho_f} = 0.678$$

➔transient response is numerically unstable

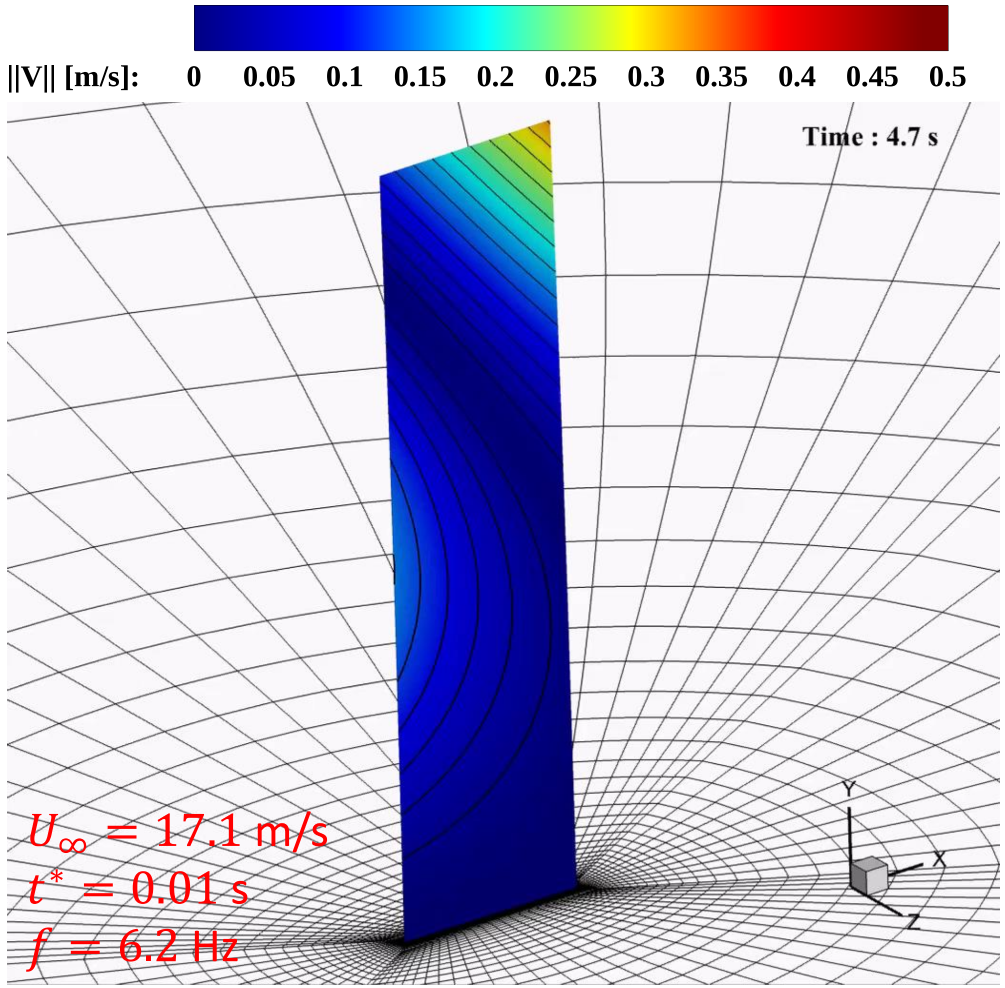
"F-B. Tian *et al.* , *J. of Computational Physics, 258*, 2014."

