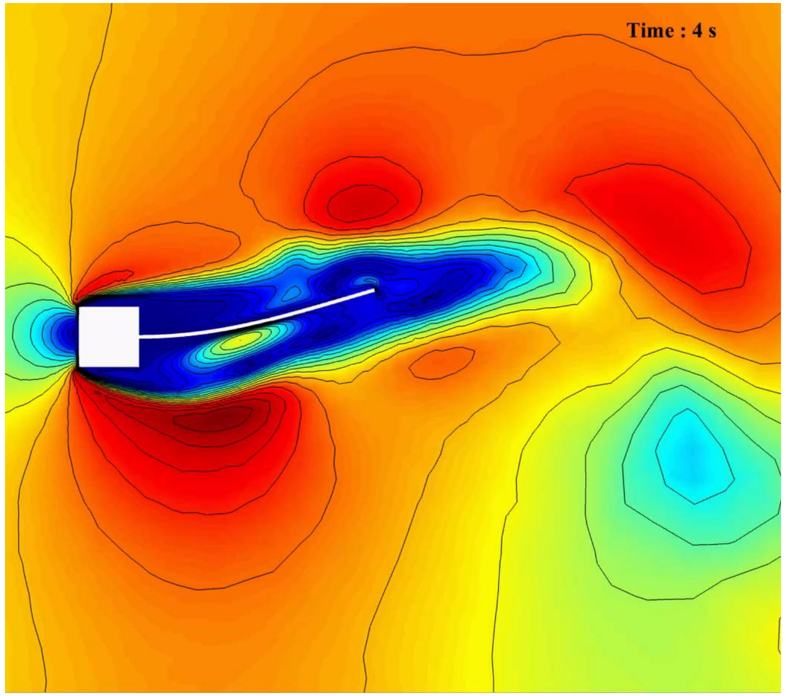
Efficient and flexible implementation of an interfacing Python-based tool for numerical simulations of fluid-structure interaction problems



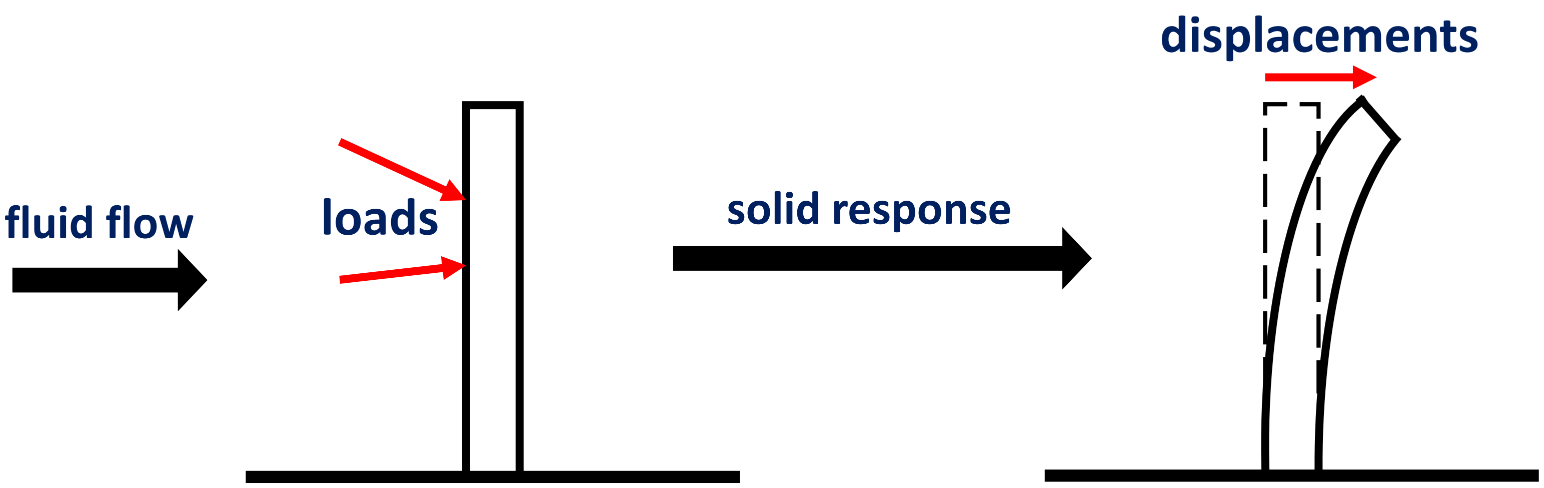
David **THOMAS**

PhD thesis defense
Liège, February 2021

LIÈGE université

Introduction

Fluid-structure interaction (FSI) ≔ structure interacting with a surrounding fluid



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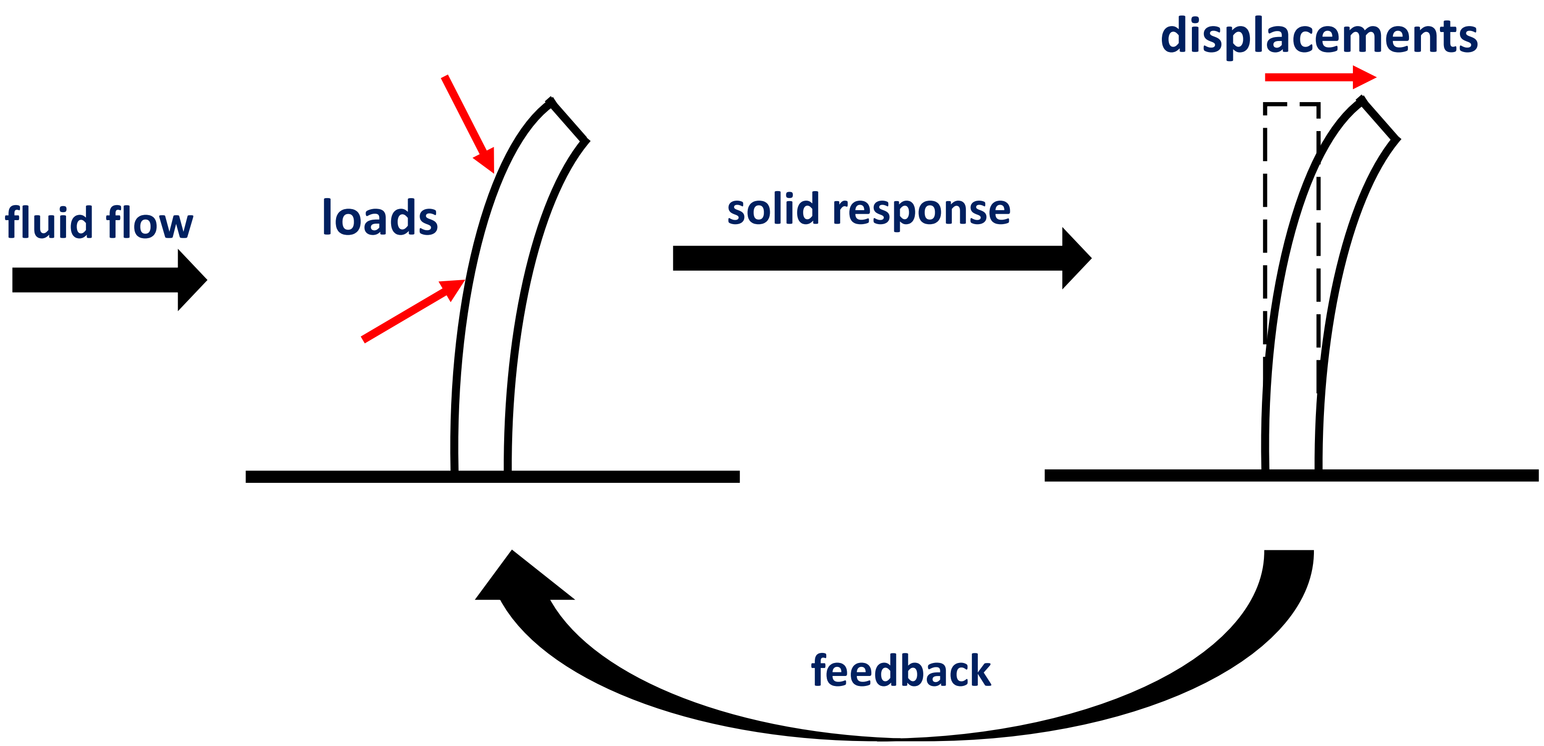

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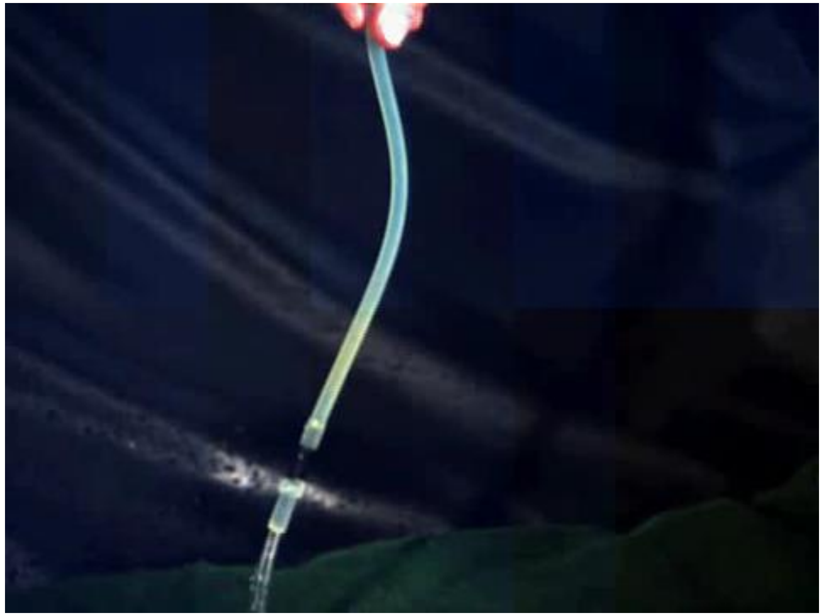

Garden hose instability

Can be reproduced at home

Context

credit Atmosphere

credit ESA – D. Ducros (illustration)

Context

credit Atmosphere

credit Donaldytong

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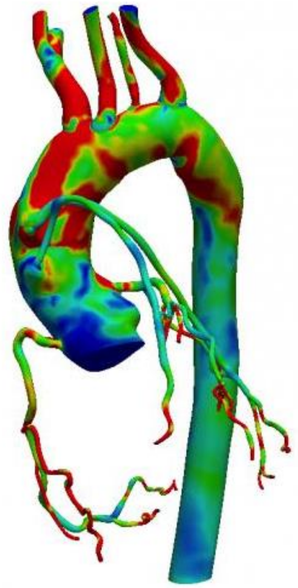
credit Gerrit Vyn

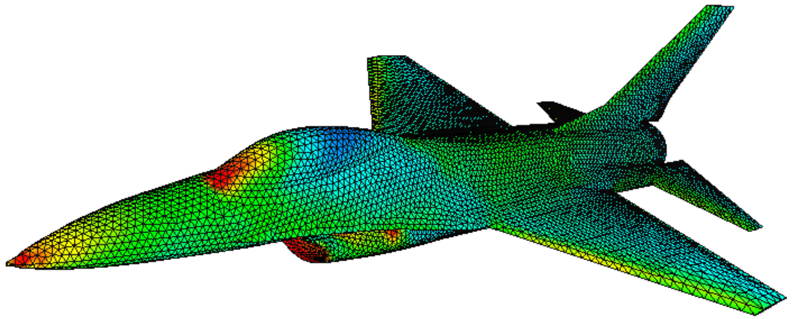


credit A. Marsden, Stanford University

FSI in engineering design and research

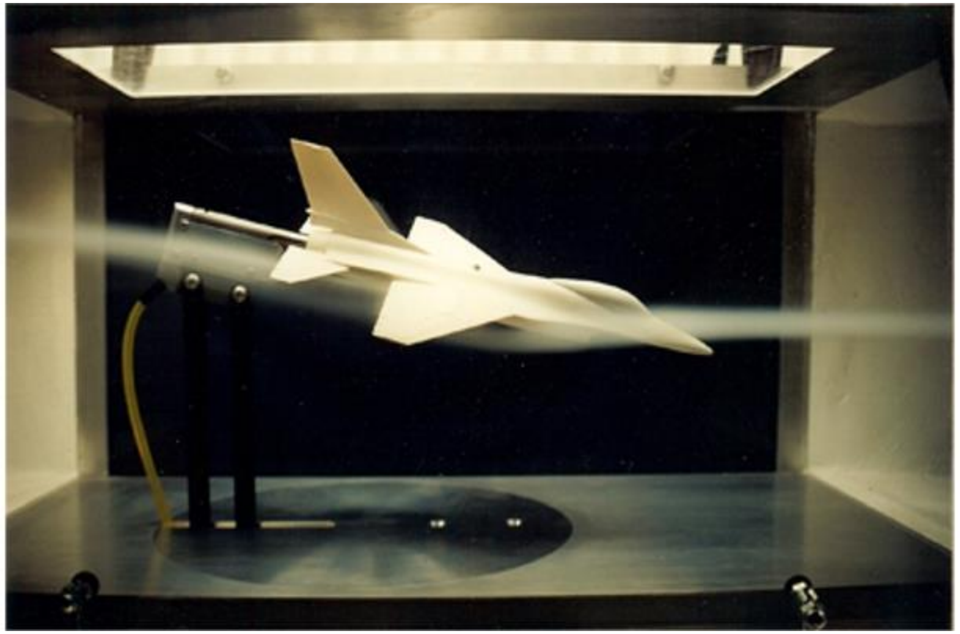
- Current design trend towards larger, slender, lighter structure (e.g. aircraft wings, wind turbine blades)
  ➔ FSI becomes more critical for **safe design**
- New research topics such as MAV* design, flapping flight and aeroelastic energy harvesting
  ➔ **understanding** of complex physics

Numerical/computational model



credit Aerosoft inc

Experimental model



credit aerolab

***MAV**: Micro Air Vehicles

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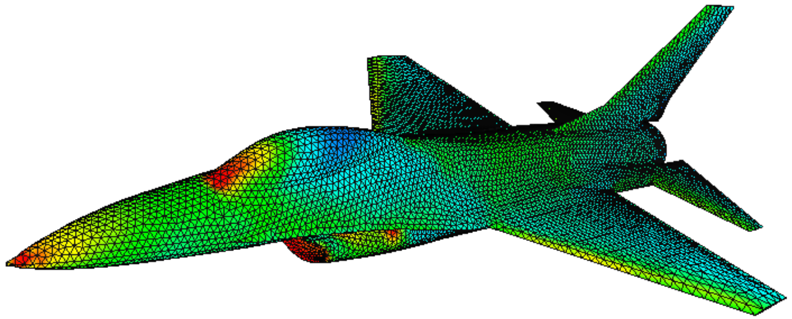

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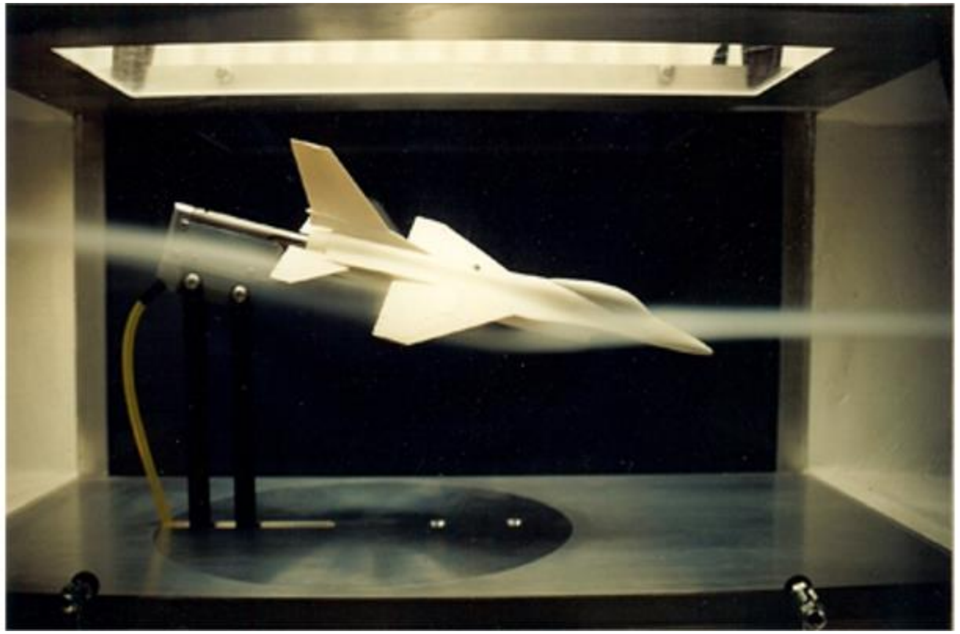
Model with **coupled physics** required

Experimental model



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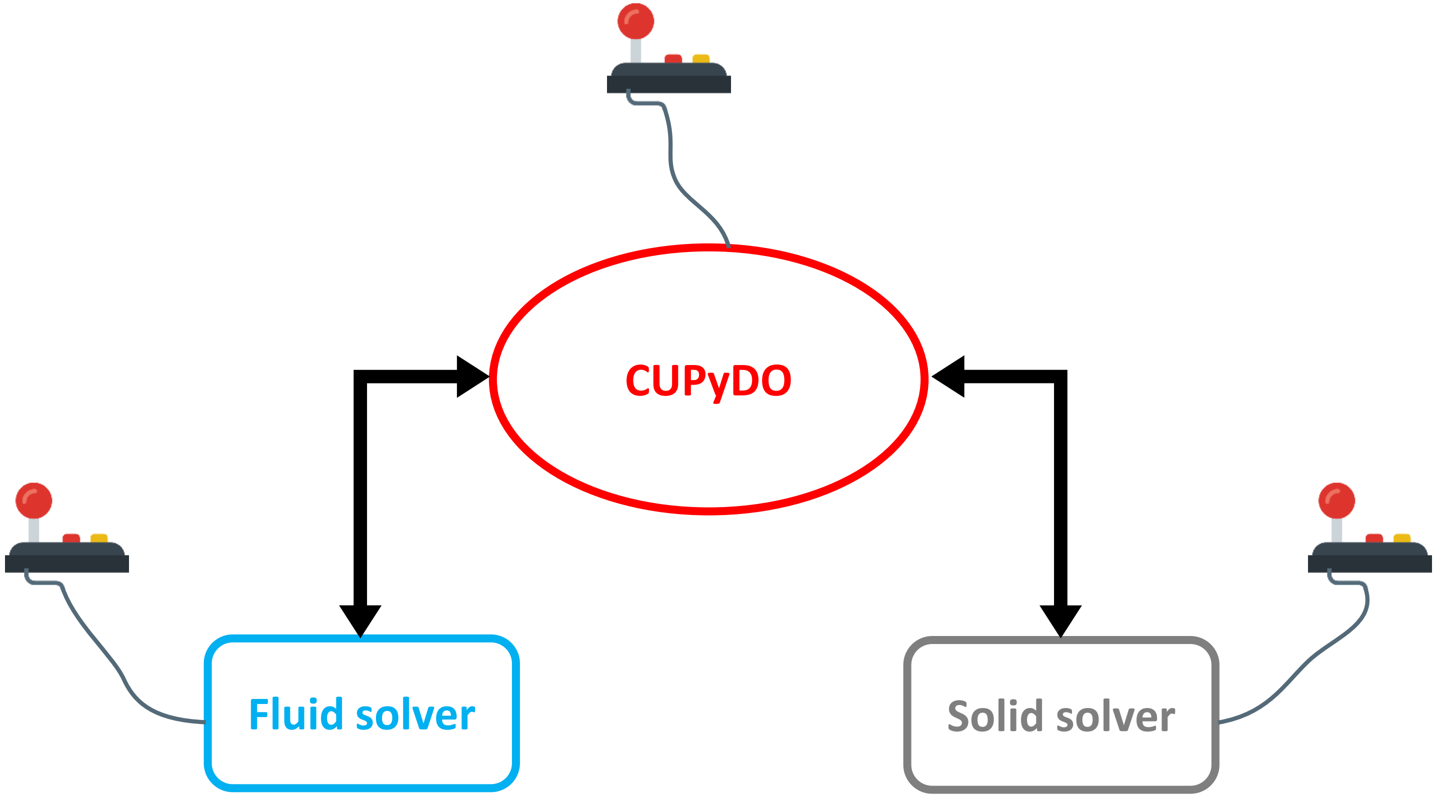
***MAV**: Micro Air Vehicles

Objectives



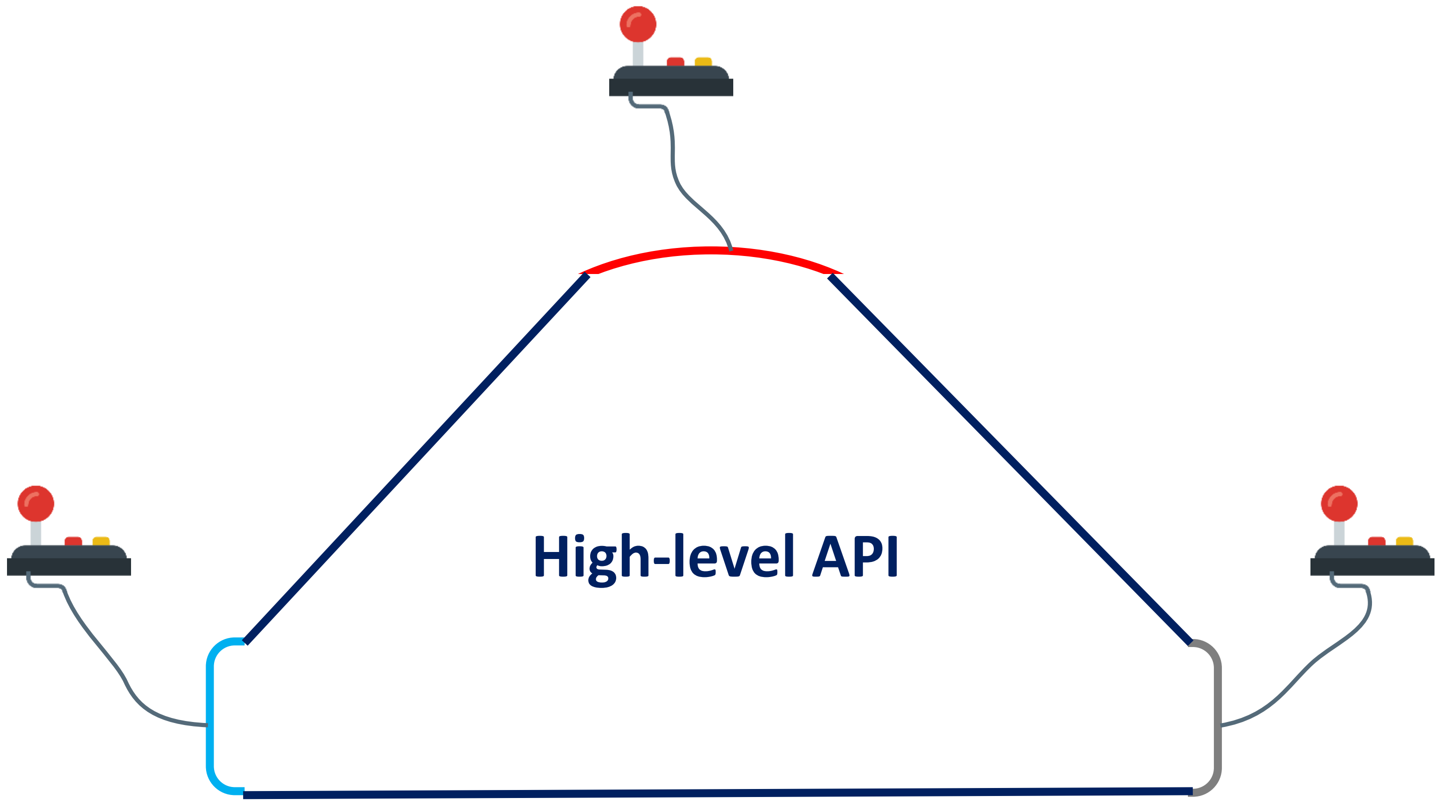
Development of the coupling tool *CUPyDO*

- **State-of-the-art** numerical algorithms
- Based on **Python wrapping** methodology
- **High-level** API*

- Flexibility, modularity, usability
- Minimal code intrusion

***API** : Application Programming Interface

Objectives



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***API** : Application Programming Interface

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PART I: The FSI problem

- Overview
- Mathematical description and numerical formulation

PART II: CUPyDO

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PART III: Verification and applications

- Verification test cases
- Aeroelastic study of a thin flat plate wing

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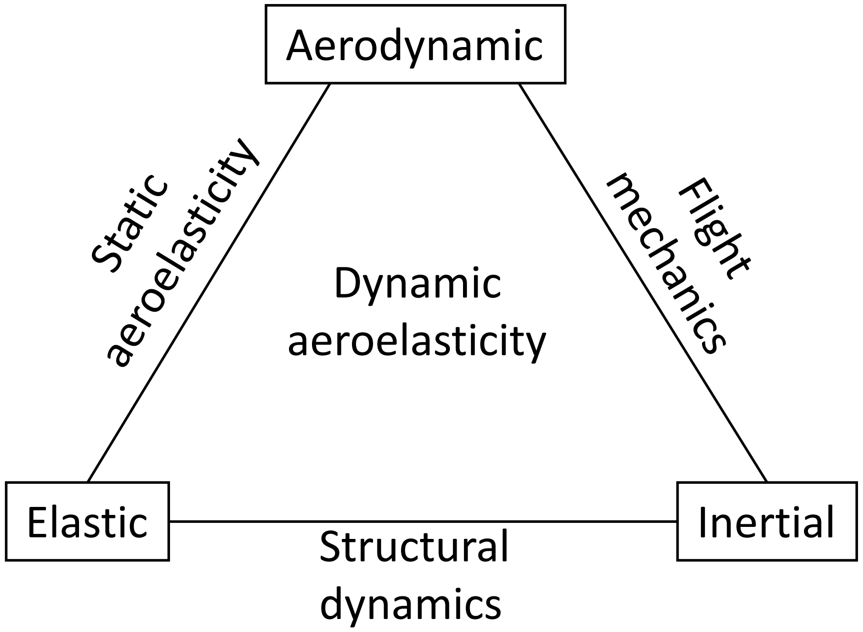
Collar’s triangle



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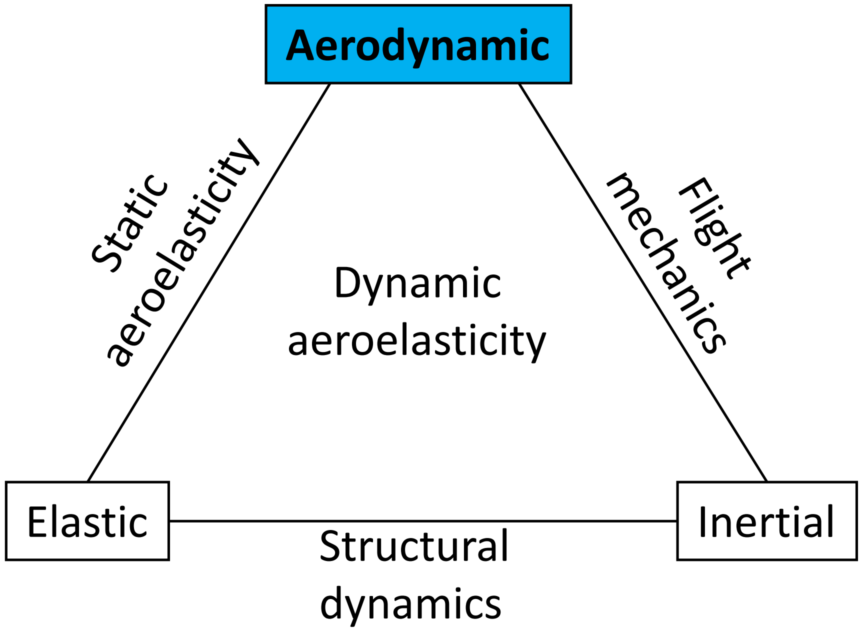

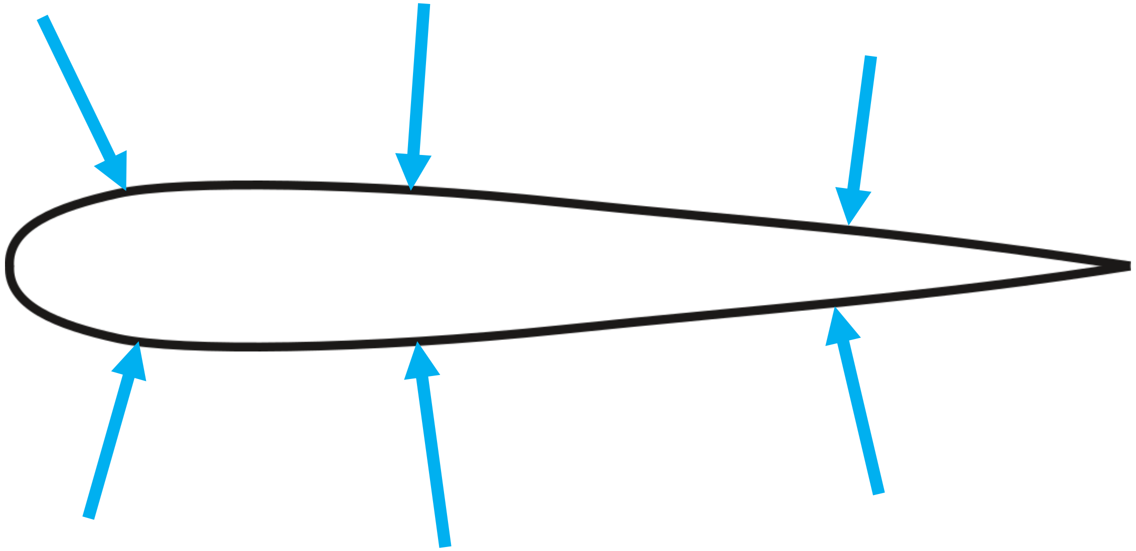

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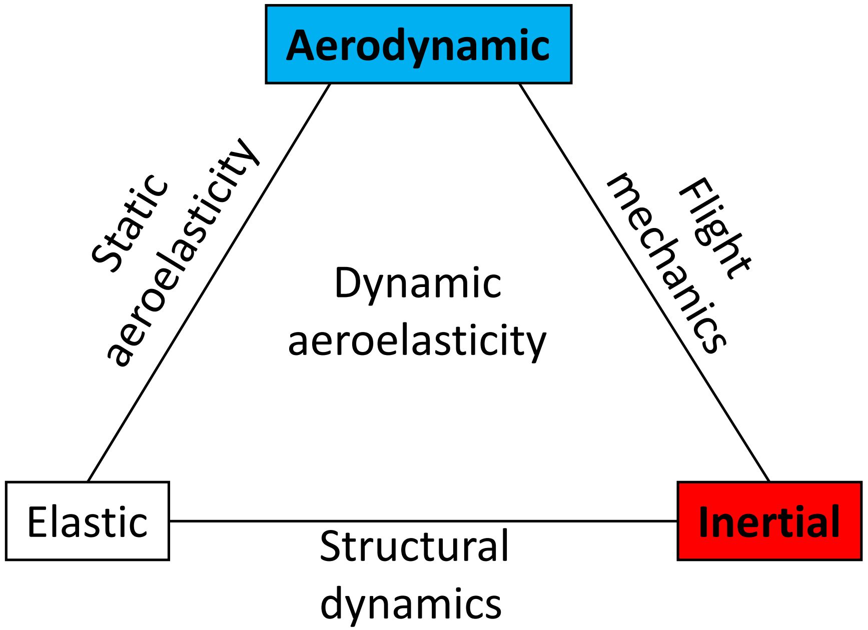

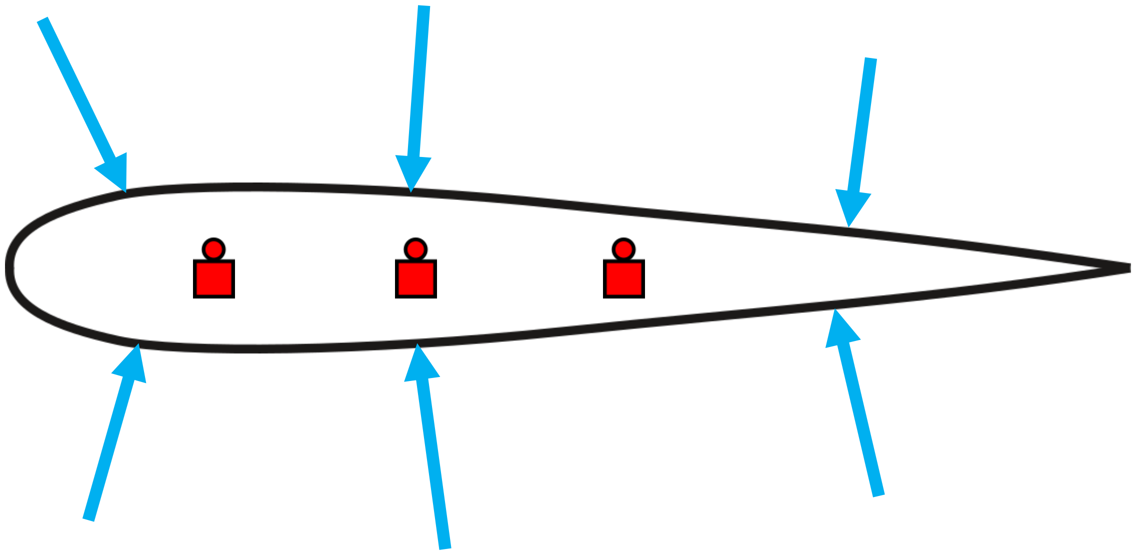

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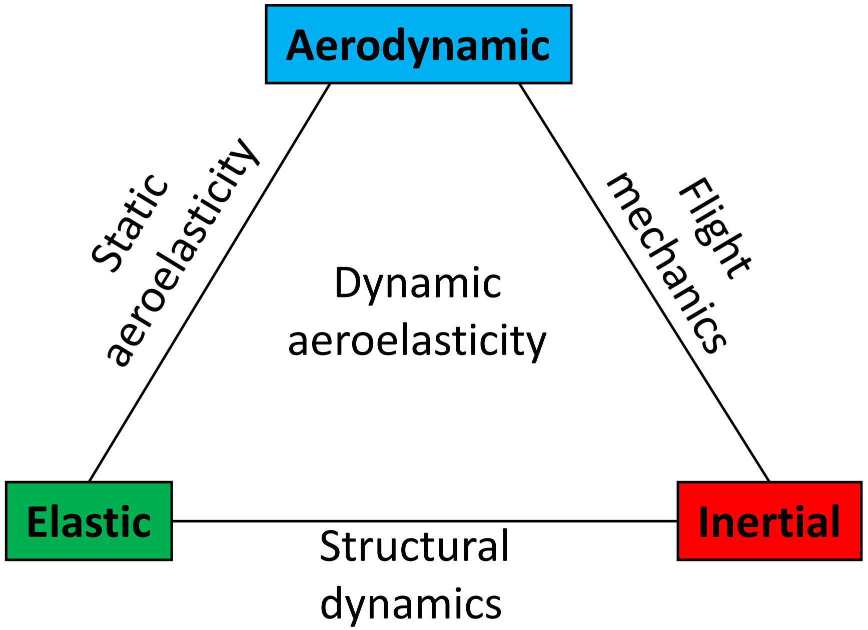
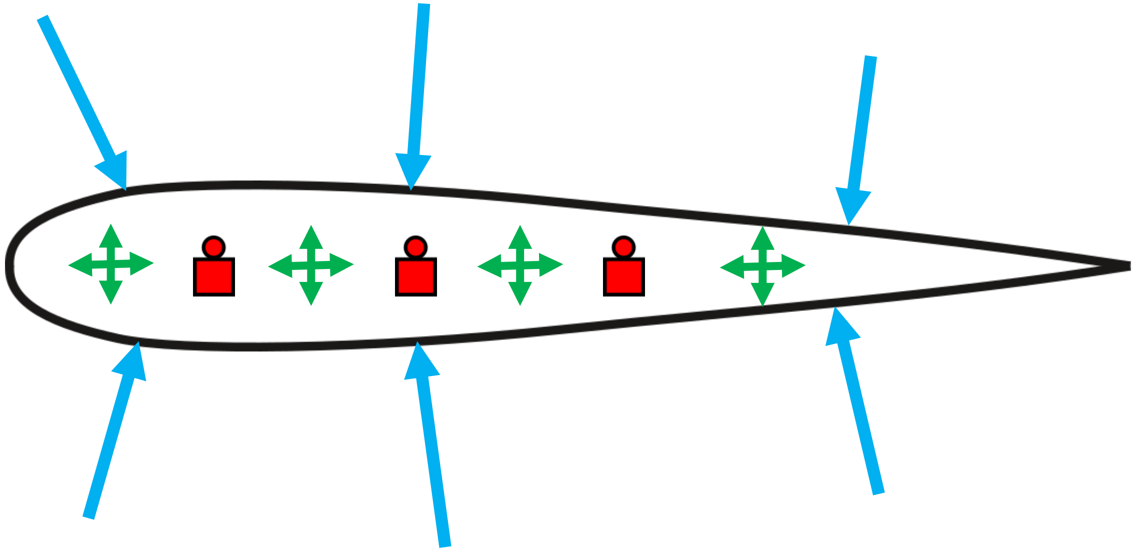
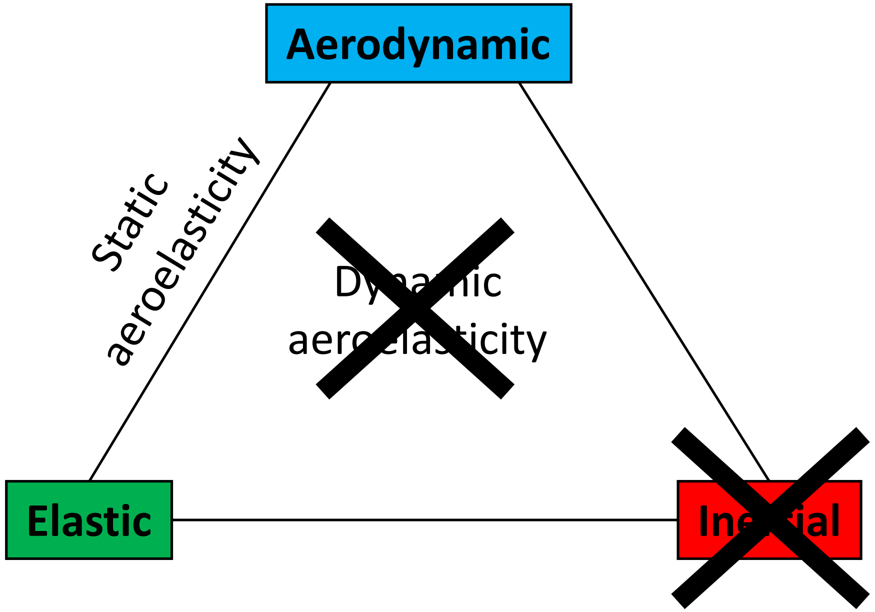




Static FSI (mechanical)

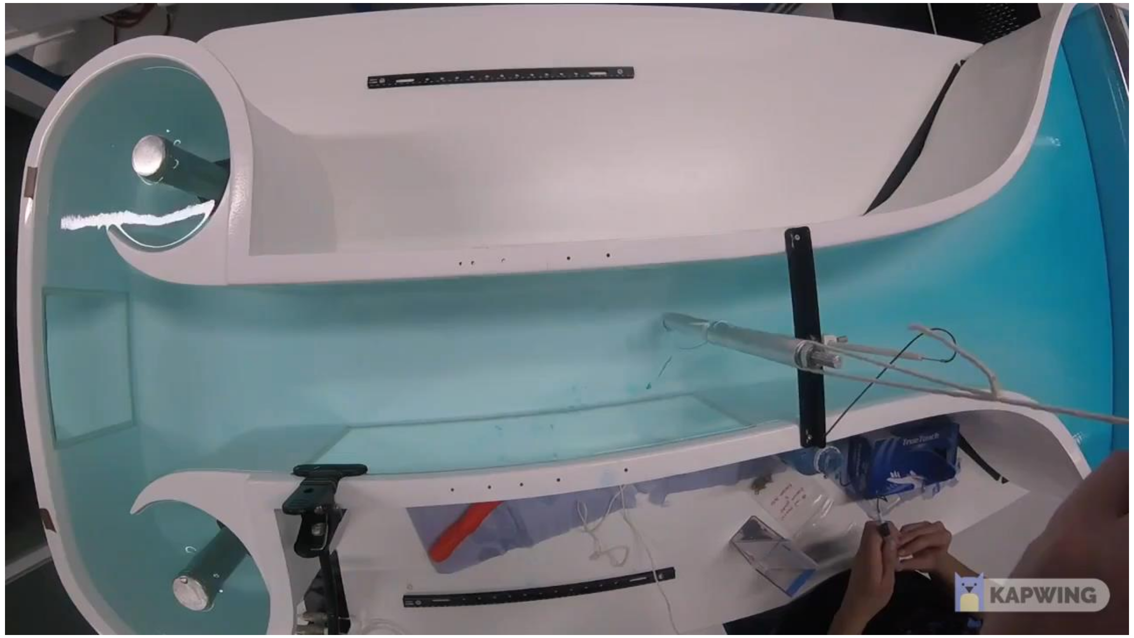


B-787 during take-off, wing tip deflection

Vortex-induced vibrations (VIV)

- Vortex shedding
  ➔Harmonic fluid loads at f_v
- Structure natural frequency f_s
- **Critical conditions** : $f_v \to f_s$
- Self-limited resonance

Examples: marine structures, bridges suspenders, towers, industrials chimneys



Experimental VIV of a cylinder in cross-flow

credit Dr Gabriel Weymouth, University of Southampton, 2018

Galloping

- No vortex shedding

- **Negative damping** of the **coupled system** above critical flow conditions
  ➔ **Instability** (1 mode)

Examples: power lines (transverse galloping) and bridge decks (torsional galloping)

Tacomas Narrows Bridge (WA), 7th Nov 1940

Flutter

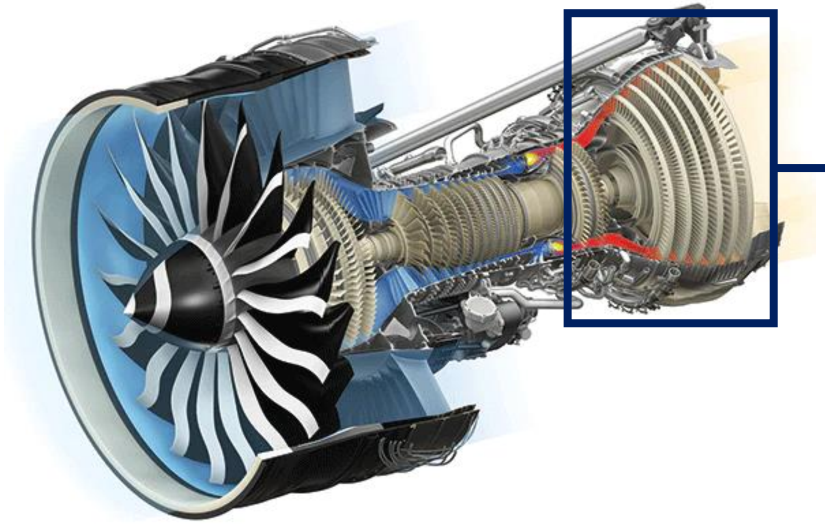
- Two structural modes interacting with each other due to the aerodynamics

- **Negative damping** of the **coupled system** above critical flow conditions
  ➔ **Instability**

Examples: aircraft lifting structures

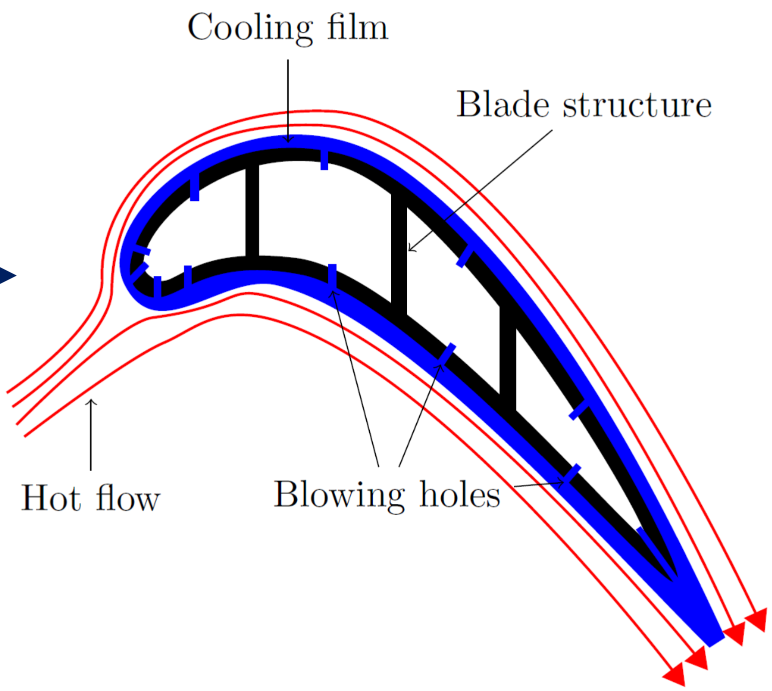
Piper PA-30 Twin Comanche during flight flutter test (NASA, 1966)

Thermal coupling: conjugate heat transfer (CHT)



GEnx turbofan

GE Aviation



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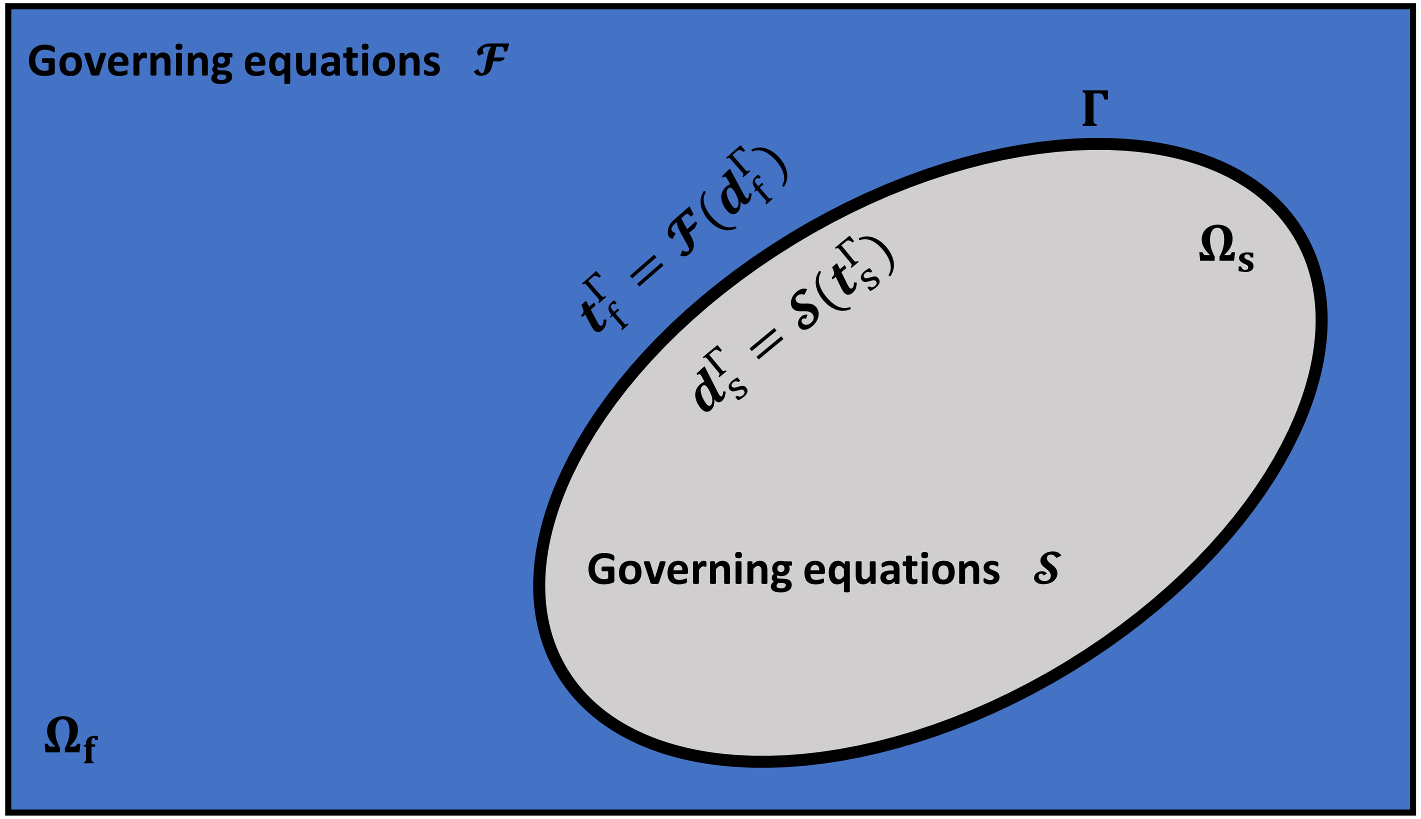
Partitioned model



Interface **loads :** $\boldsymbol{t}^\Gamma$
displacements : $\boldsymbol{d}^\Gamma$

Governing equations

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

+

Coupling conditions

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

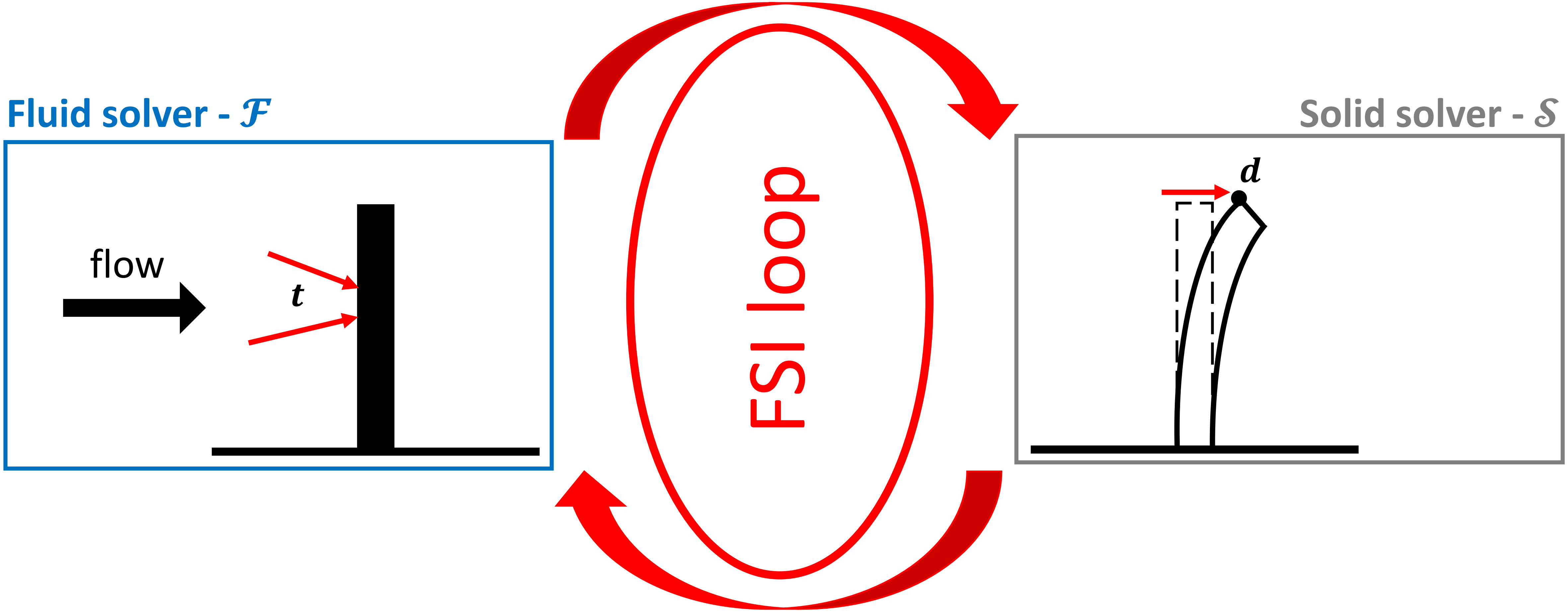
=

Fixed-point formulation

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

Partitioned two-way coupling

Fluid **loads** transfered to the solid surface as structural loads



Displacements transfered to the fluid as new wall boundary conditions

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Development of a coupling framework

Key requirements

Coupling tool - WANTED

- Coupling flexibility
- Minimal intrusiveness
- Usability
- Numerical stability
- Minimize CPU cost overhead
- Do not degrade parallel scalability

Coupled solvers – MUST HAVE

- Re-compute the same time step(s) with different interface conditions
- Interface data must be exposed and editable
- Dynamic mesh treatment