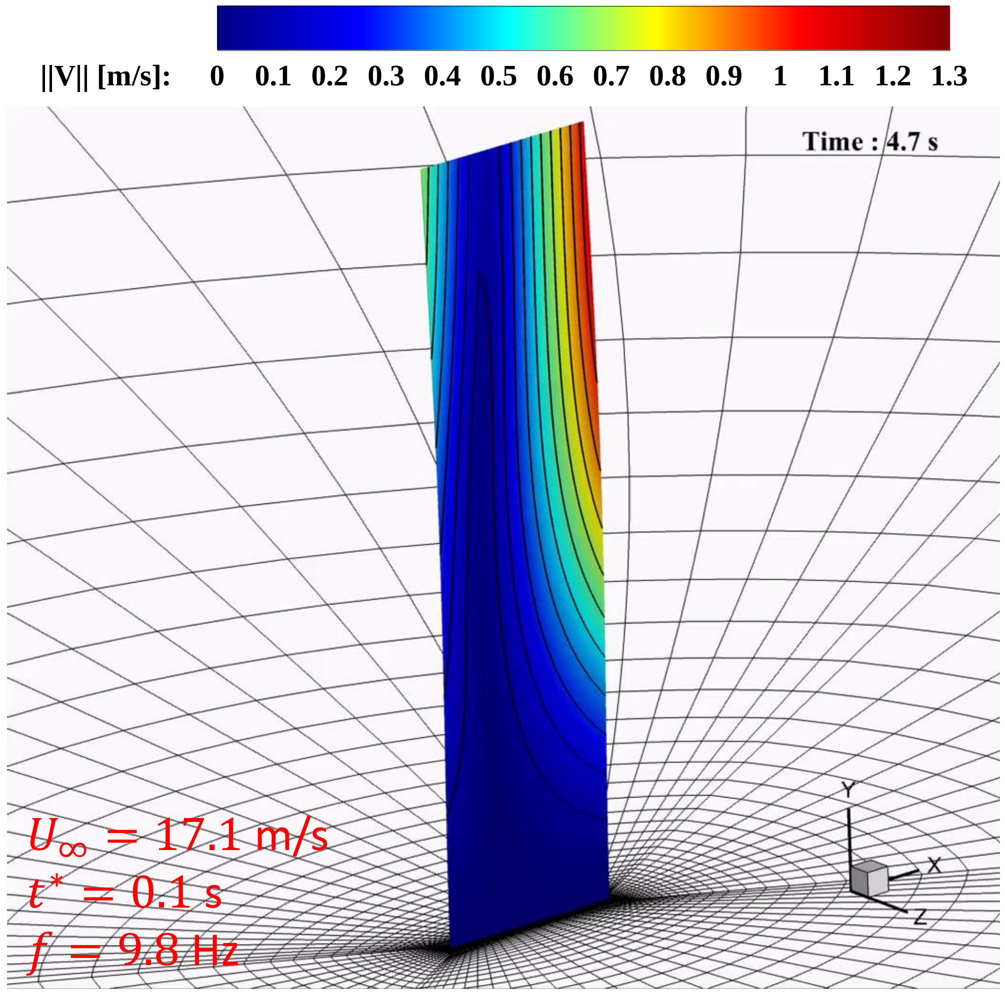
Cantilever flat wing

SU2+Metafor

- Material : aluminium | Fluid : air
- High aspect ratio plate with very small thickness
- Very flexible structure

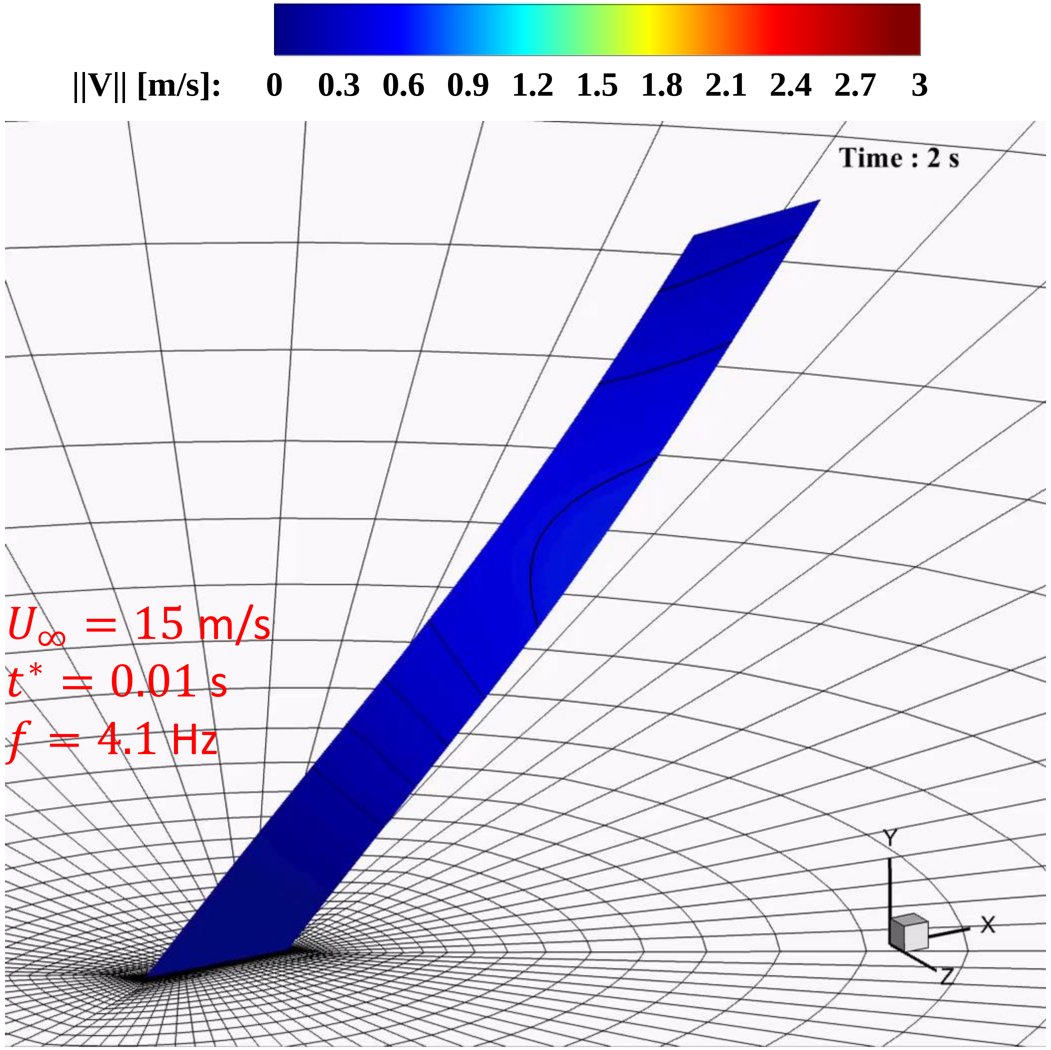
- Two perturbation amplitudes
- Two distinct limit cycles