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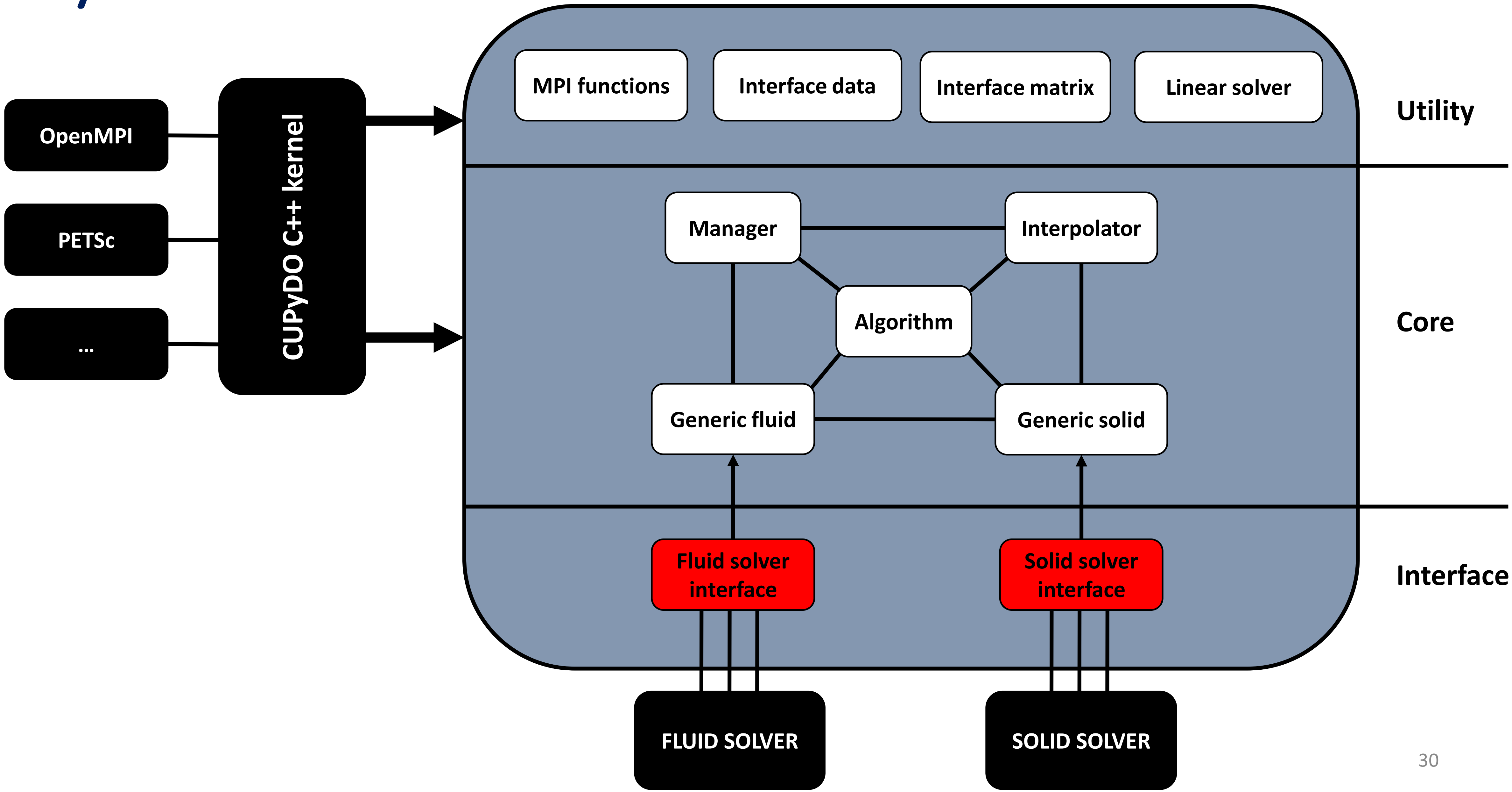
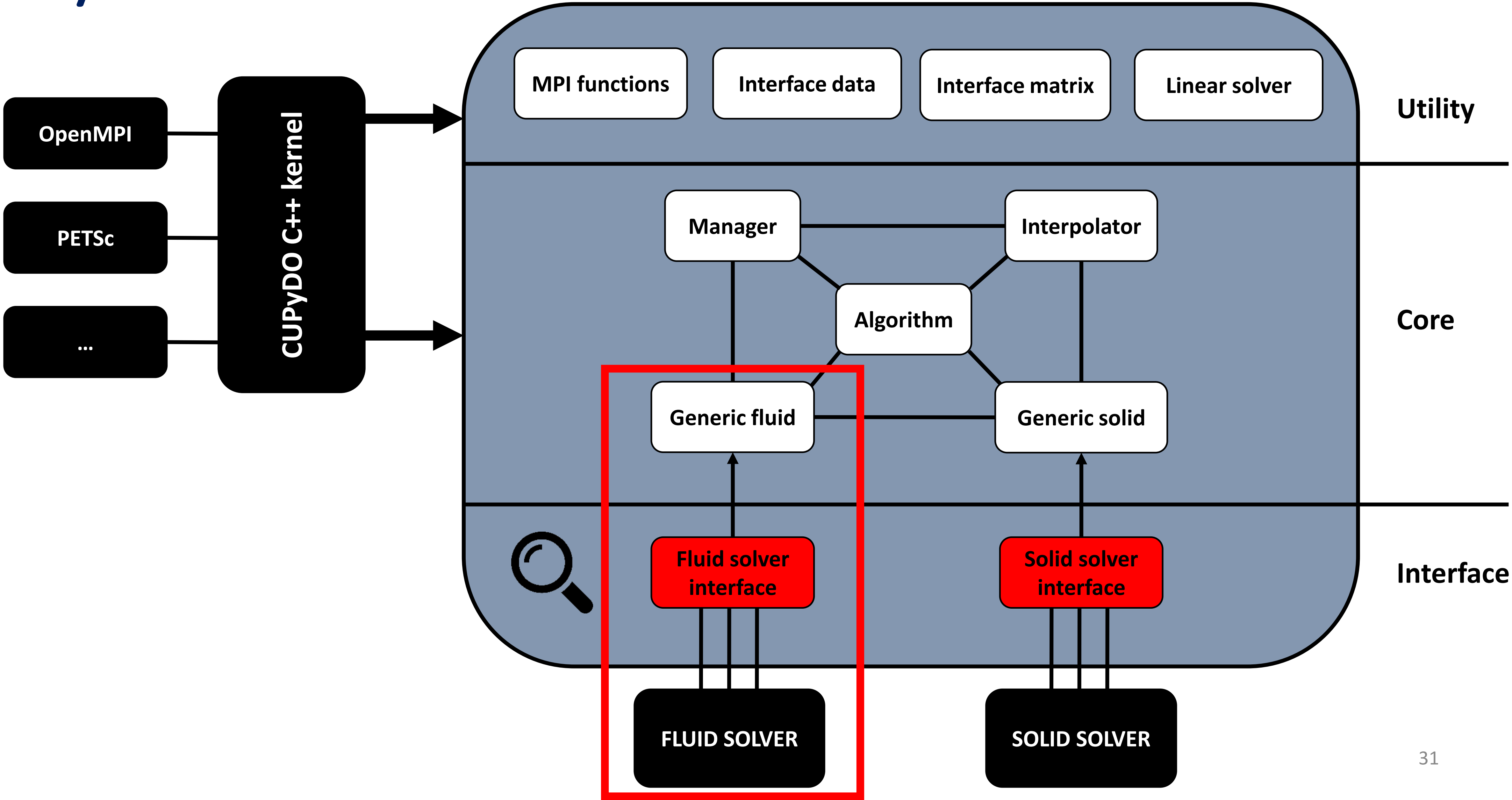
There is no magic, code adaption is still required… but can be minimized with no drastic change of the native data structure and architecture

CUPyDO architecture



CUPyDO architecture



Solver interfacing

Python wrapper

ToyObject.h (C++)

```
class ToyObject
{
   double _data;
public:
   ToyObject() { _data = 0.0;}
   ~ToyObject() {}
   void setData(double data) {_data = data;}
   double getData() const { return _data;}
};
```

swig_config.i

SWIG*

ToyModule.py

***Python wrapper** of ToyObject*

calls

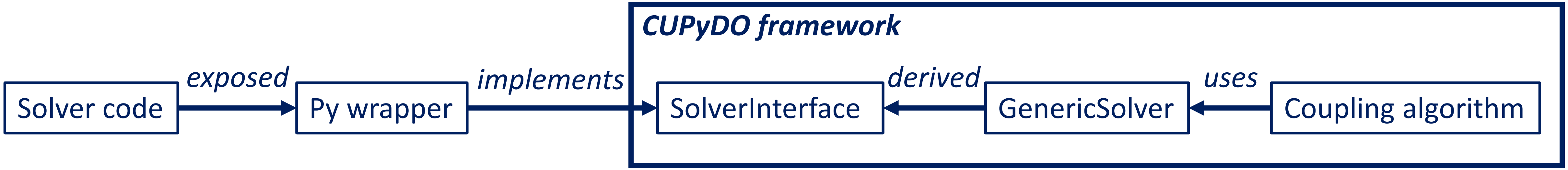
ToyExample.py

```
import ToyModule

my_toy = ToyModule.ToyObject()
my_toy.setData(100.0)
data = my_toy.getData()
```

***SWIG** : Simplified Wrapper and Interface Generator

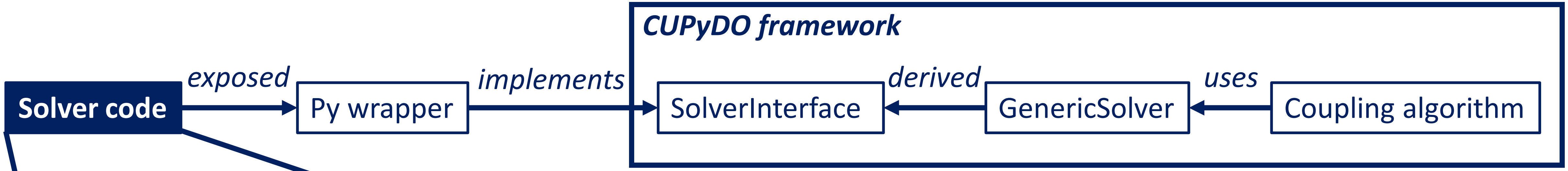
Solver interfacing

Compatibility chain



Solver interfacing

Compatibility chain

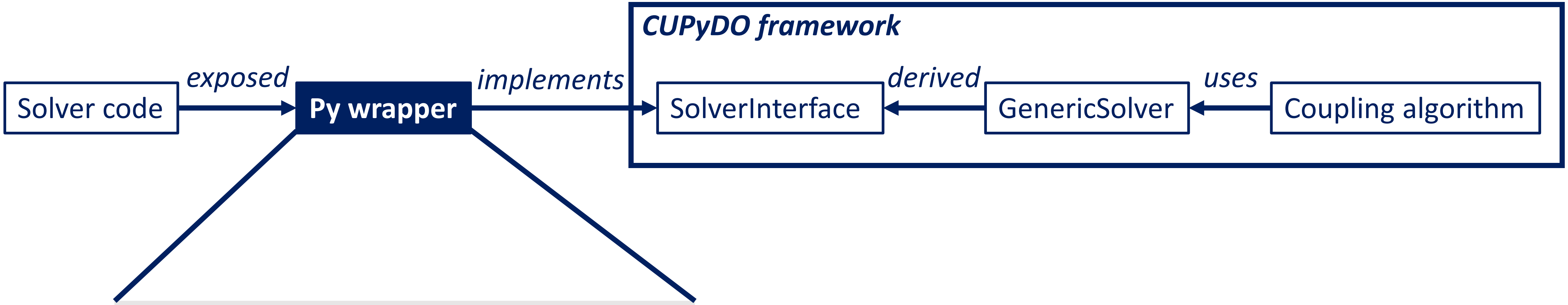


- Main source code
- Contains full **solver implementation**
- **Proper** language (e.g. C++) and data structure

Zero CUPyDO routine introduced in the source code

Solver interfacing

Compatibility chain

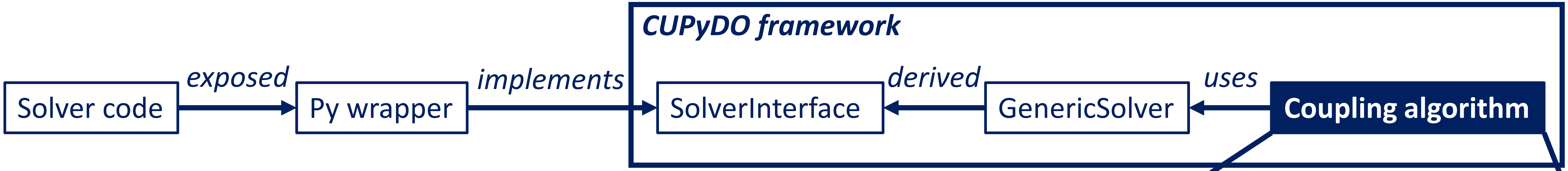


- **Exposes** the source code to Python
- **Automatically** generated by SWIG
- **Requires minimal** interfacing capabilities

Flexibility of Python + efficiency of the C++

Solver interfacing

Compatibility chain

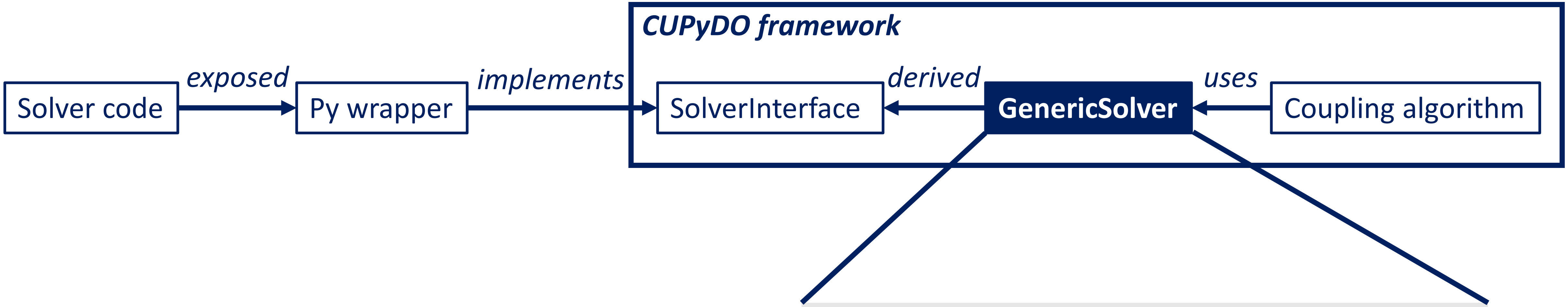


- The coupled solvers are seen as a **black-box tools**
- Interacts with the solvers through the **generic members** of *GenericSolver*

Eases algorithm customization

Solver interfacing

Compatibility chain



Compatibility with coupling algorithm is ensured

- **Generic representation** of fluid or solid solver
- Defines **minimal interfacing capabilities** used by the coupling algorithm

Solver interfacing

Compatibility chain

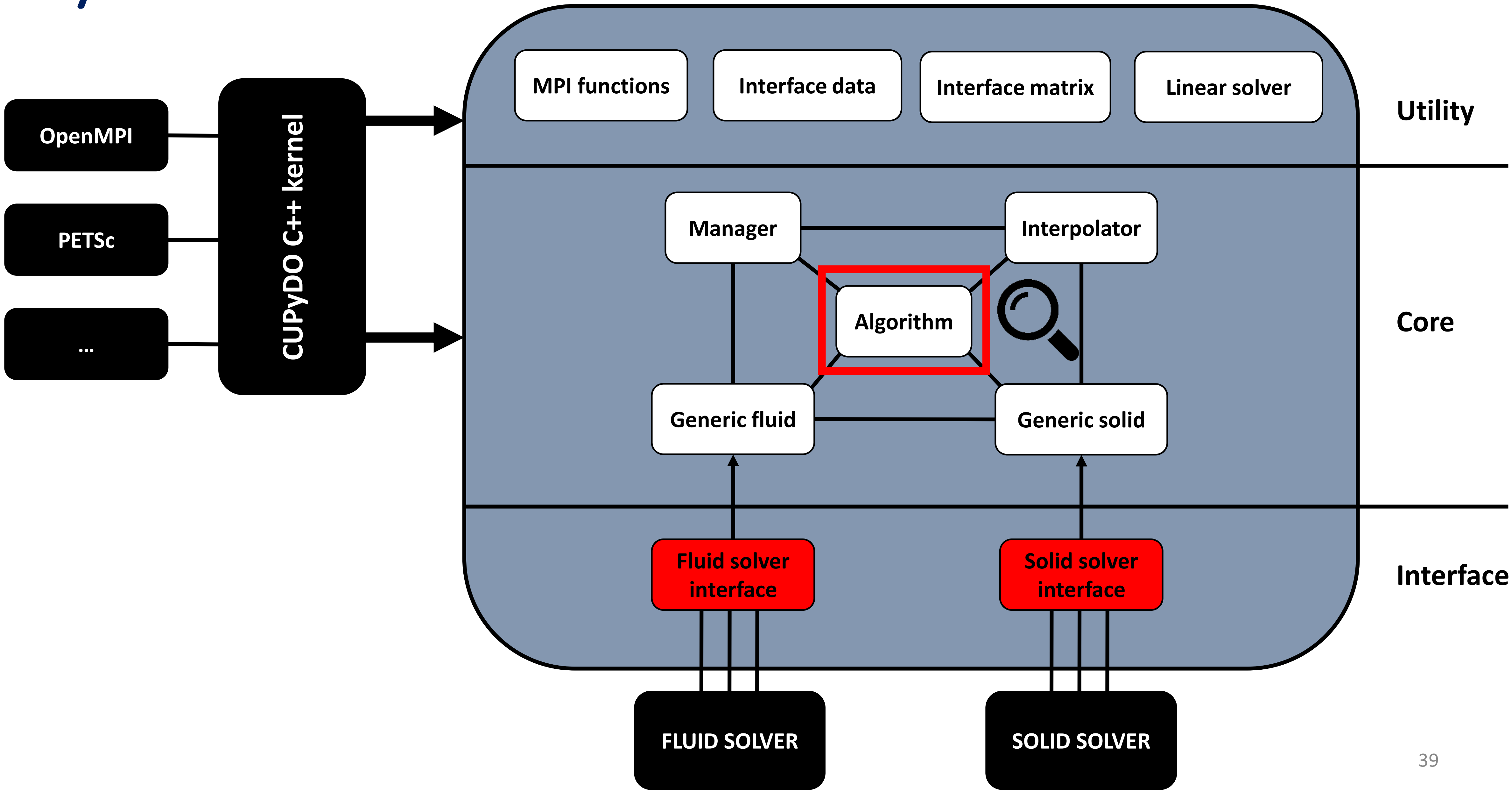

```
import FluidSolver
Import GenericFluidSolver

class FluidSolverInterface(GenericFluidSolver):
 def __init__(self):
  self,solver = FluidSolver.FluidSolver()
  self.solver.readMesh()
  self.solver.buildDataStructure()

 def run_time_step(self):
  self.solver.advanceInTime()

 def get_loads(self):
  self.solver.getLoads()
```

(Schematic example)

- A **unique** Python class for each compatible solver
- **Imports** solver wrapper
- **Inherits** from *GenericSolver*
- **Overloads** the members of *GenericSolver* **with solver wrapper**

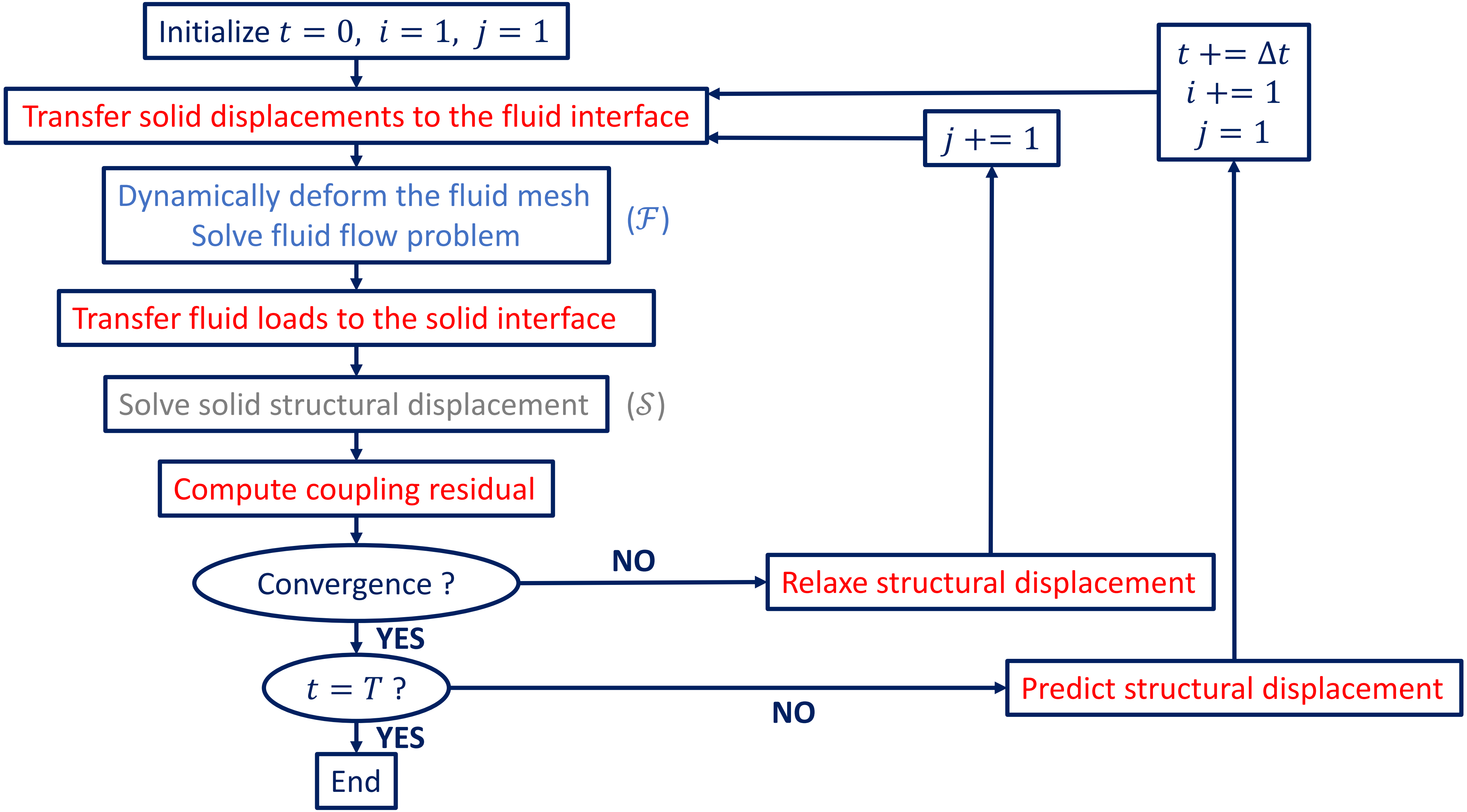
Releases constraints on the solver Py wrapper (not strictly FSI-oriented)

CUPyDO architecture



Strong coupling algorithm

Block Gauss-Seidel with relaxation

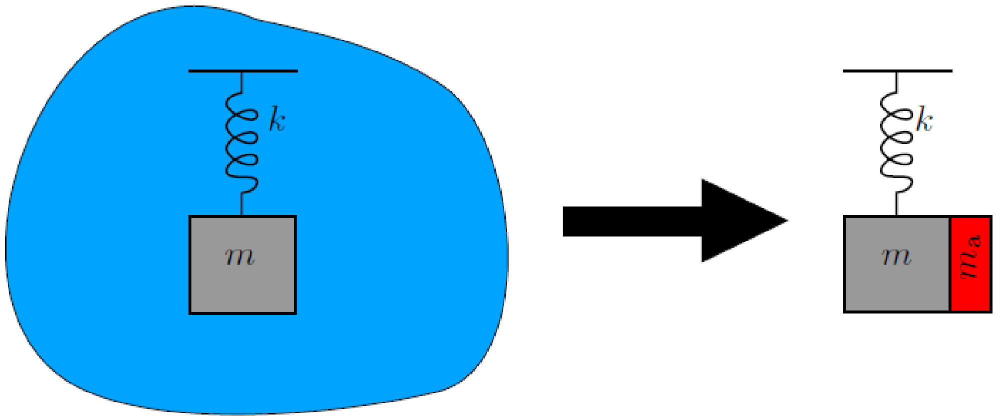


Stability of the mechanical coupling

Added-mass

- Fluid-solid interaction with **strong feedback**
  ➔ **numerical instability** of the iterative coupling
- Usually referred to as **added-mass effect**

Added mass ≈ inertia of the fluid that has to be displaced by the solid



After stability analysis on simple FSI systems, **instability appears when Ma $\rightarrow$ 1$^+$**

$$\mathrm{Ma} = \frac{\rho_s}{\rho_f}$$

Stability of the mechanical coupling

Stabilization techniques

Relaxation

$$\boldsymbol{d}_j^\Gamma = \boldsymbol{d}_{j-1}^\Gamma + \omega_j \boldsymbol{r}_j^\Gamma$$

coupling residual $\boldsymbol{r}_j^\Gamma = \widetilde{\boldsymbol{d}}_j^\Gamma - \boldsymbol{d}_{j-1}^\Gamma$

relaxation factor $0 < \omega \leq 1$

- Fixed
- Dynamic (Aitken's method)

Newton-based (IQN-ILS)

(implemented by M.L. Cerquaglia)

$$\boldsymbol{d}_{j+1}^\Gamma = \boldsymbol{d}_j^\Gamma + \Delta \boldsymbol{d}_j$$

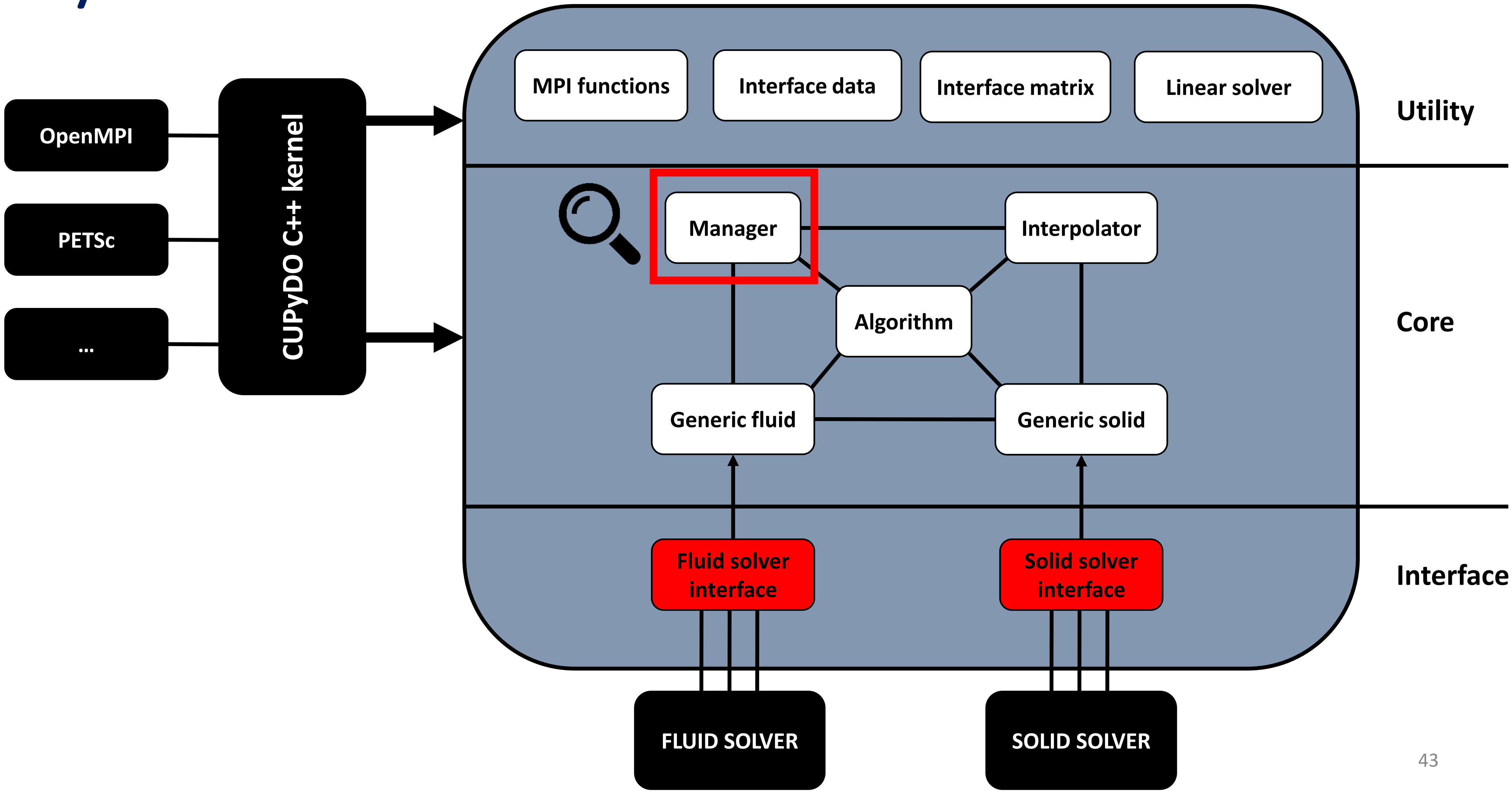
$$\Delta \boldsymbol{d}_j = -\left[\frac{\partial \boldsymbol{r}}{\partial \boldsymbol{d}}\right]_j^{-1} \boldsymbol{r}_j^\Gamma$$

approximated by solving **least-square** problem formed by the successive **outputs** of the solid solver

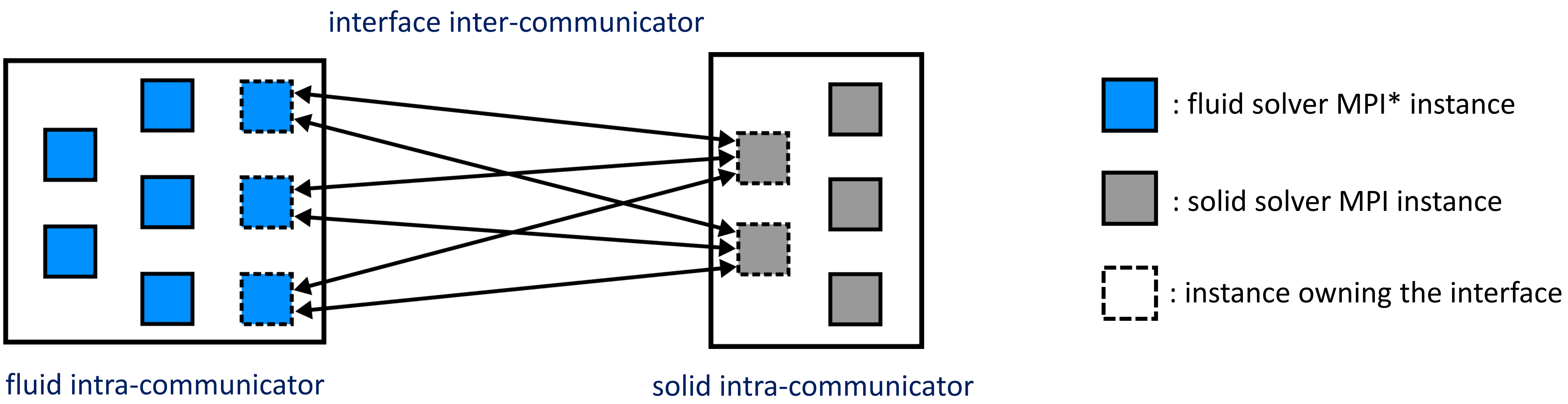
Only requires the basic output of the solid computation

j ≔ FSI iteration

CUPyDO architecture



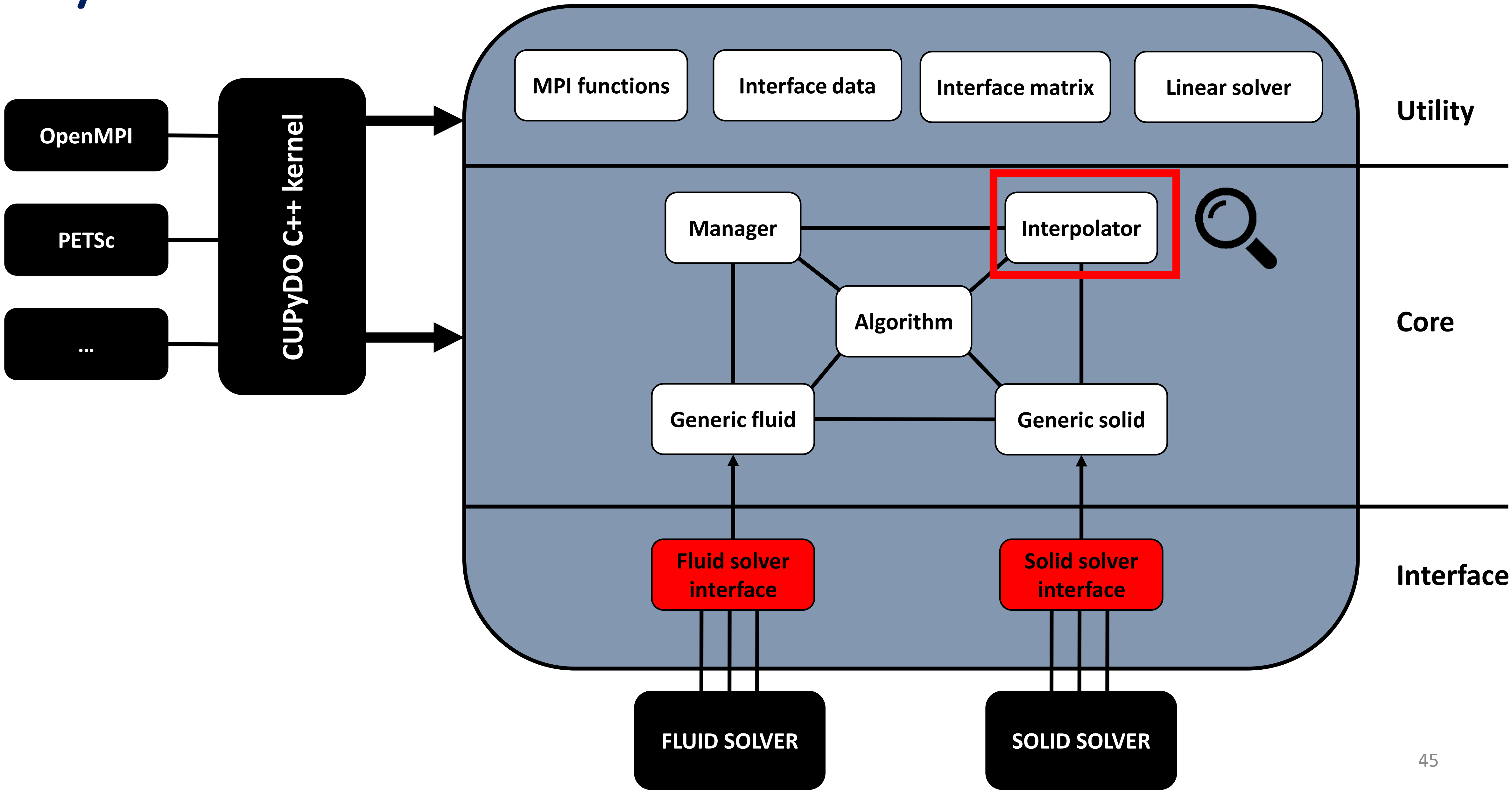
Coupling partitioned (MPI) solvers



- Distinct communicators could be created
- The coupled solvers must accept to run on **dedicated communicators** (not available !)
- Currently, ***MPI_COMM_WORLD*** is used for inter- and intra-communications

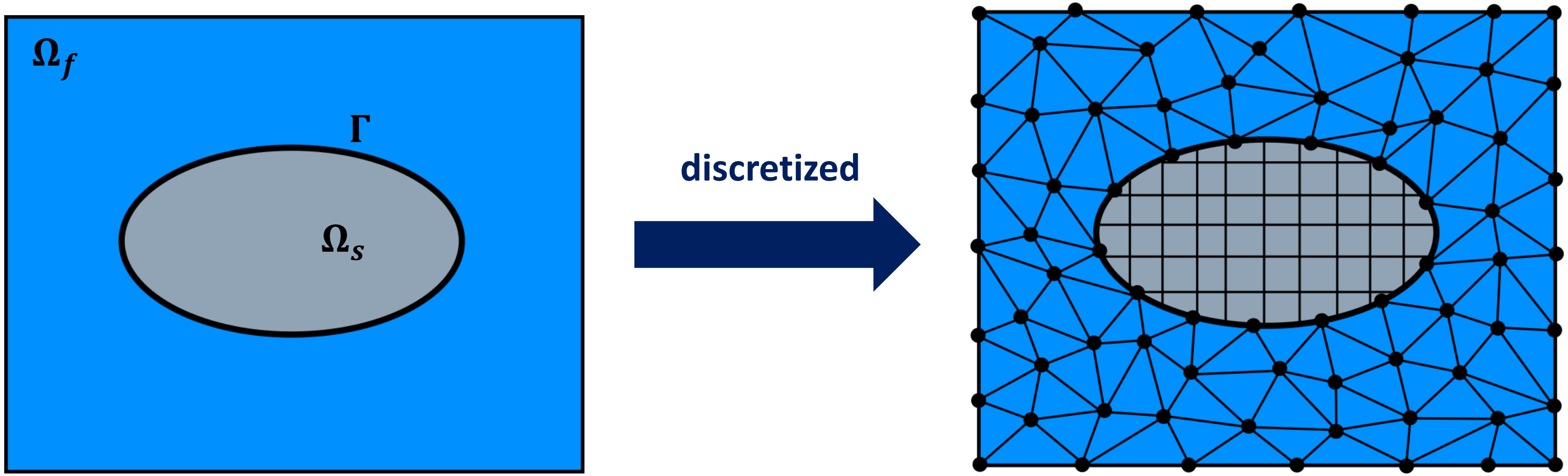
***MPI** : Message Passing Interface

CUPyDO architecture



Interface treatment

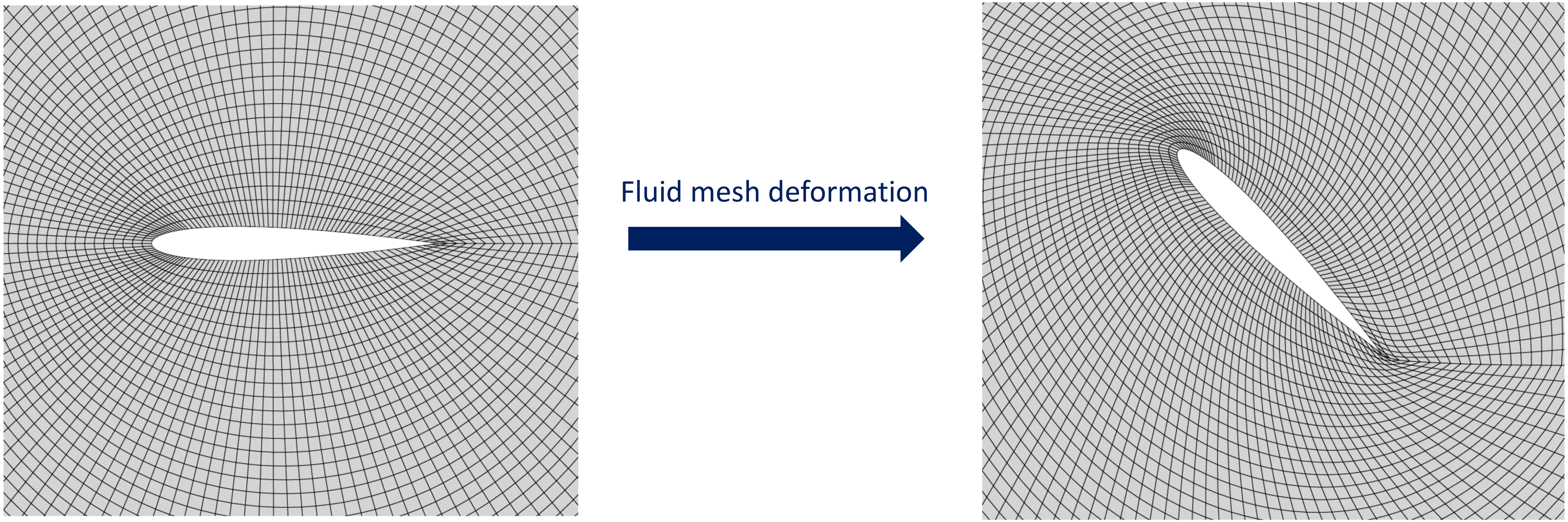
Interface tracking



- Interface **data exchange** at the **interface nodes** of each mesh
- **Interpolation** of interface data for non-matching discretization
- **Dynamic fluid mesh** that tracks the solid motion

Interface treatment

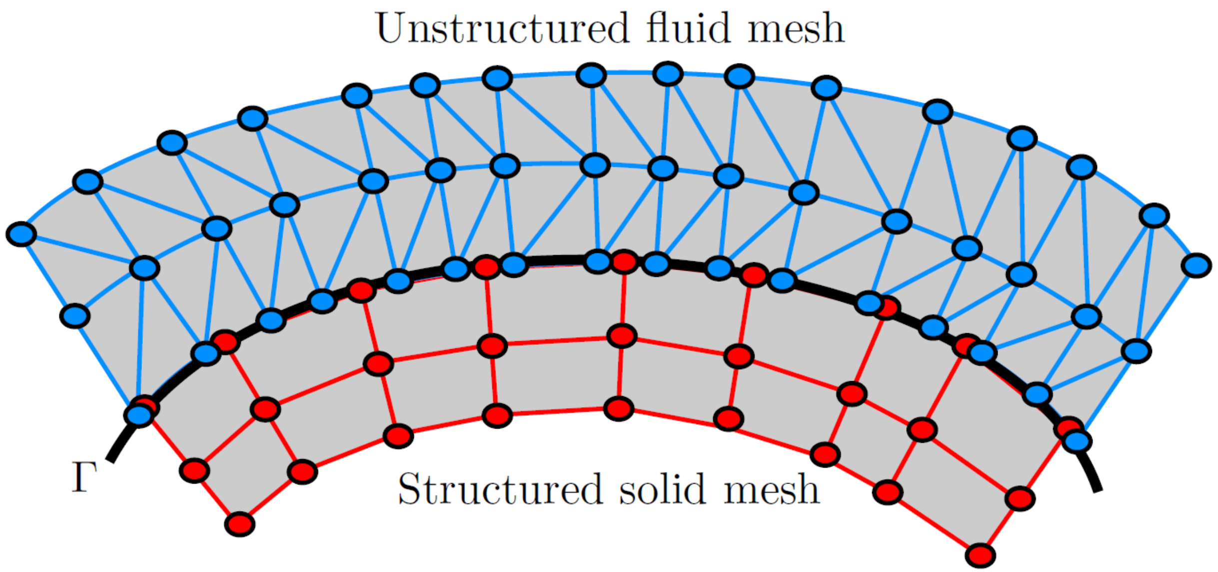
Interface tracking



+ Arbitrary Lagrangian-Eulerian (ALE)

Interface mesh treatment

Non-matching interface discretization



$$\boldsymbol{d}_{\mathrm{f}}^{\Gamma} = \mathbf{H}\, \boldsymbol{d}_{\mathrm{s}}^{\Gamma}$$

conservative $\boldsymbol{t}_{\mathrm{s}}^{\Gamma} = \mathbf{H}^{T}\, \boldsymbol{t}_{\mathrm{f}}^{\Gamma}$ **or** $\boldsymbol{t}_{\mathrm{s}}^{\Gamma} = \mathbf{G}\, \boldsymbol{t}_{\mathrm{f}}^{\Gamma}$ **consistent**

Interface mesh treatment

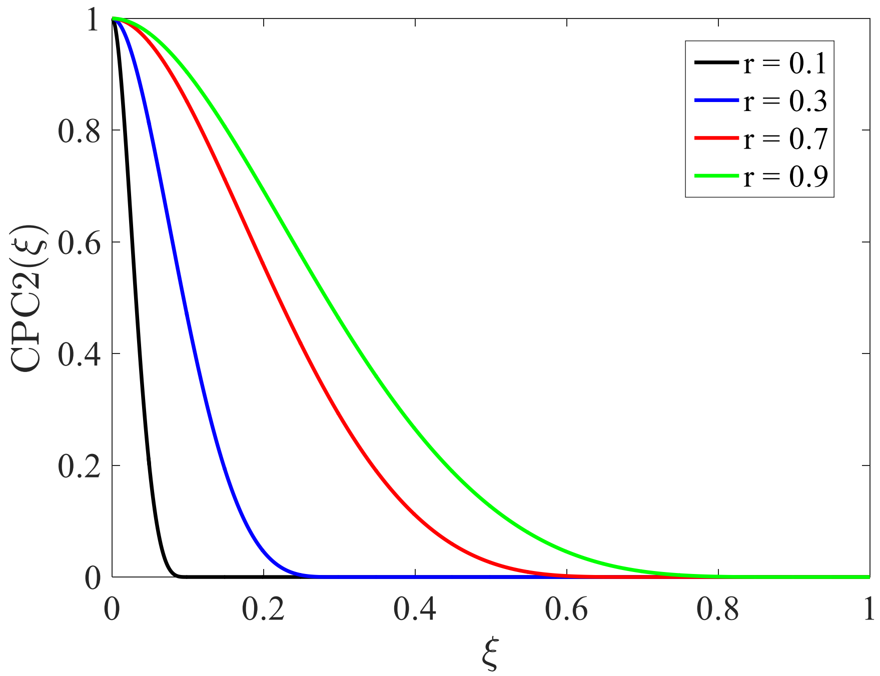
Mapping with Radial Basis Functions (RBF)

Only node coordinates and distance computation

$$w(\boldsymbol{x}) = \sum_{k=1}^{N} \alpha_k \phi(\underline{\|\boldsymbol{x} - \boldsymbol{x}_k\|}) + p(\boldsymbol{x})$$

Linear polynomial $\beta_0 + \beta_1 x + \beta_2 y + \beta_3 z$

Global support	$\|\boldsymbol{x}\|^2 \log\|\boldsymbol{x}\|$	(TPS)
Local support	$(1-\xi)_+^4\,(4\xi+1)$ with $\xi = \frac{\|\boldsymbol{x}\|}{r}$	(CPC2)



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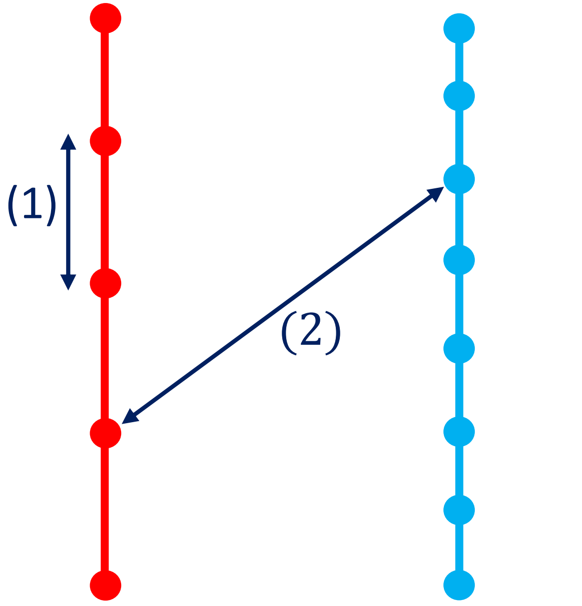
Step 1: compute $\boldsymbol{\alpha}_k$ and $\boldsymbol{\beta}_i$
- Impose exact recovery at donor nodes
- Linear system to solve

$$\begin{bmatrix}\boldsymbol{\alpha}\\ \boldsymbol{\beta}\end{bmatrix} = \mathbf{A}^{-1}\begin{bmatrix}\boldsymbol{d}_S^{\Gamma}\\ \mathbf{0}\end{bmatrix}$$

Step 2: interpolate on target
- Use the computed coefficients

$$\boldsymbol{d}_f^{\Gamma} = \mathbf{B}\begin{bmatrix}\boldsymbol{\alpha}\\ \boldsymbol{\beta}\end{bmatrix}$$

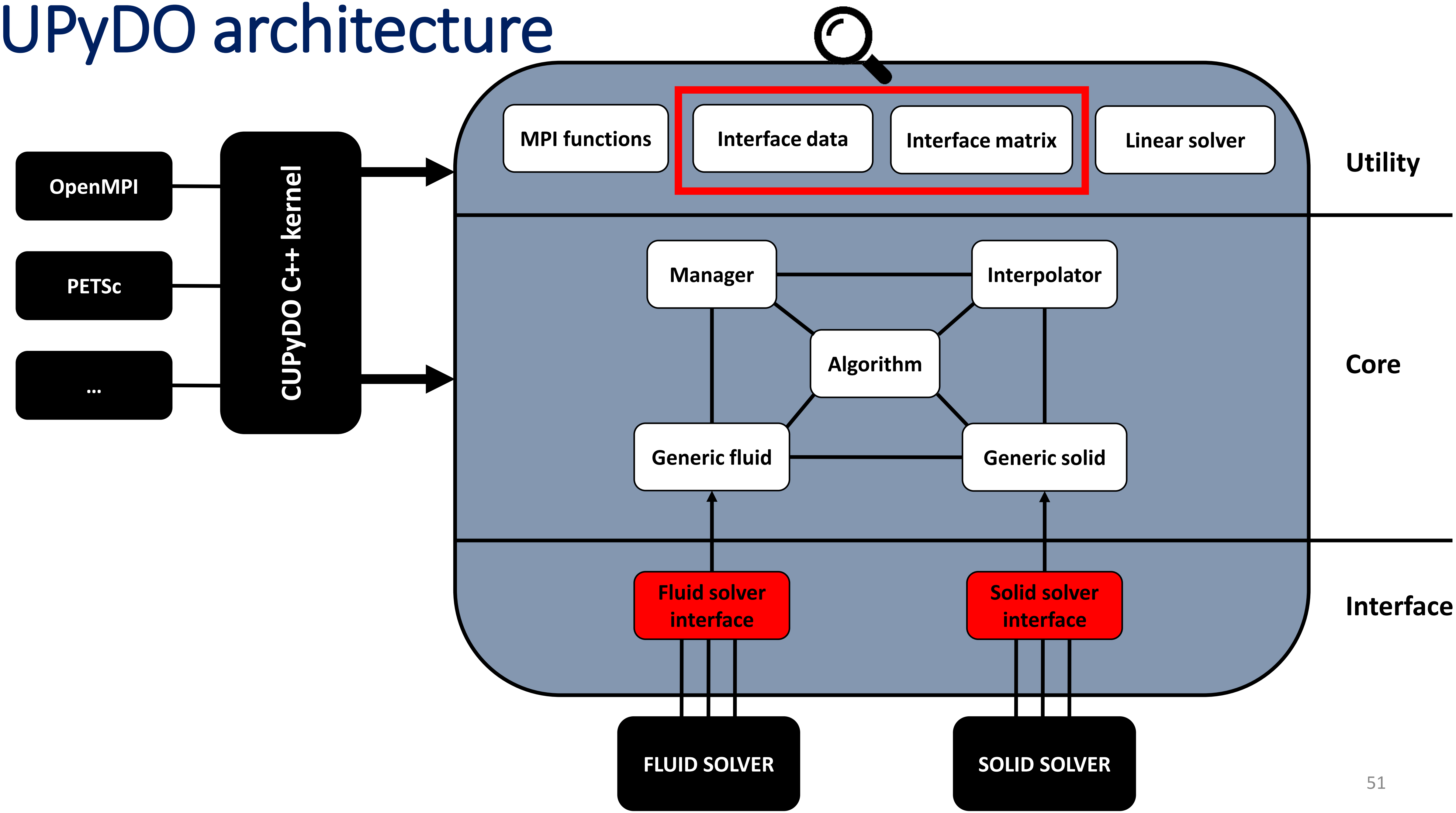


Donor (size N_s)

Target (size N_f)

Step 1 + step 2: $\mathbf{BA}^{-1} \rightarrow \mathbf{H}$

CUPyDO architecture



Interface data structure

Interface data

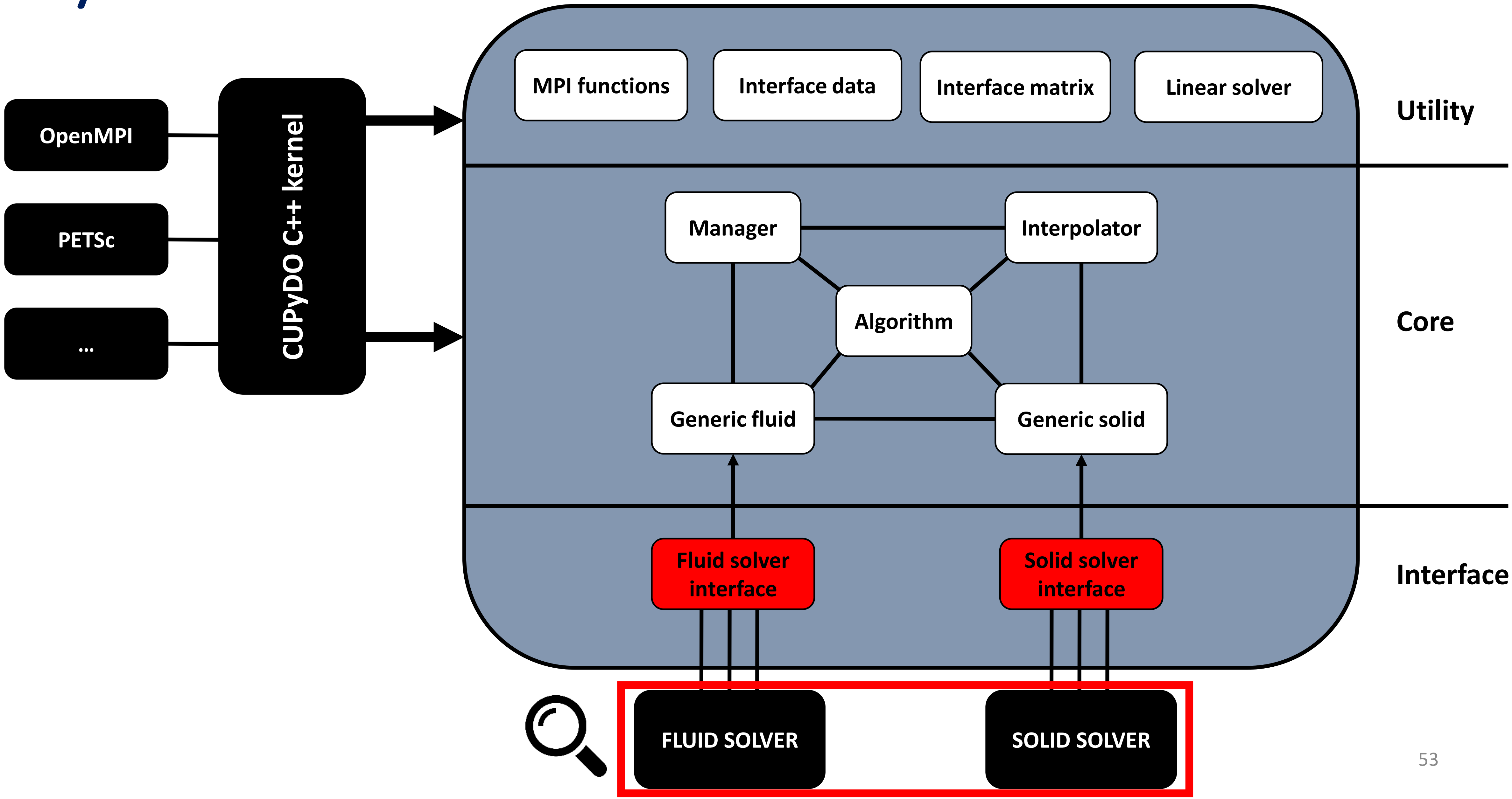
- Generic partitioned **data container**
- Used to **store interface** physical quantities or coupling residuals
- Parallel **algebraic operations**

Interface matrix

- Typically used to store and compute $\mathbf{A}$ and $\mathbf{B}$ in parallel
- Parallel **matrix-vector operations** with *Interface Data*