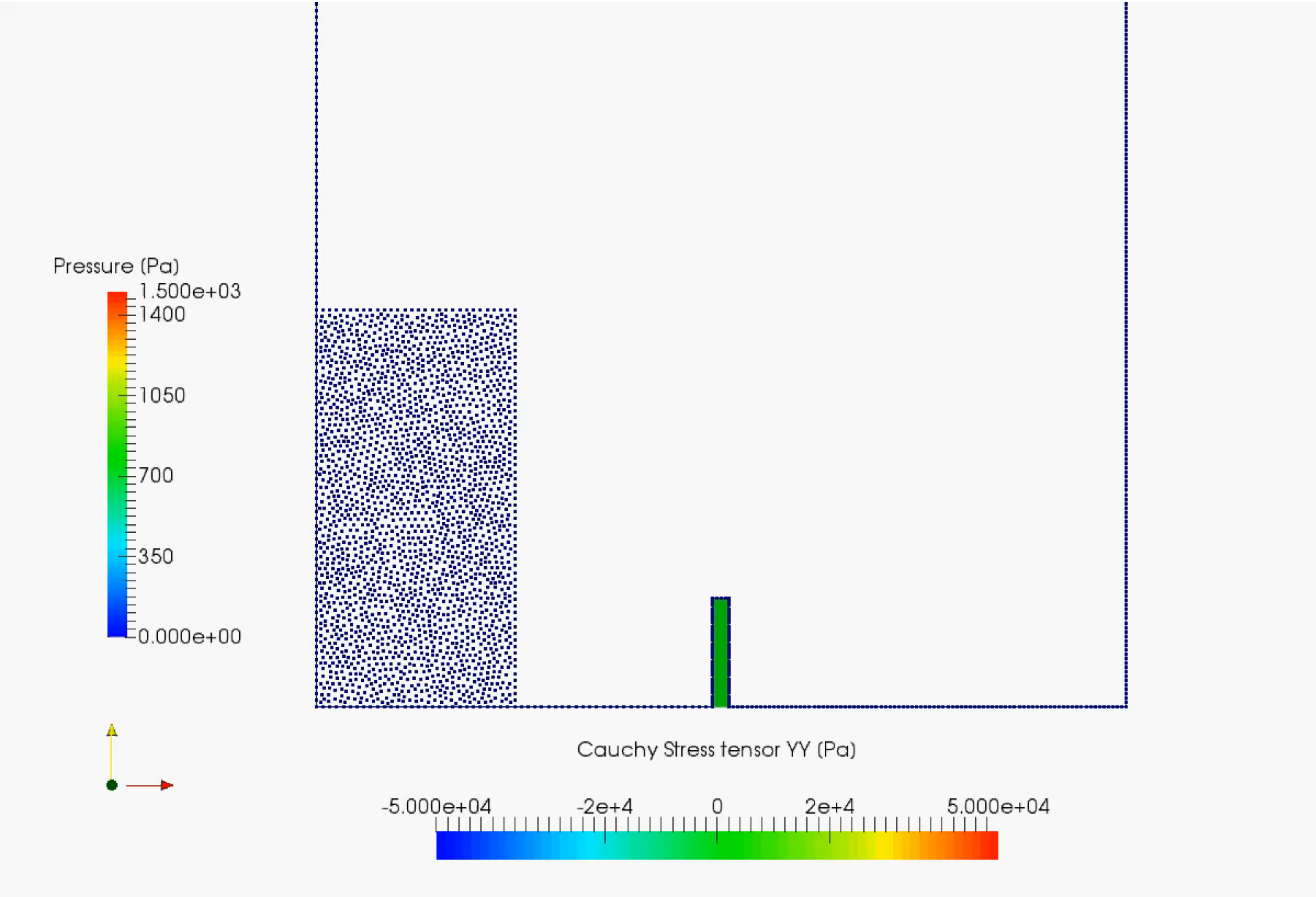
Cantilever swept flat wing

SU2+Metafor



Wind tunnel test under the same conditions

Dam break with flexible obstacle



- Incompressible free-surface flow computed with PFEM
- Large structural displacement

Conclusions

- Developed for research and design
- Interfacing tool for strong coupling of independent solvers
- High fidedility models for nonlinear FSI
- Flexible partitioned tool for large range of physics
- Validated on typical benchmarks

Acknowledgements

RÉGION WALLONNE

C.E.C.I

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aerospace**design**lab