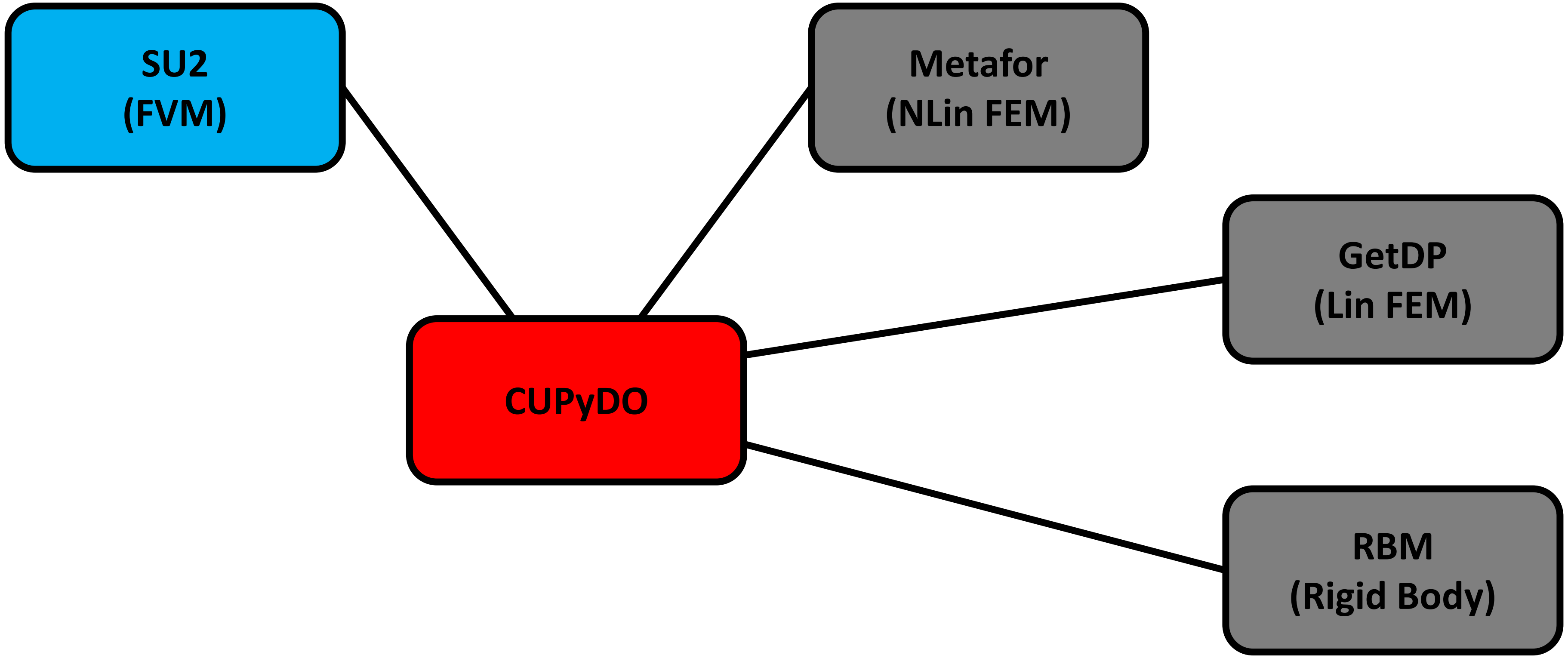
Powered by PETSc

CUPyDO architecture



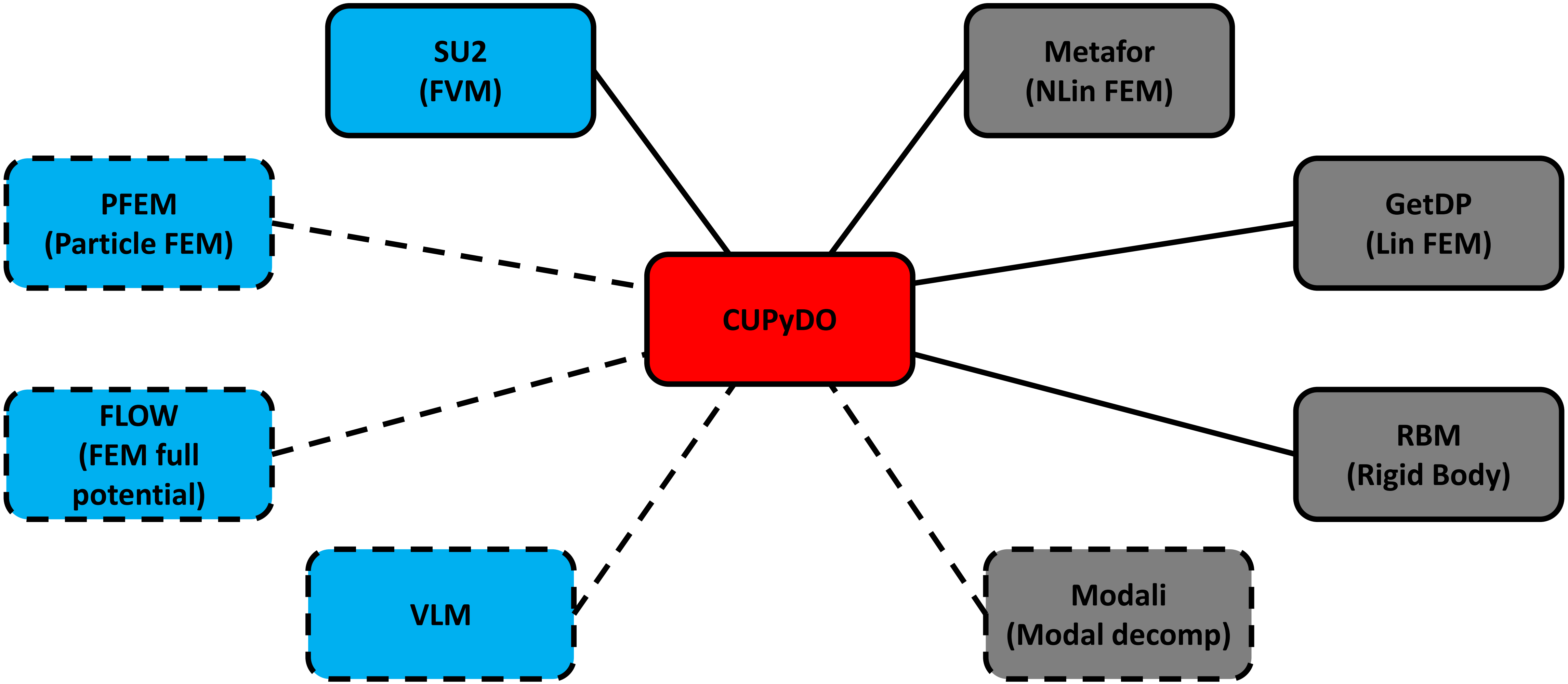
Coupled solvers

In this thesis



Coupled solvers

Beyond this thesis



Outline

PART I: The FSI problem

- Overview
- Mathematical description and numerical formulation

PART II: CUPyDO

- Data structure and numerical models

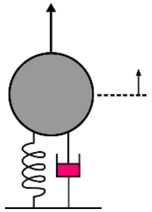
PART III: Verification and applications

- Verification test cases
- Aeroelastic study of a thin flat plate wing

CONCLUSION

Overview

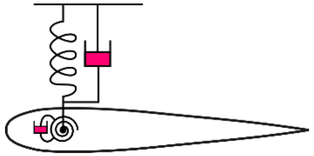
- **VIV**



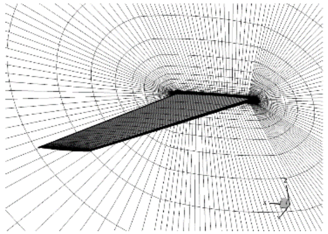
1D oscillator

Elastic solid (added-mass effect)

- **Flutter**



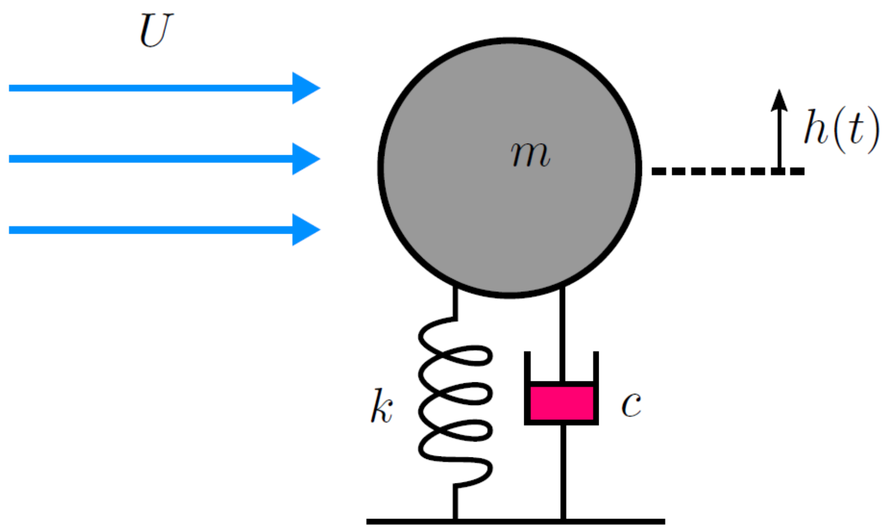
2D pitch-plunge airfoil



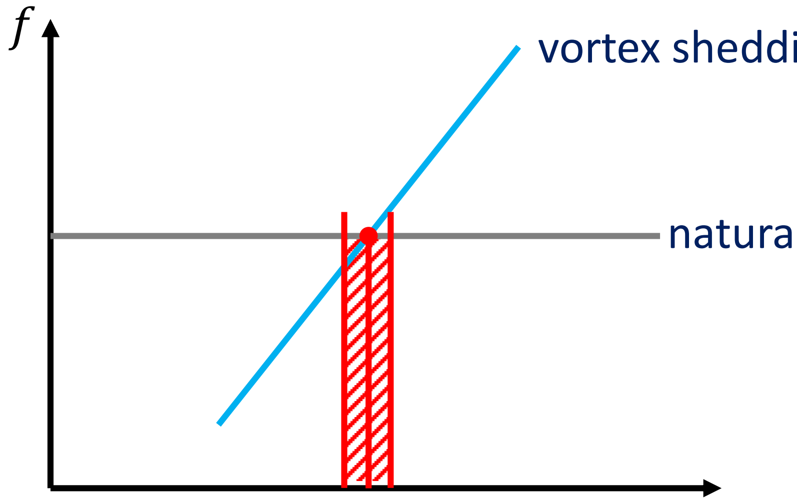
3D wing model

VIV of a rigid cylinder - 1D oscillator

$$\mathrm{Re_D} = \frac{UD}{\nu} = 90 \text{ to } 120$$
$$\mathrm{Ma} = 148$$



Initial conditions: $\ddot{h} = \dot{h} = h = 0$
→until solid motion reaches an established regime

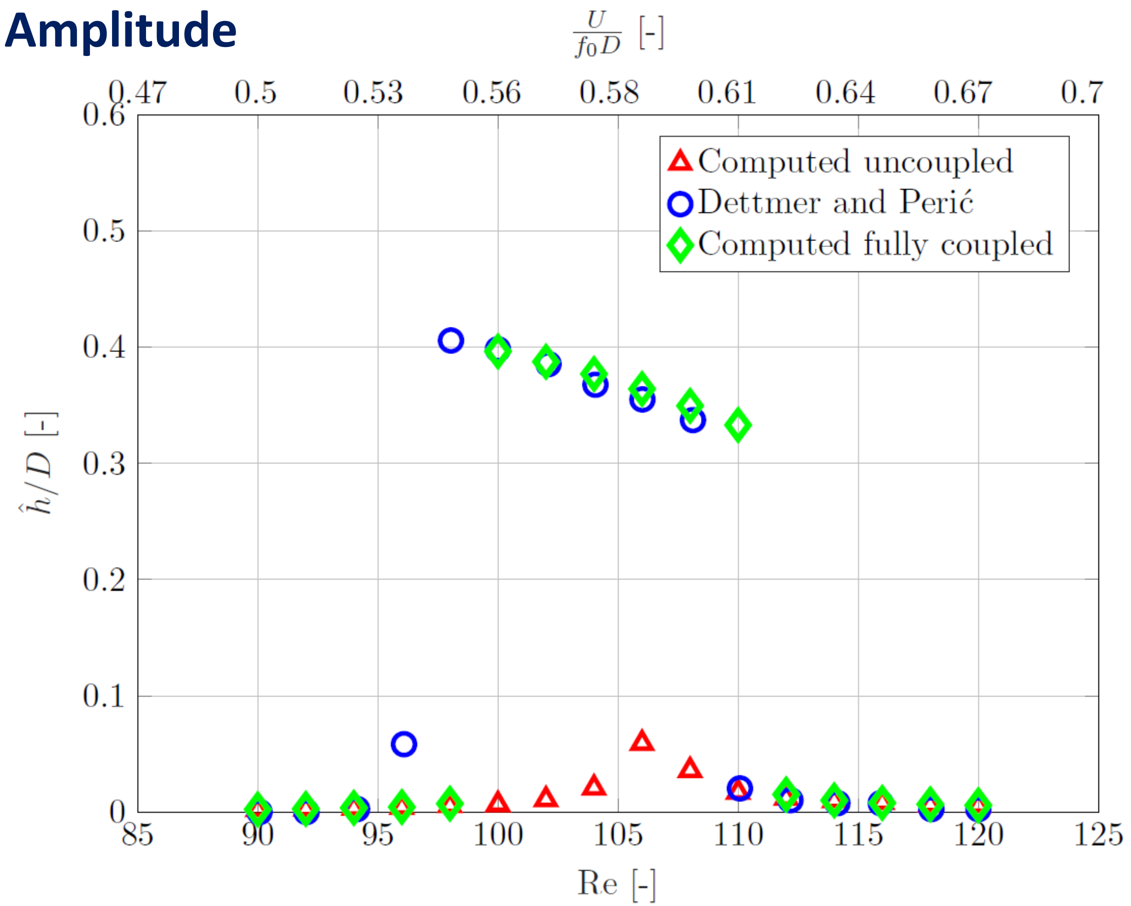


Fluid: viscous laminar flow
Solid: oscillator equation $m\ddot{h} + c\dot{h} + kh = L$

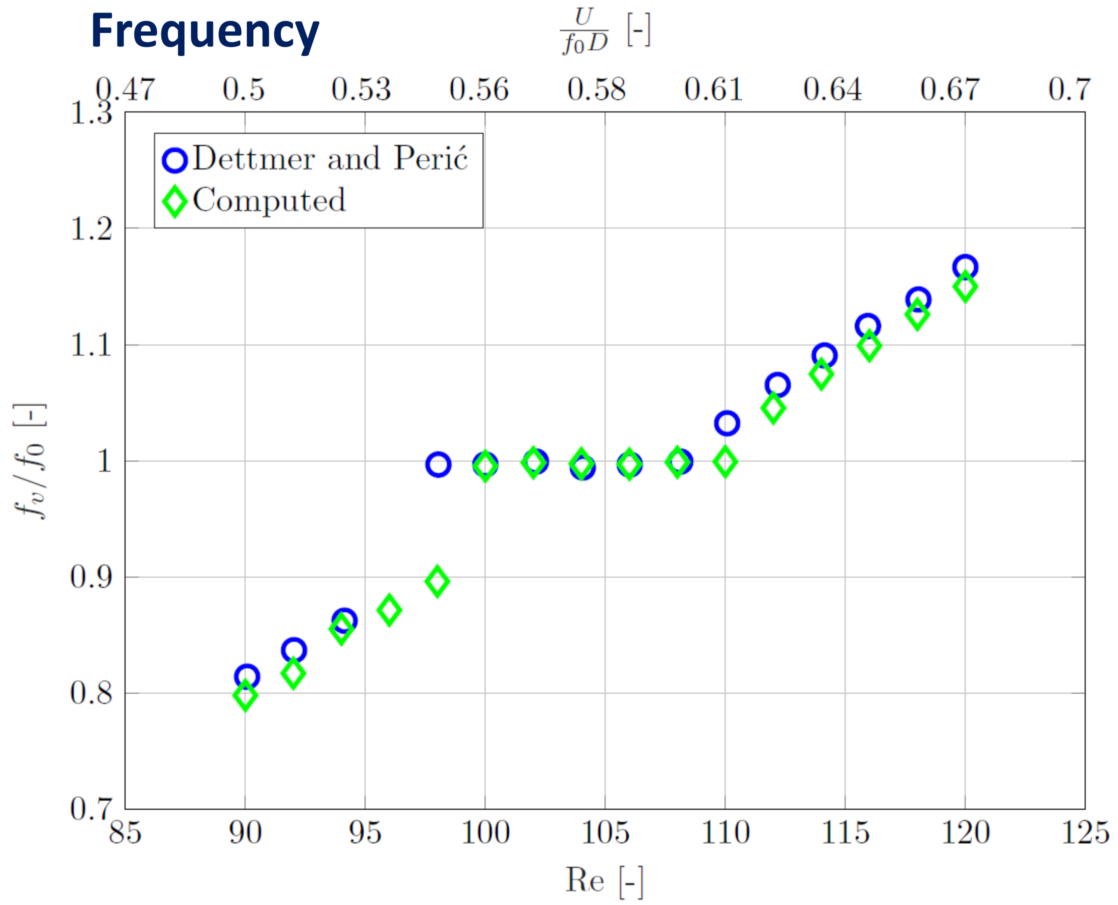
VIV of a rigid cylinder

SU2+RBM

Amplitude



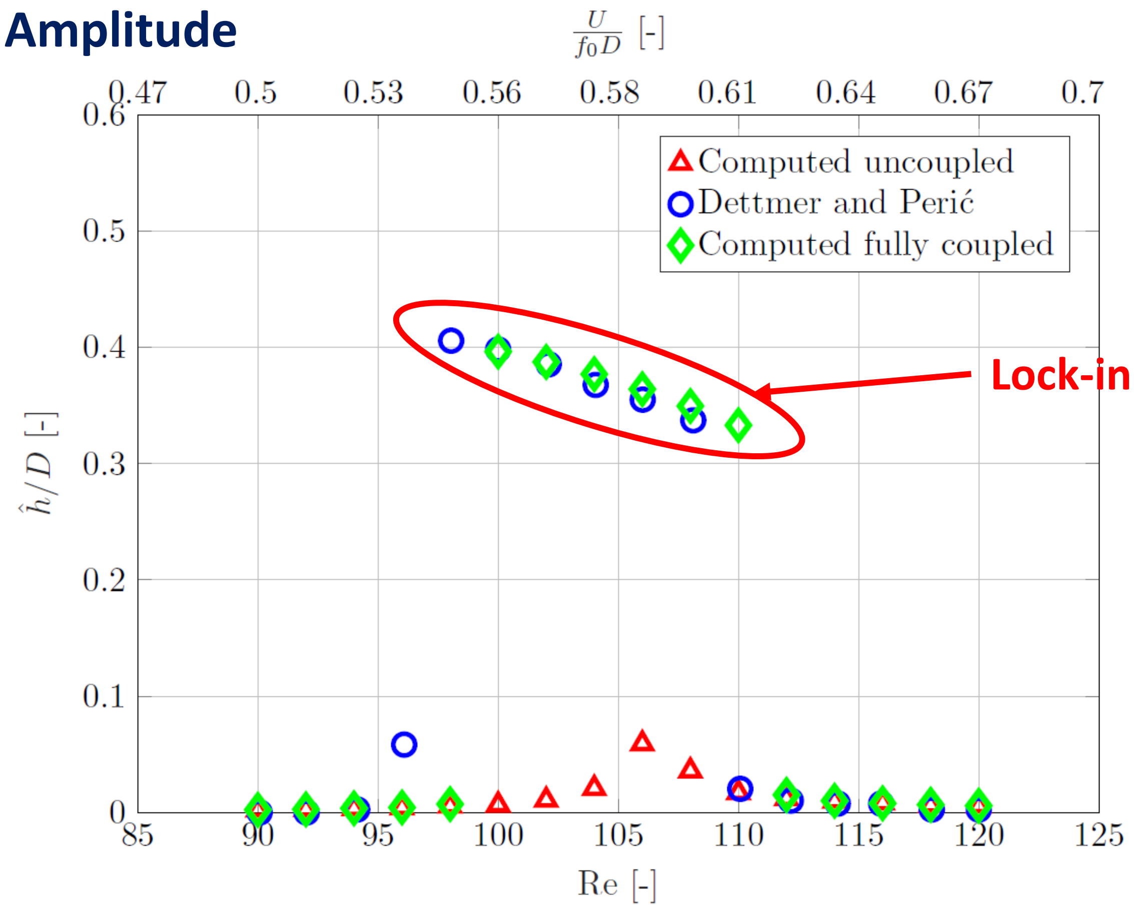
Frequency



VIV of a rigid cylinder

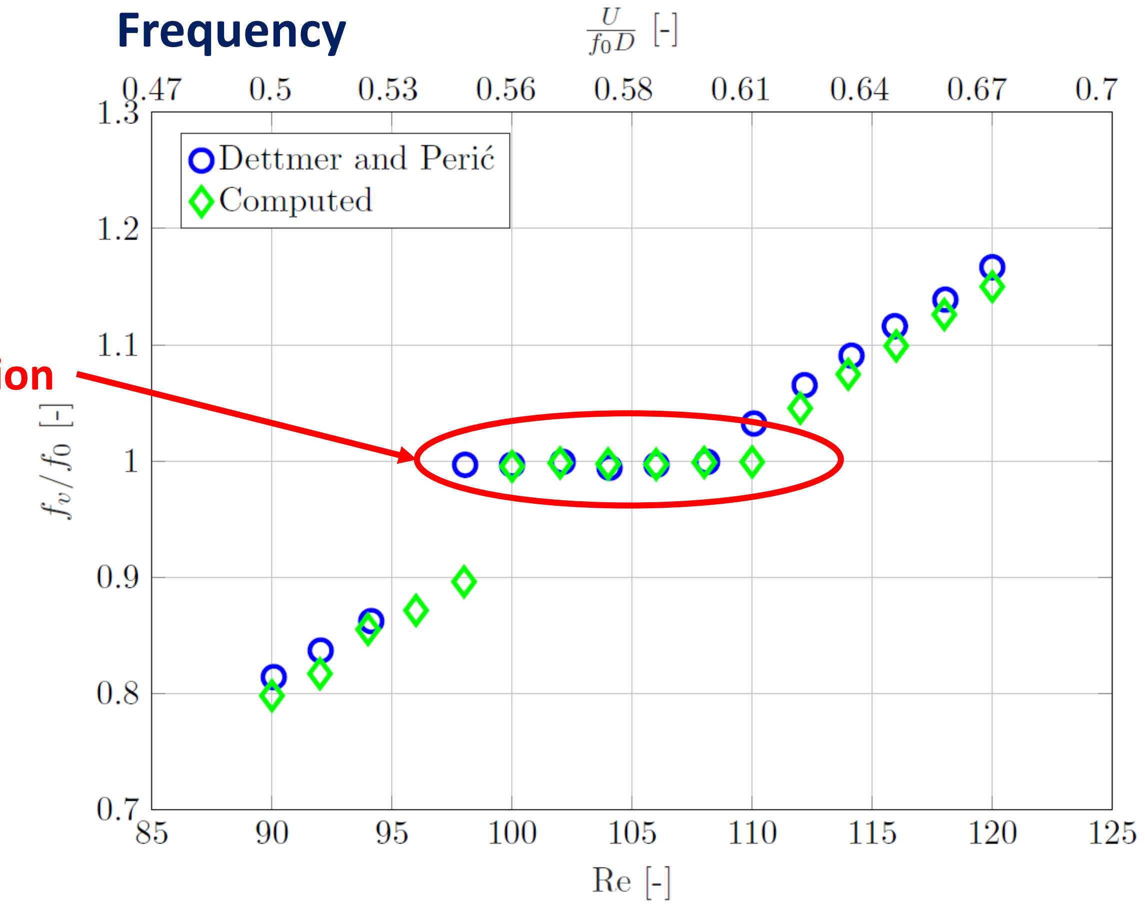
SU2+RBM

Amplitude



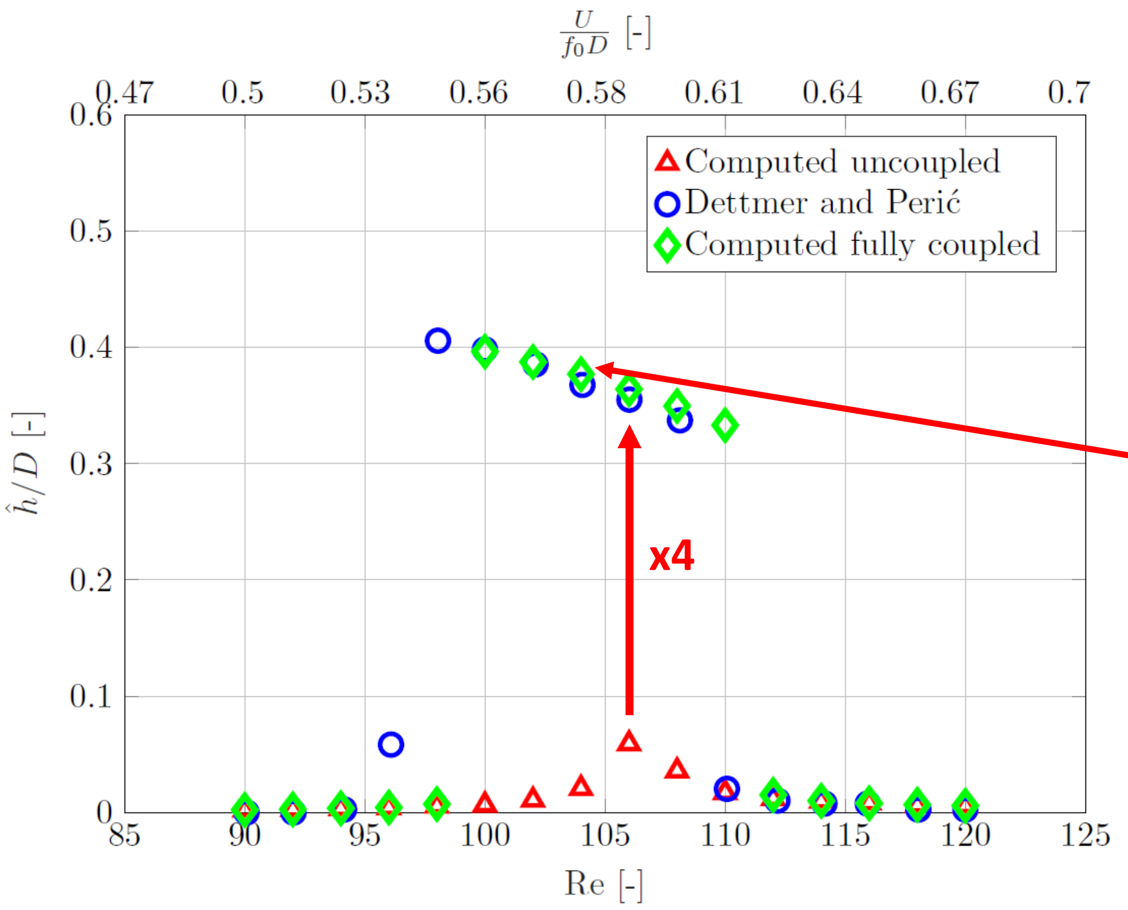
Lock-in region

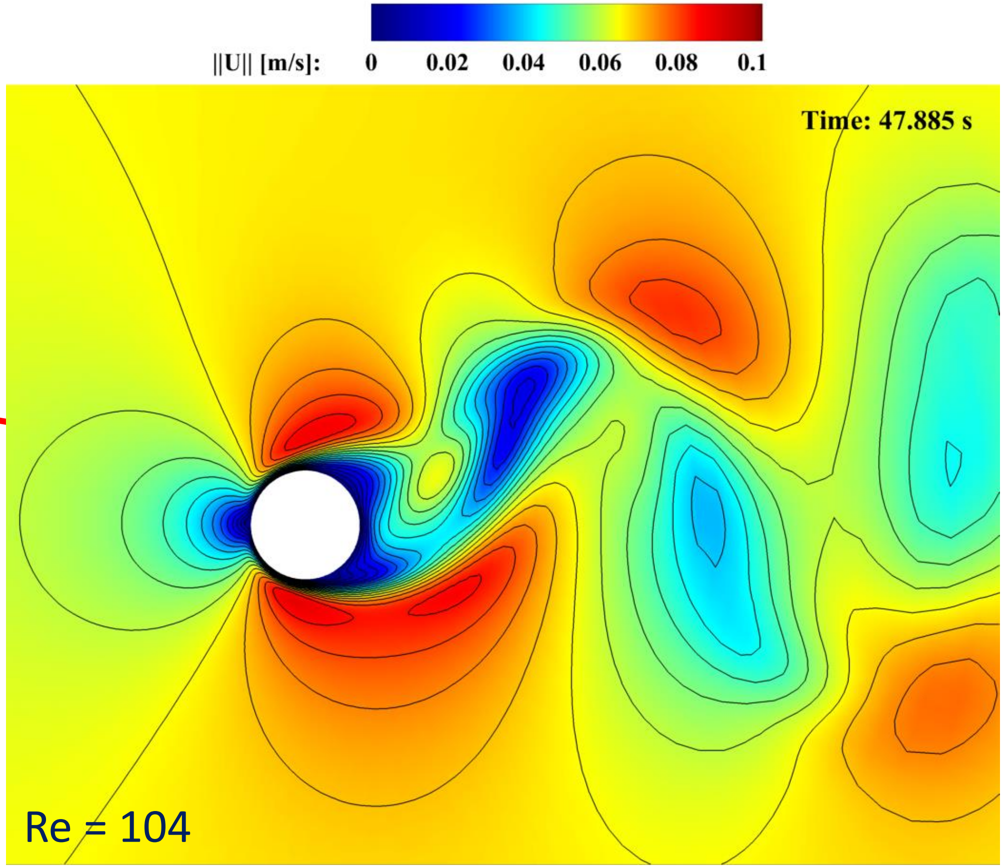
Frequency



- **Inside lock-in region**: strong feedback between coupled physics
- **Outside lock-in region**: marginal effect of solid motion
- **Good match** with numerical references

VIV of a rigid cylinder



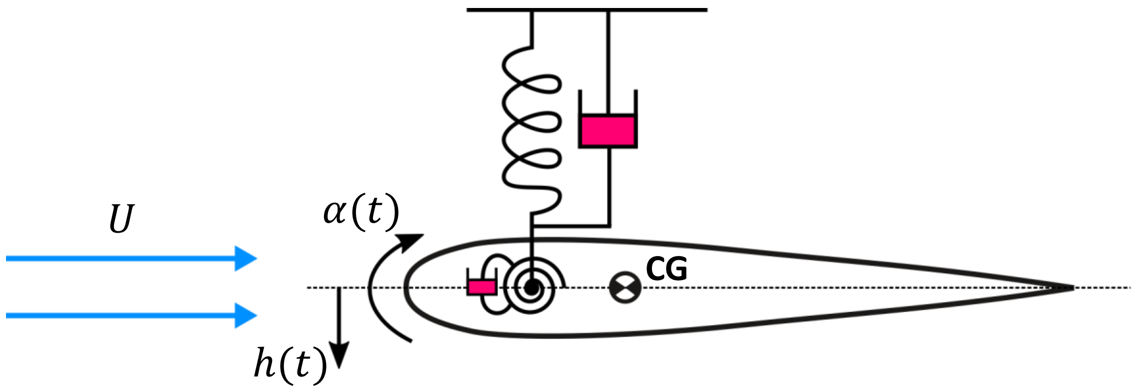


Uncoupled model misses important physics

SU2+RBM

Flutter – Isogai wing section

SU2+RBM



$$\mathrm{Re_c} = 12.56\ 10^6$$
$$\mathrm{M} = \frac{U}{a} = 0.75 \text{ to } 0.895$$
$$\mathrm{Ma} = 60$$

Initial condition: $\alpha = 1°$

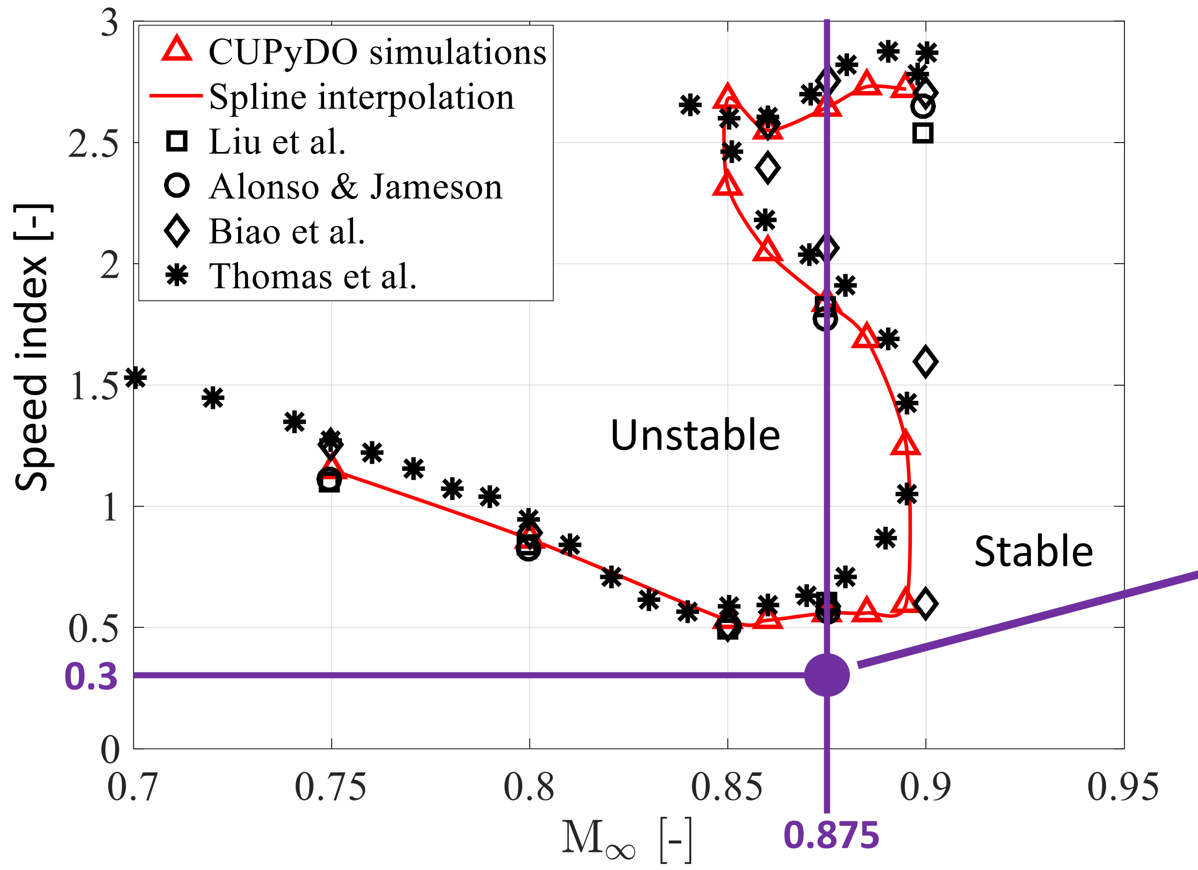
Damping extracted from the aeroelastic response and used for **flutter inception**

Fluid: transonic inviscid flow solved with Euler equations
Solid: 2-DoF oscillator equation for h and α

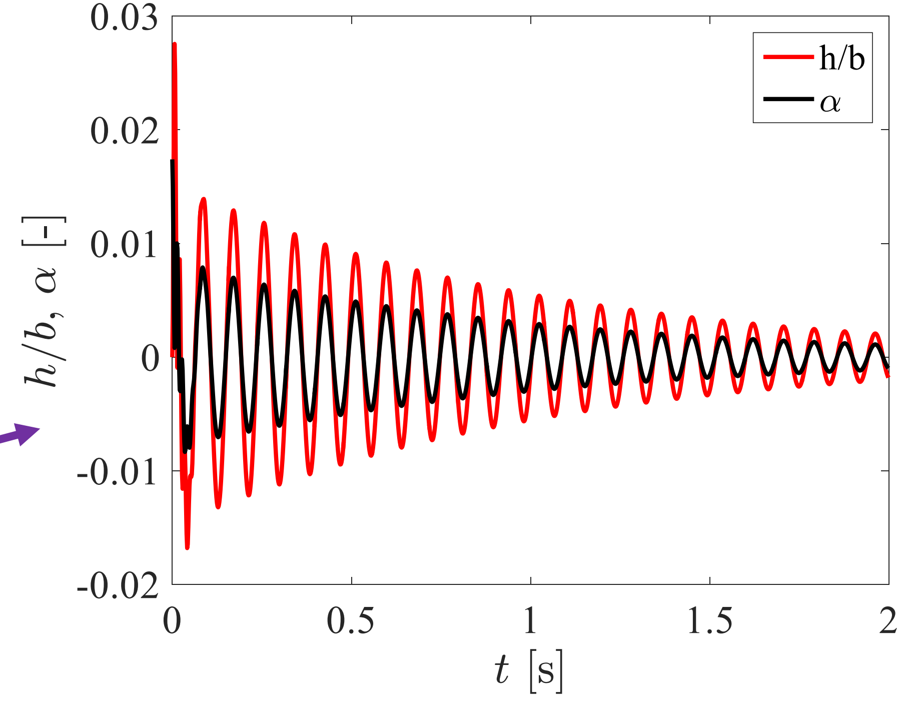
Flutter - Isogai wing section

SU2+RBM

Flutter boundary

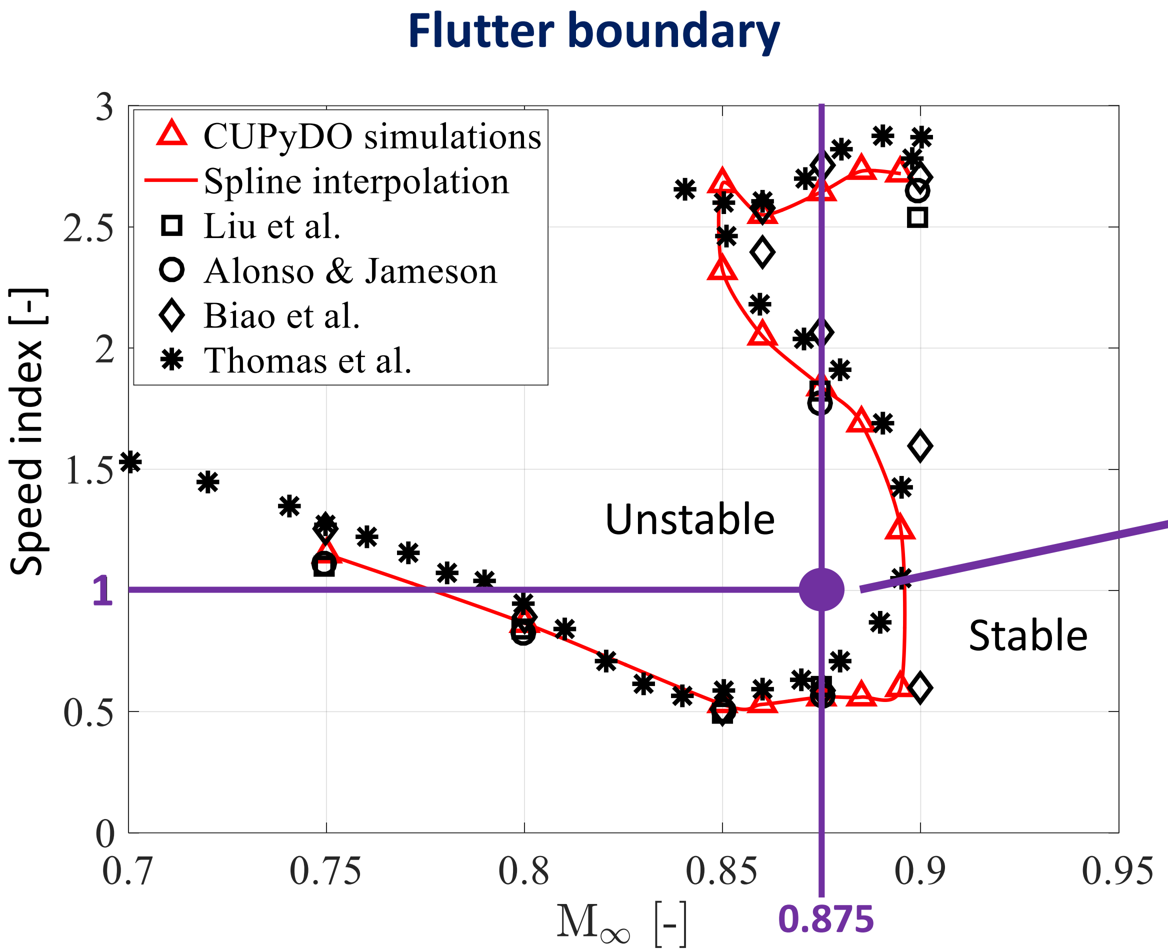


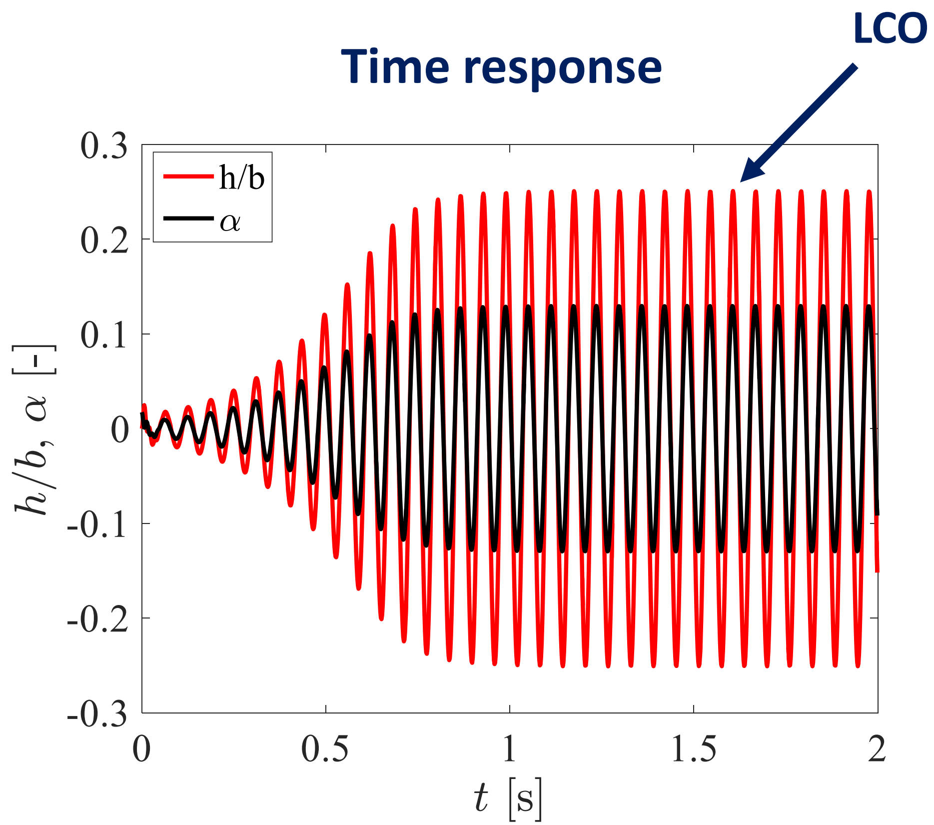
Time response



Flutter - Isogai wing section

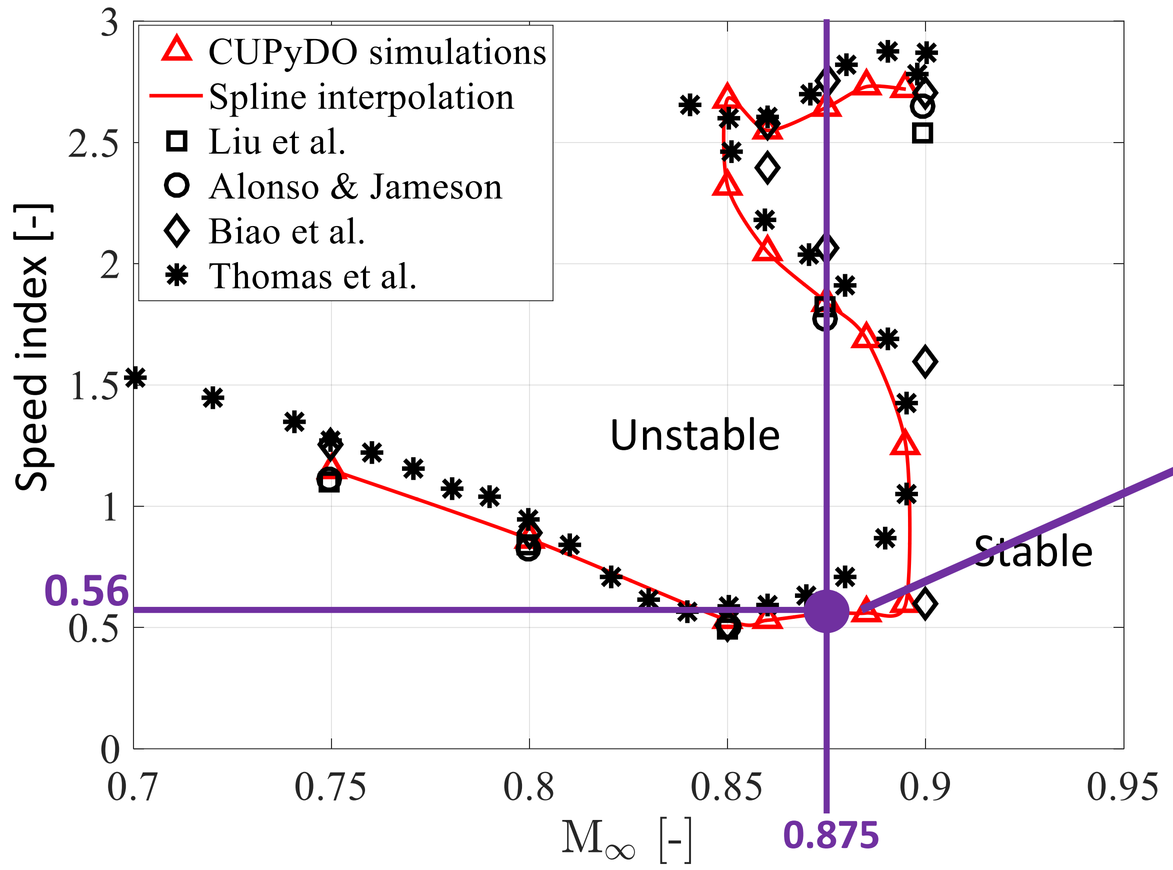
SU2+RBM



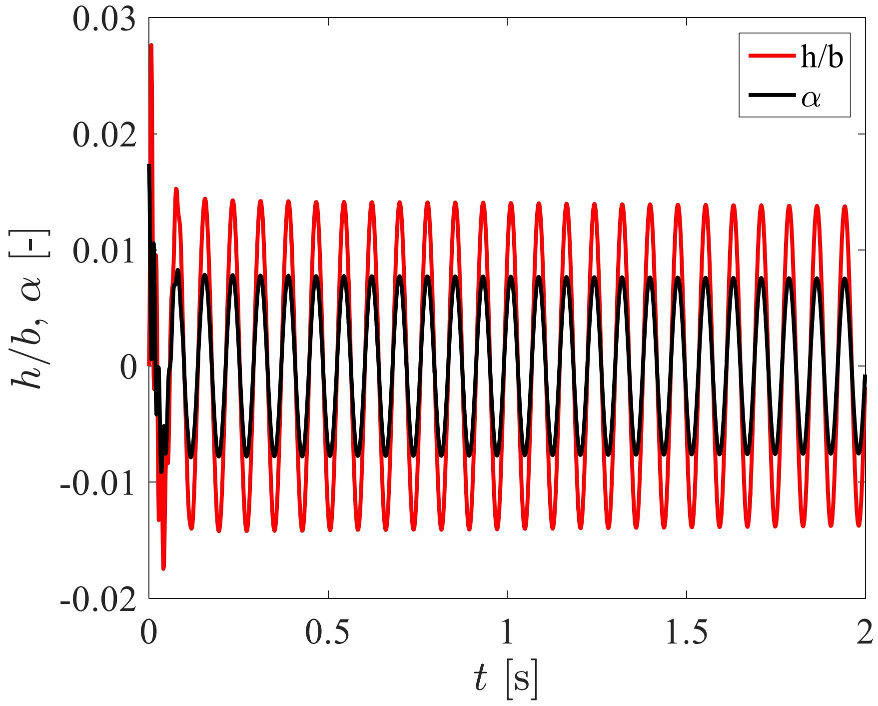


Flutter - Isogai wing section

Flutter boundary



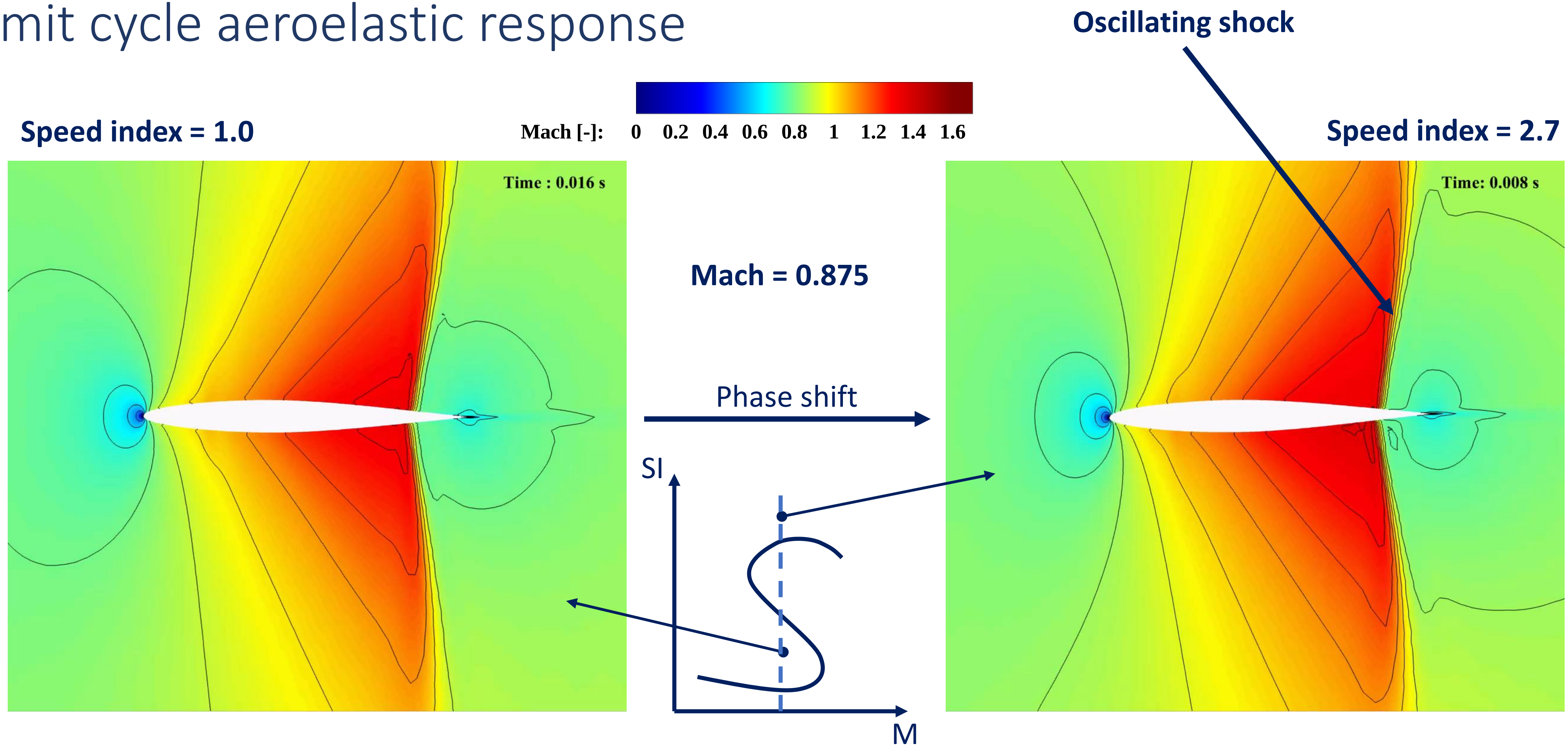
Time response



Isogai wing section

Limit cycle aeroelastic response

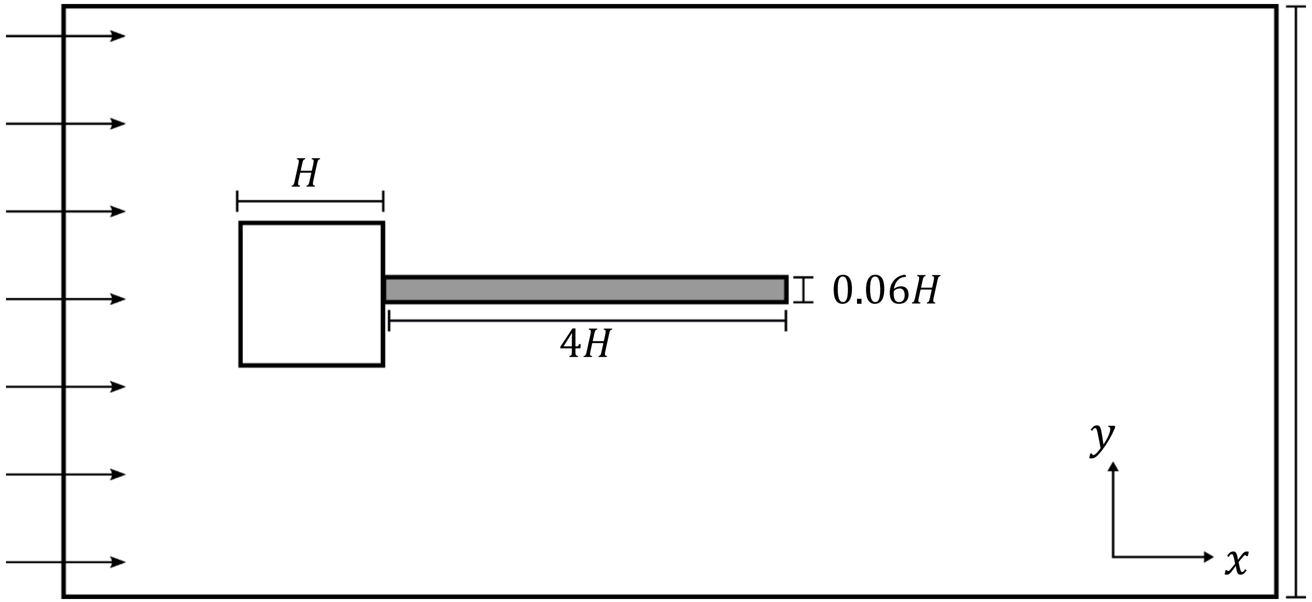
SU2+RBM



Pitch-plunge in phase

Pitch-plunge in opposite phase

VIV of a flexible cantilever
Coupled model



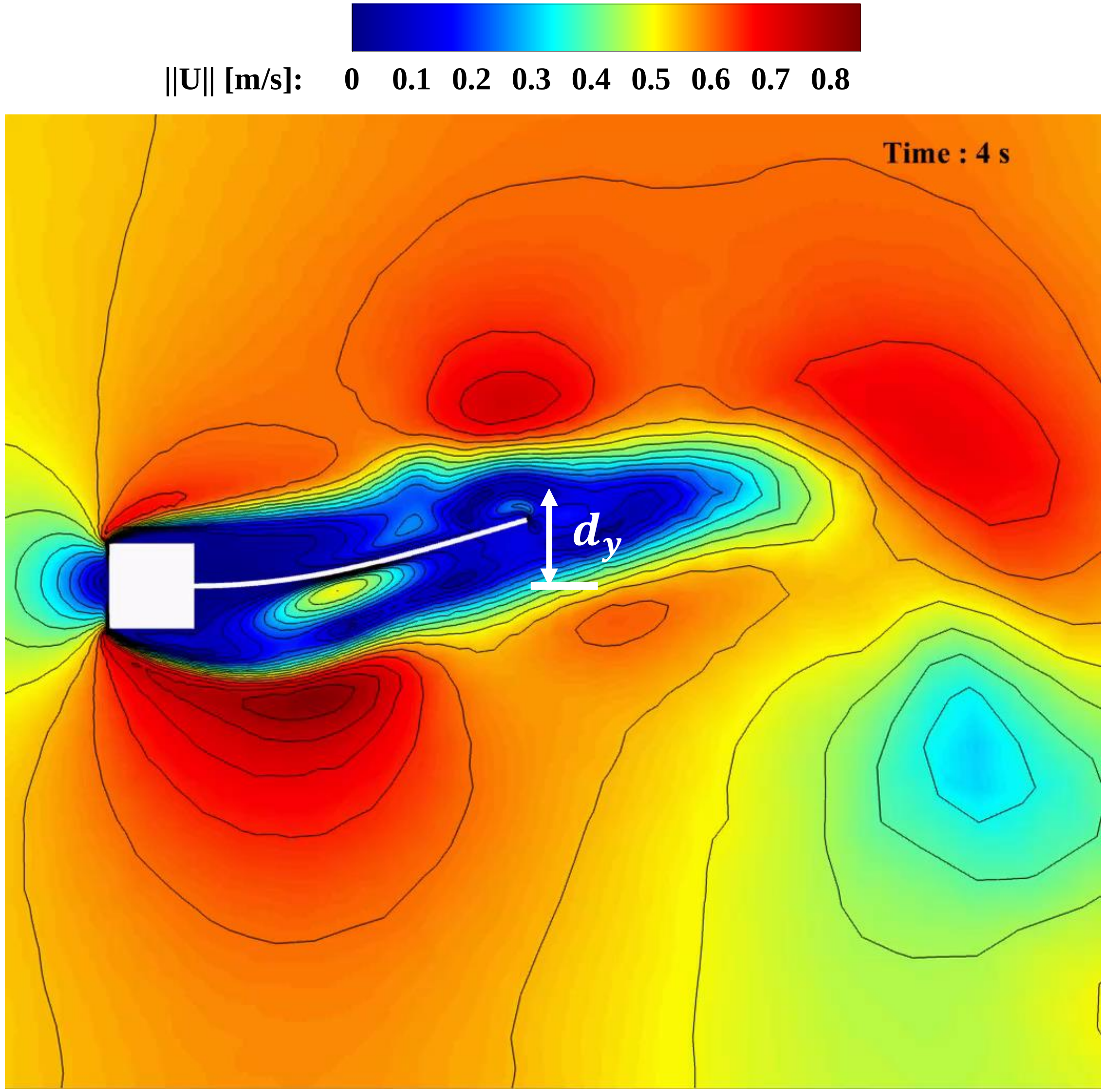
$H = 1$ cm
$\mathrm{Re_H} = 333$
$\mathrm{Ma} = 84.7$ to 0.8

Fluid: viscous laminar flow
Solid (cantilever): nonlinear FE, elastic material

Interface: matching discretization

VIV of a flexible cantilever

Tip displacement and frequency



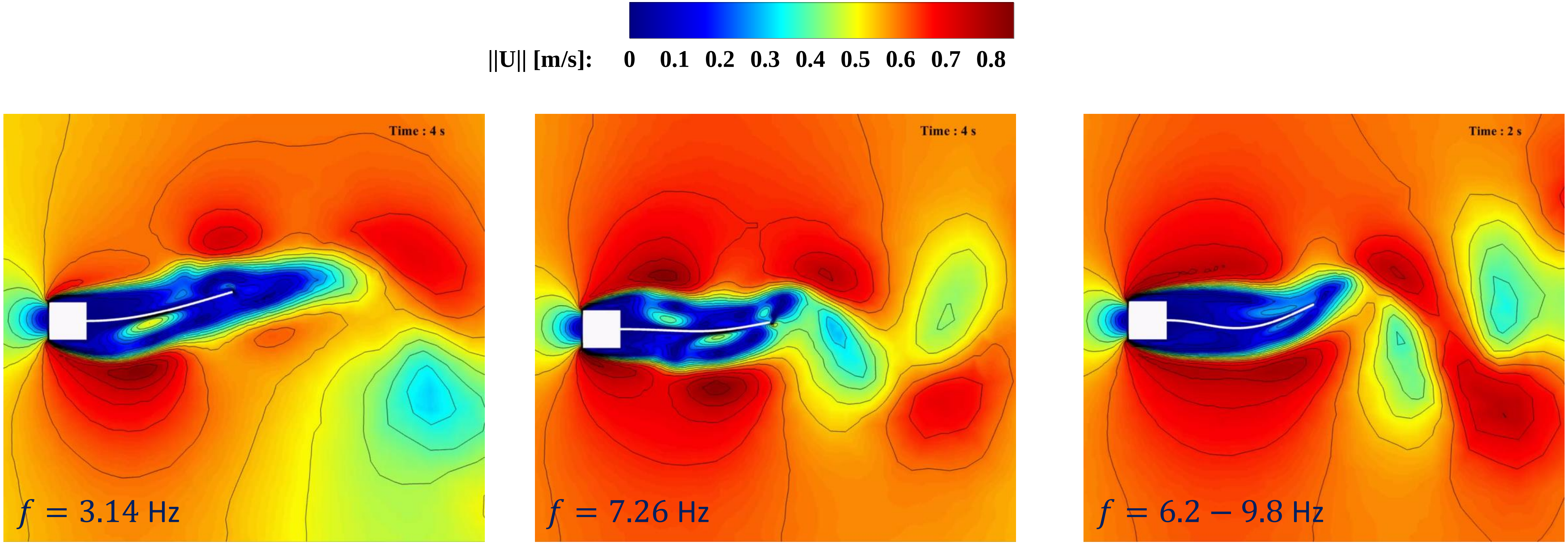
- Laminar **vortex shedding in the wake** of the square
  ➔ harmonic loads on the cantilever
  ➔ harmonic response
- The case is setup to have $f_v \approx f_0$

	max d_y [cm]	f [Hz]
CUPyDO	1.14	3.20
Sanchez *et al.*	1.05-1.15	3.05-3.15
Habchi *et al.*	1.02	3.25
Kassiotis *et al.*	1.05	2.98
Wood *et al.*	1.15	2.94
Olivier *et al.*	0.95	3.17

SU2+Metafor

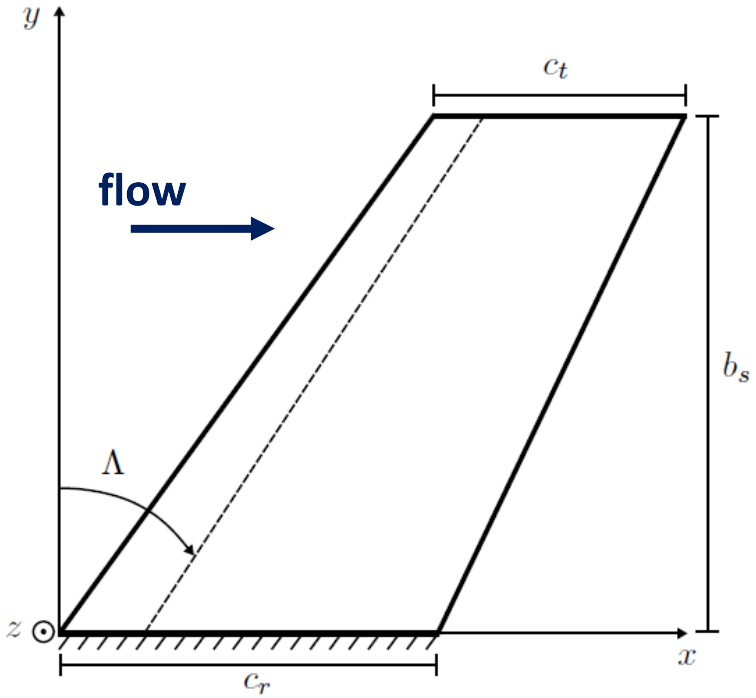
VIV of a flexible cantilever

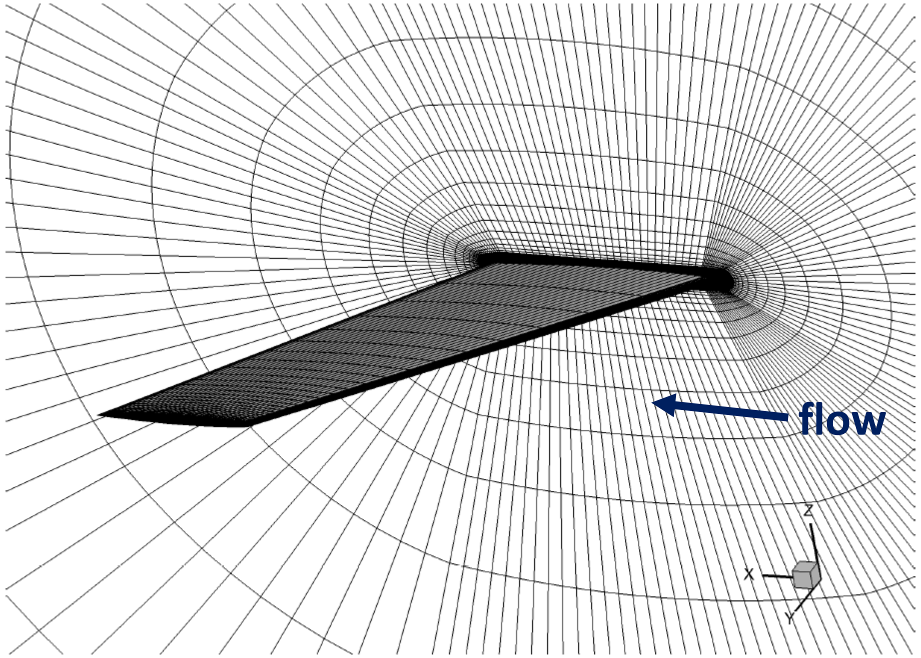
Added-mass effect



$\mathbf{Ma = 85}$	$\mathbf{Ma = 8.5}$	$\mathbf{Ma = 0.8}$
No relaxation	Aitken (max) $\overline{\omega} = 0.1$	Aitken (min) $\overline{\omega} = 0.1$
$\overline{N}_{FSI} = 2.7$	$\overline{N}_{FSI} = 6.9$	$\overline{N}_{FSI} = 31.9$

AGARD 445.6
Aeroelastic model





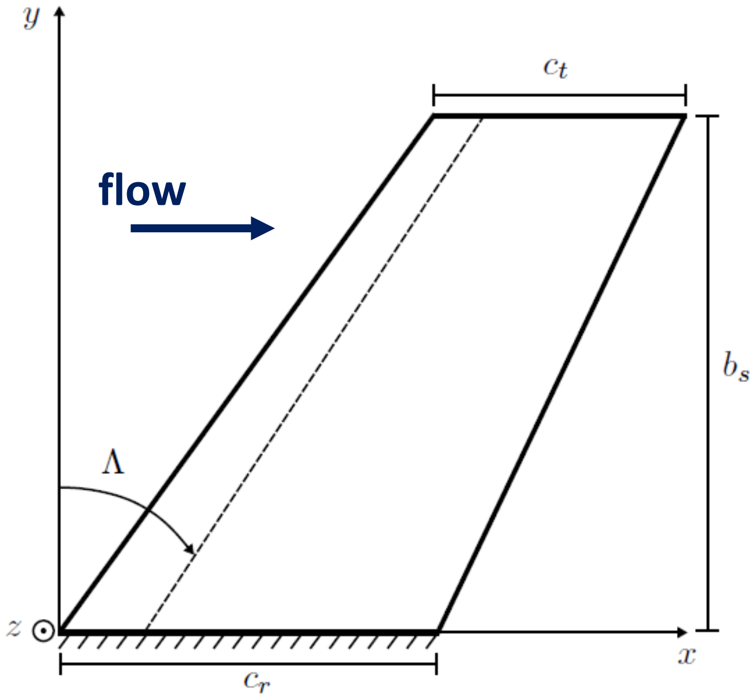
Flow: transonic inviscid flow (Euler eqn.)
Solid: nonlinear FE, elastic material

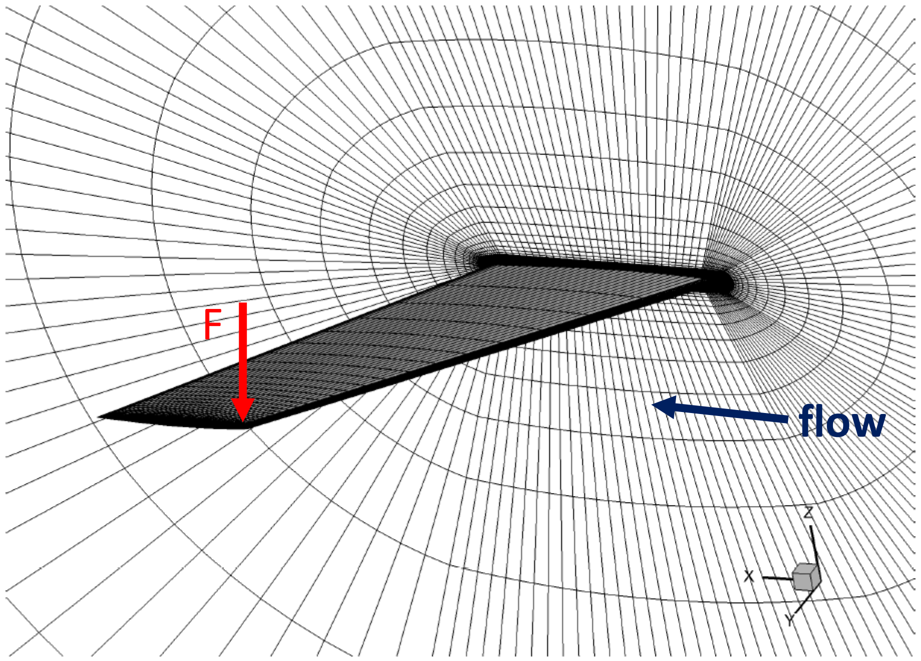
$M = 0.5$ to 1.4
$Ma = 23$ to 259

Interface: non-matching discretization ➔ use of RBF interpolator (TPS)

AGARD 445.6

Aeroelastic model





Initial perturbation (load) to trigger the aeroelastic response

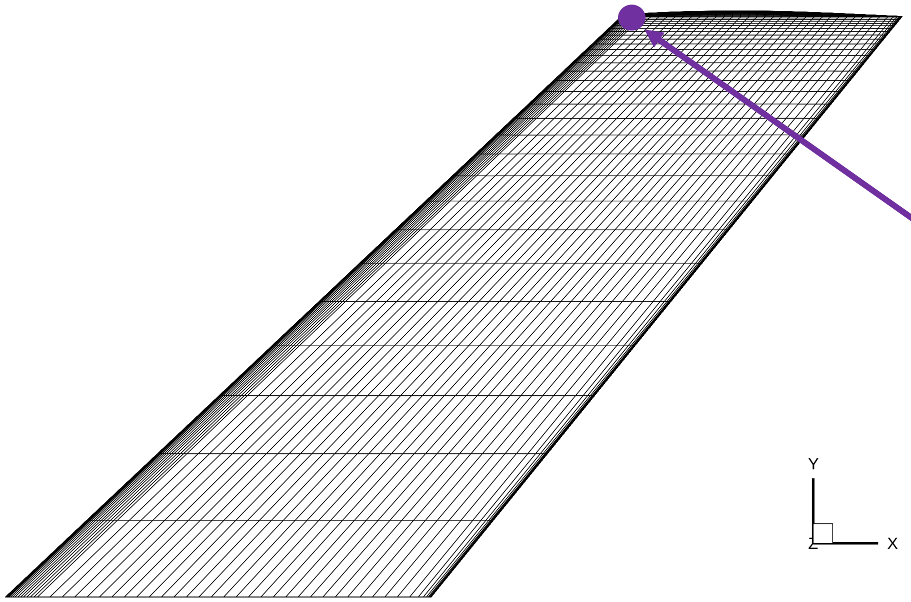
Damping extracted from the aeroelastic response and used for **flutter inception**

Flow: transonic inviscid flow (Euler eqn.)
Solid: nonlinear FE, elastic material

Interface: non-matching discretization ➔ use of RBF interpolator (TPS)

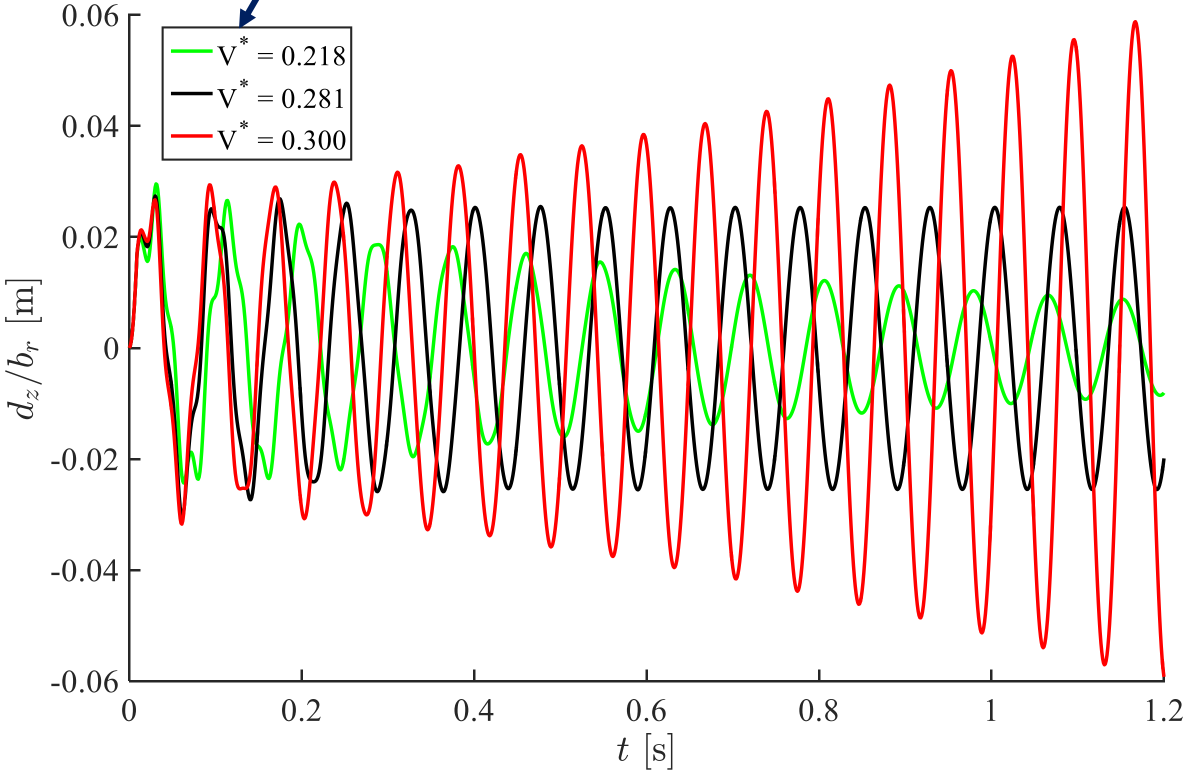
AGARD 445.6

Aeroelastic response



speed index

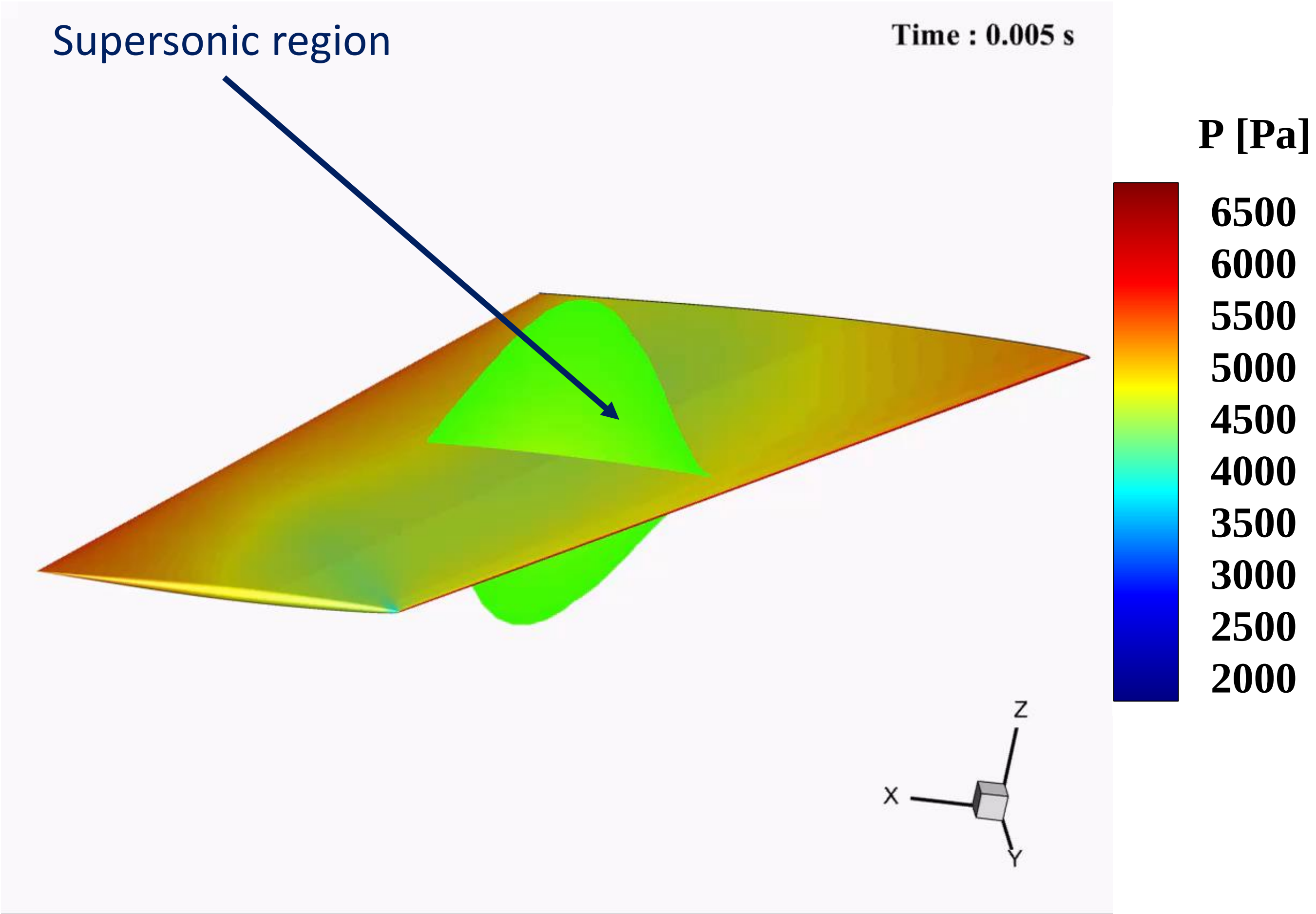
Mach = 0.96



AGARD 445.6

Aeroelastic response

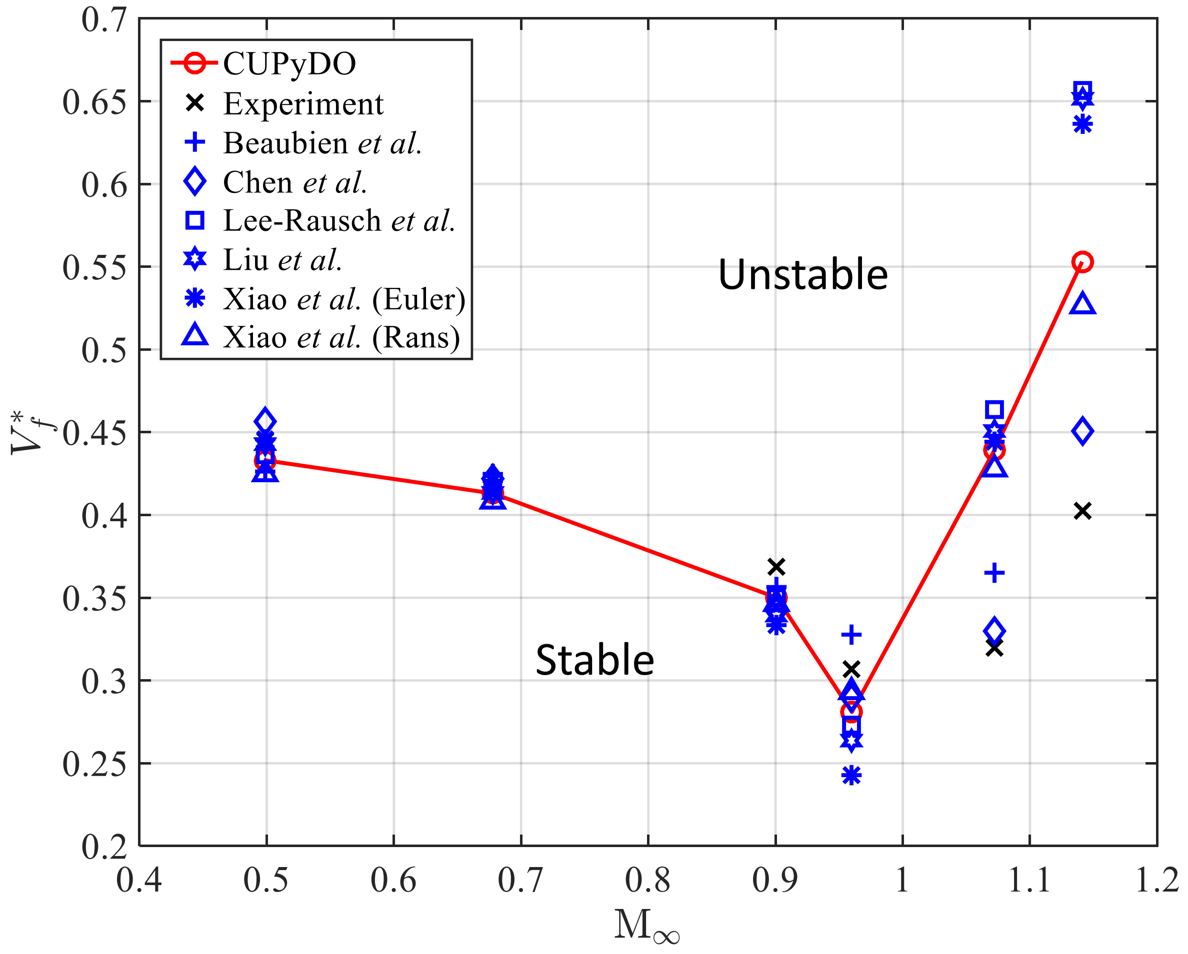
SU2+Metafor



Post-critical conditions, speed index = 0.3
Mach = 0.96

AGARD 445.6

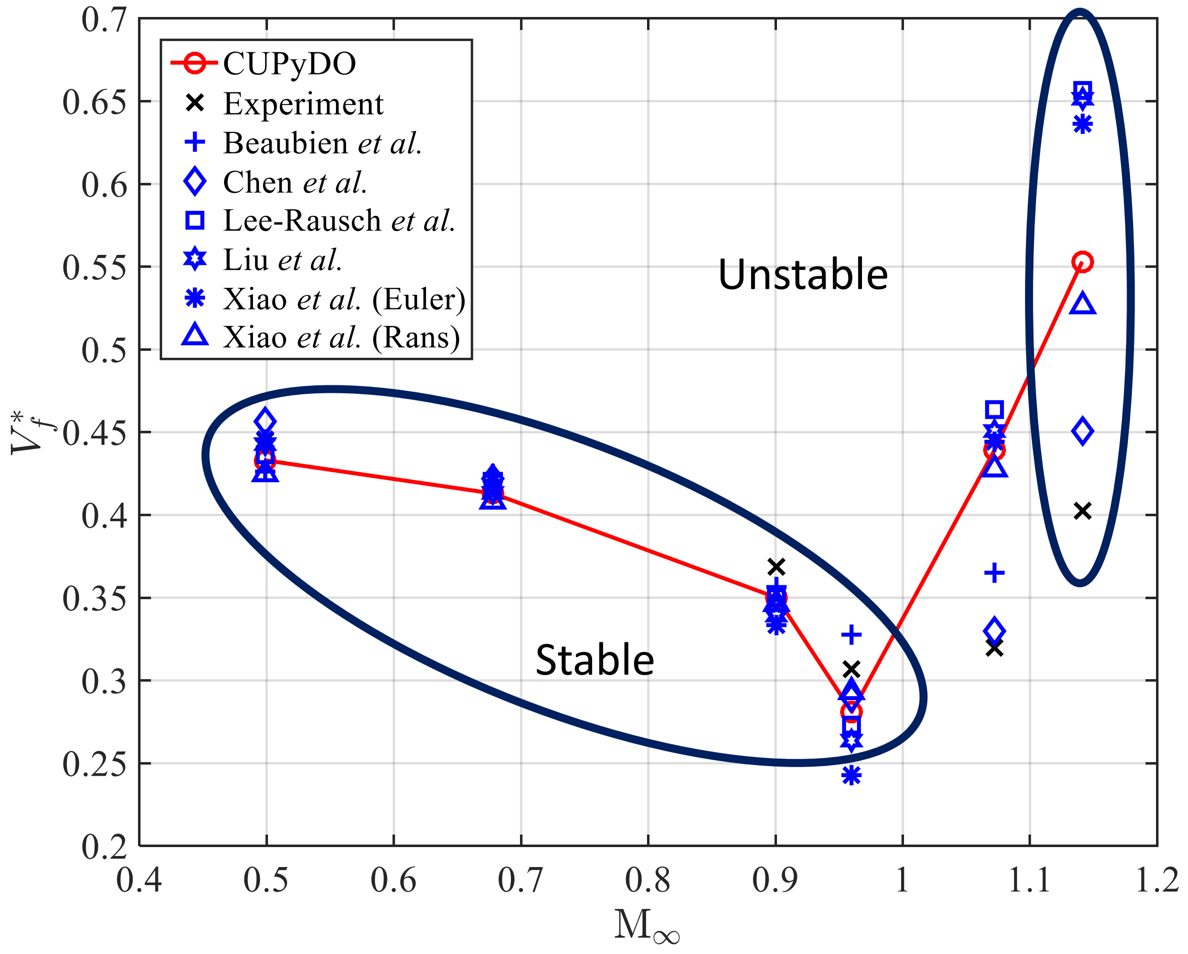
Flutter boundary



AGARD 445.6

Flutter boundary

SU2+Metafor



- Good agreement in the transonic regime (+ transonic dip)
- Increased spread of the results in the supersonic regime

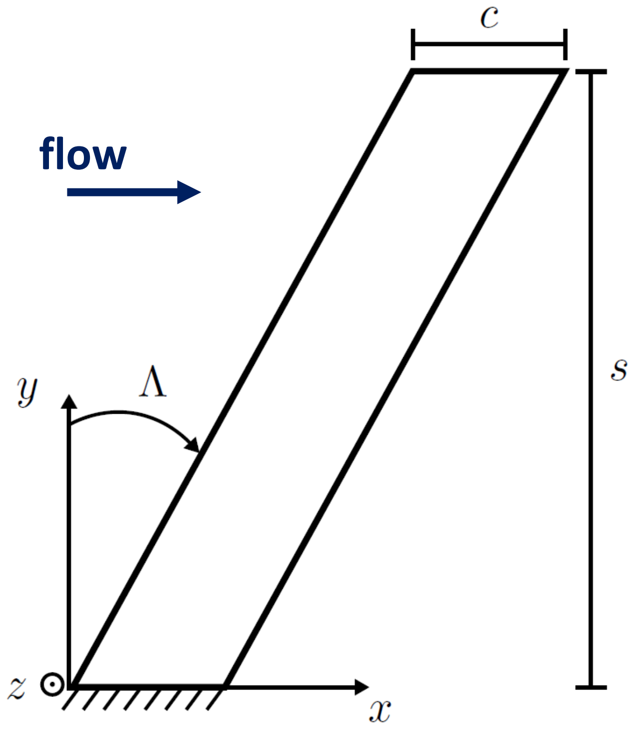
Outline

Thin flat plate wing

Aeroelastic model

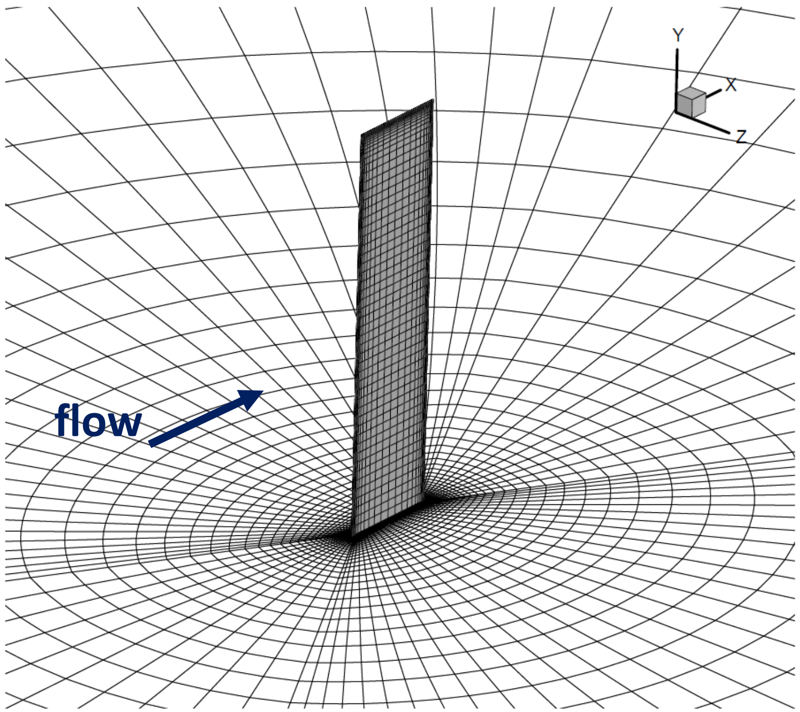
$$\mathrm{Re}_c^{\max} = 2.6\ 10^5$$

SU2+Metafor

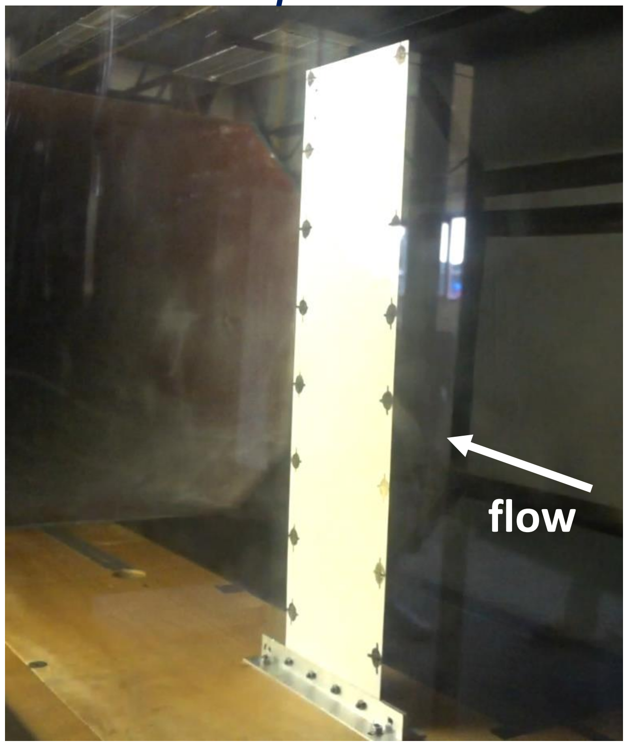


Geometry
$s = 0.8$ m
$c = 0.2$ m
$t = 1$ mm (thickness)
$\Lambda = 0° \mid 20° \mid 45°$

Numerical model



Wind tunnel experimental model



G. Dimitriadis

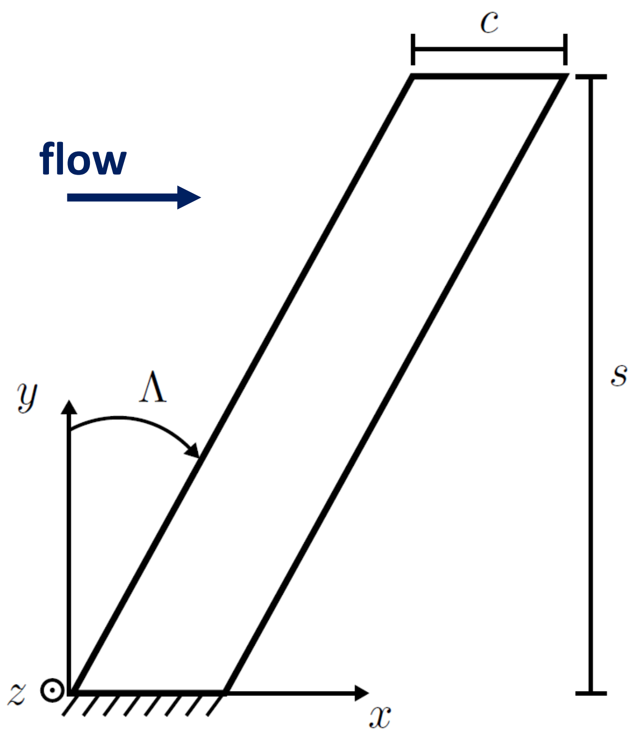
Flow: turbulent flow (URANS)
Solid: nonlinear FE model, elastic material (aluminum)

Interface: non-matching discretization ➔ use of RBF interpolator (CPC2)

Thin flat plate wing

Aeroelastic model

$\mathrm{Re}_c^{max} = 2.6\ 10^5$



Geometry

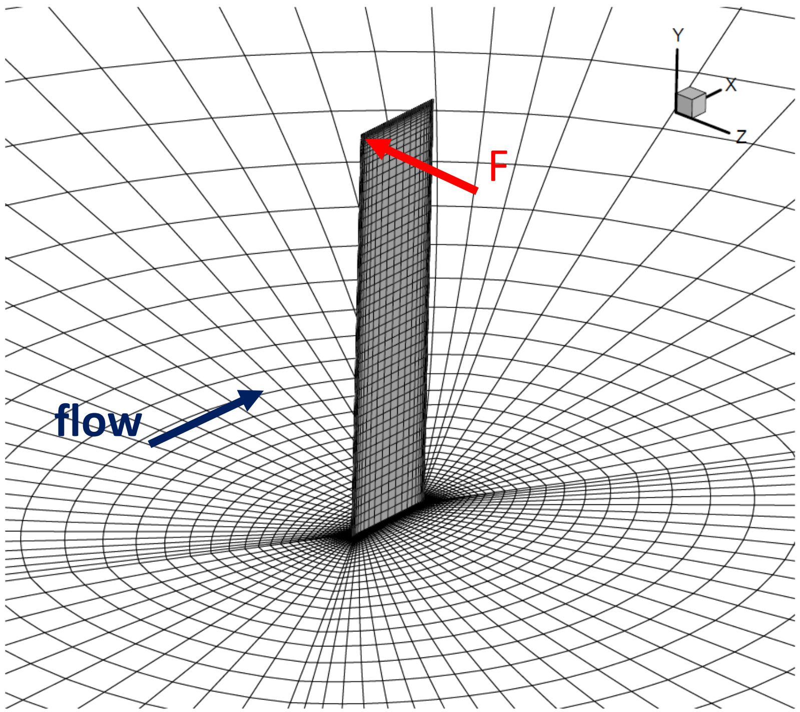
$s = 0.8$ m

$c = 0.2$ m

$t = 1$ mm (thickness)

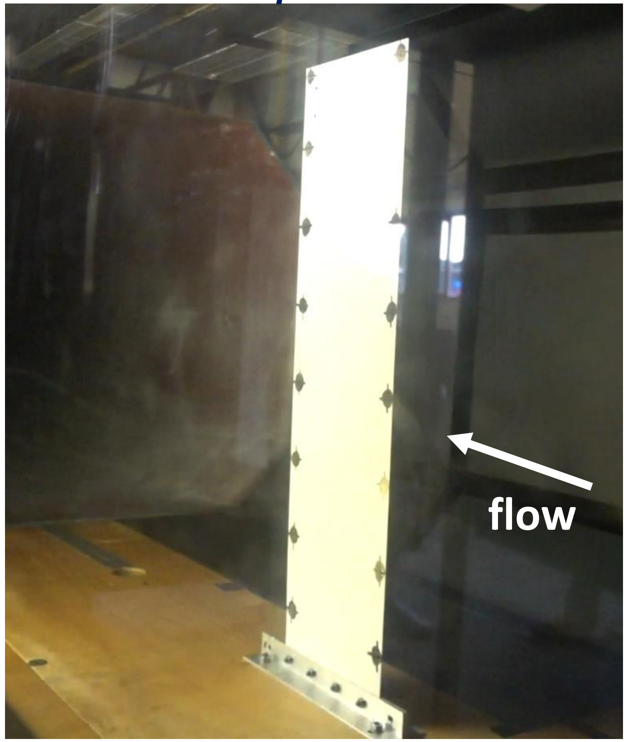
$\Lambda = 0° \mid 20° \mid 45°$

Numerical model



- **Initial perturbation** (load) to trigger the aeroelastic response
- Controlled by **perturbation duration** t^*

Wind tunnel experimental model

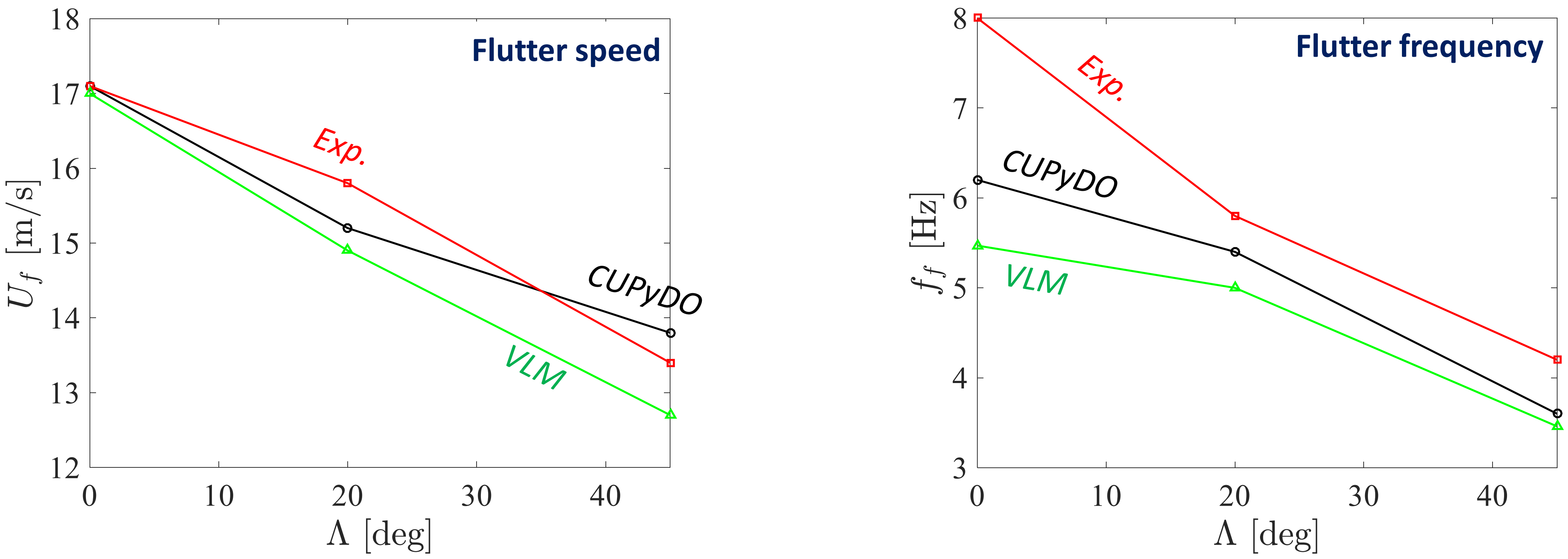


G. Dimitriadis

SU2+Metafor

Thin flat plate wing

Flutter speed and frequency



Computation time
VLM : a few seconds
CUPyDO: 12h for one cycle

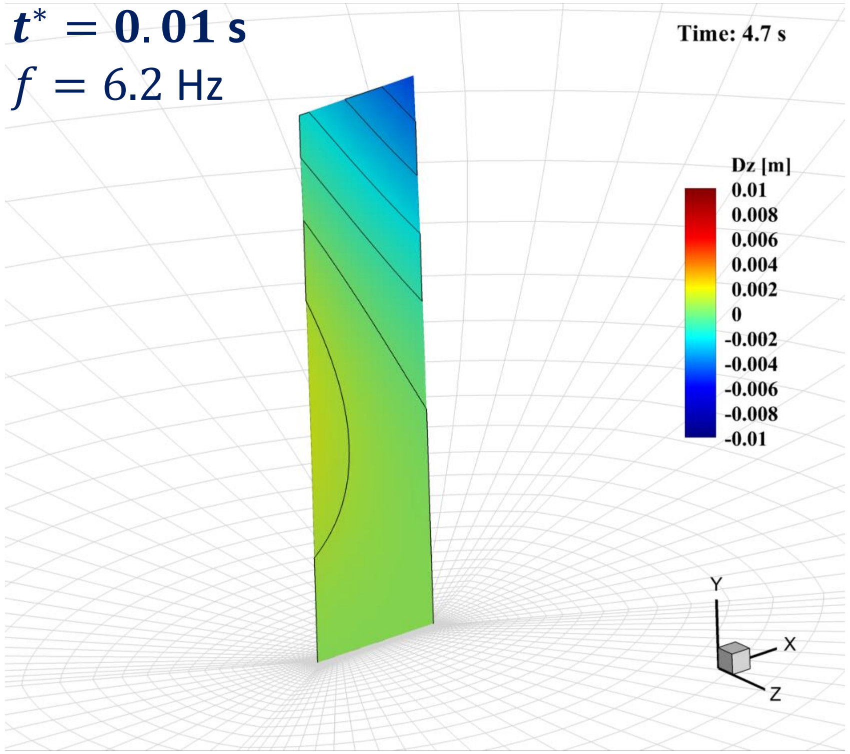
Thin flat plate wing

Post-critical aeroelastic response

SU2+Metafor

Low frequency LCO
Dominated by **bending**

$t^* = 0.01$ s
$f = 6.2$ Hz

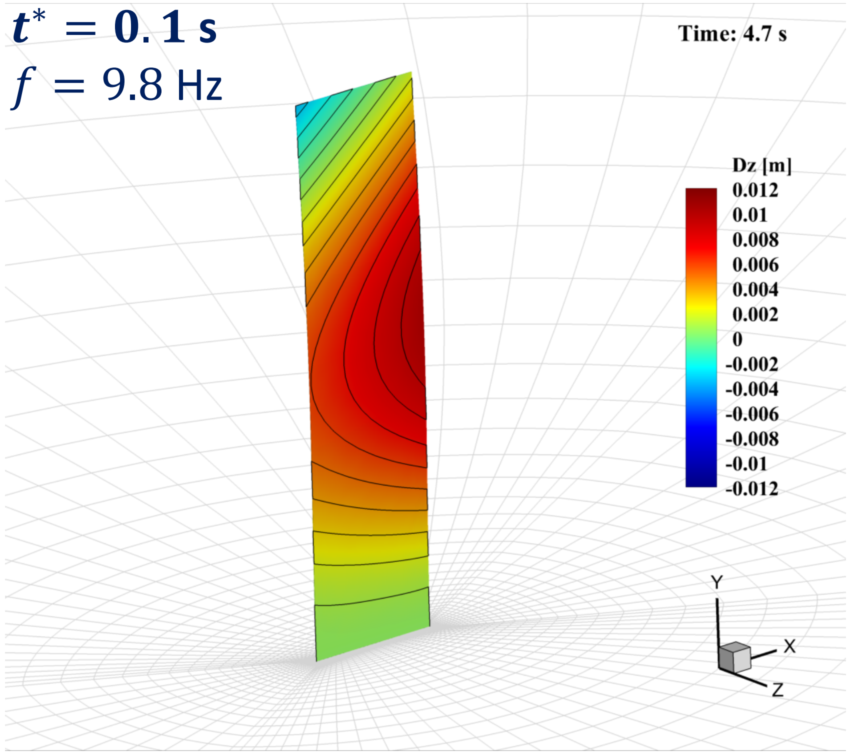


$\Lambda = 0°$

$U = 1.01\, U_f$

High frequency LCO
Dominated by **torsion**

$t^* = 0.1$ s
$f = 9.8$ Hz

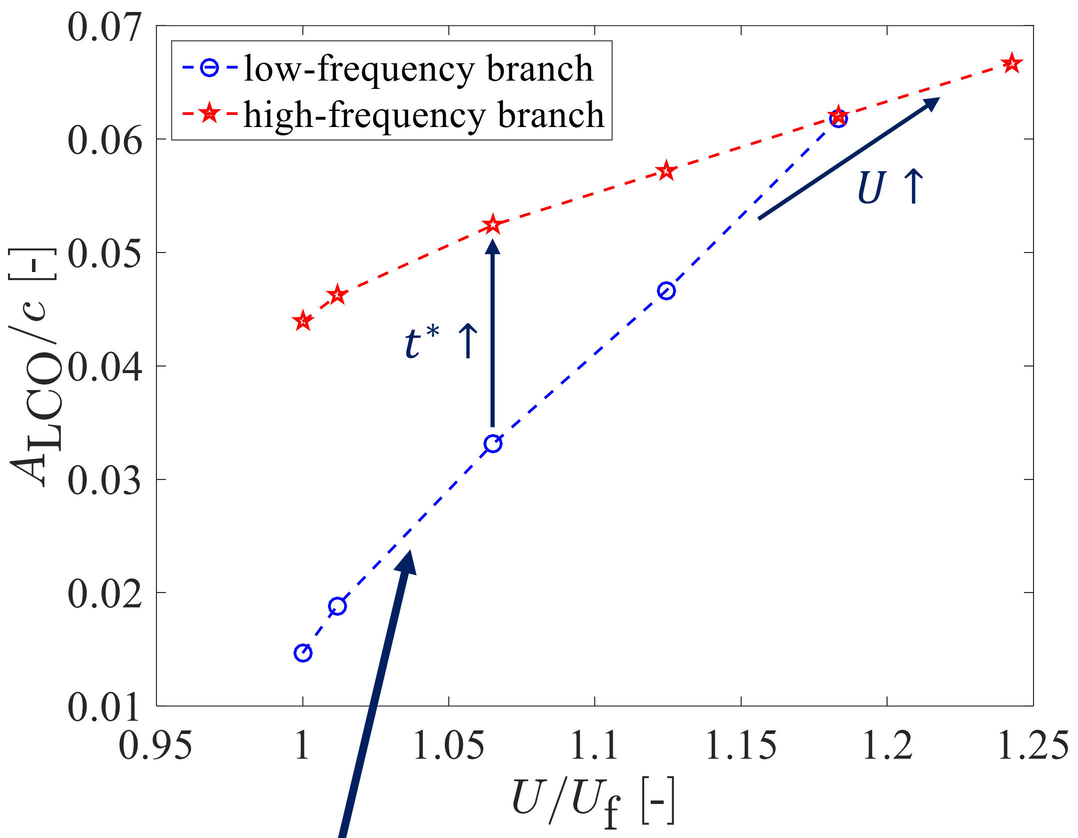


Thin flat plate wing

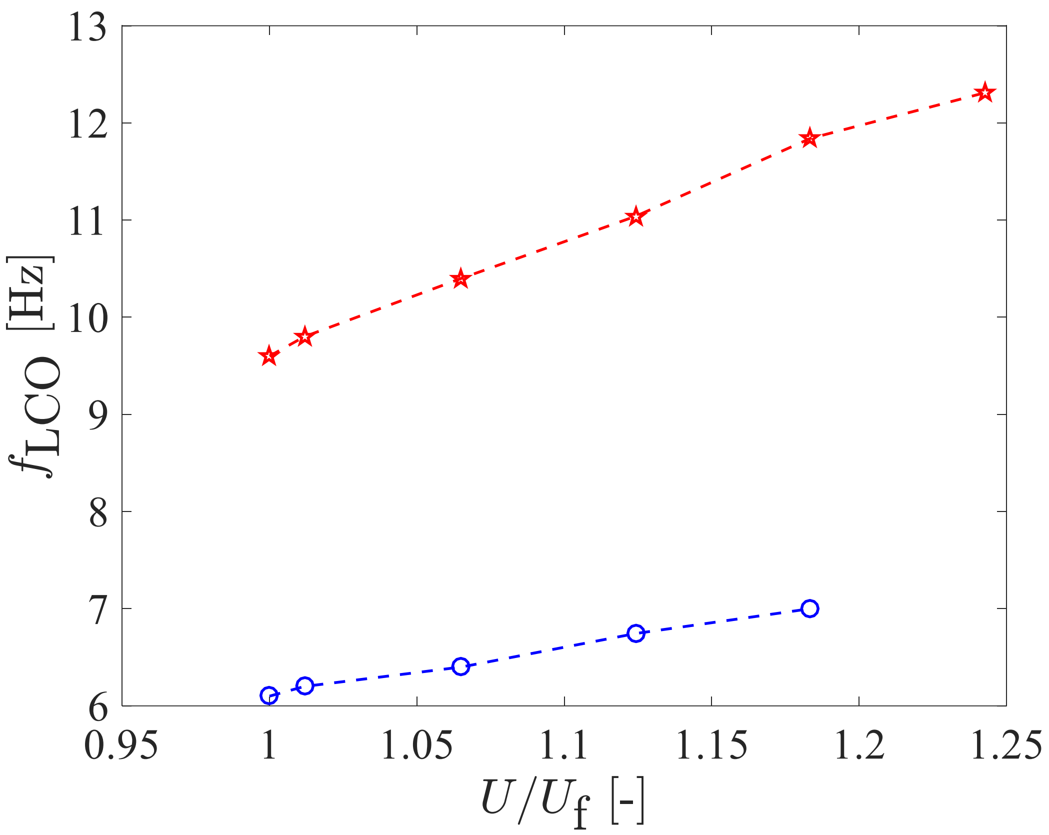
SU2+Metafor

$\boldsymbol{\Lambda = 0°}$

Amplitude



Frequency



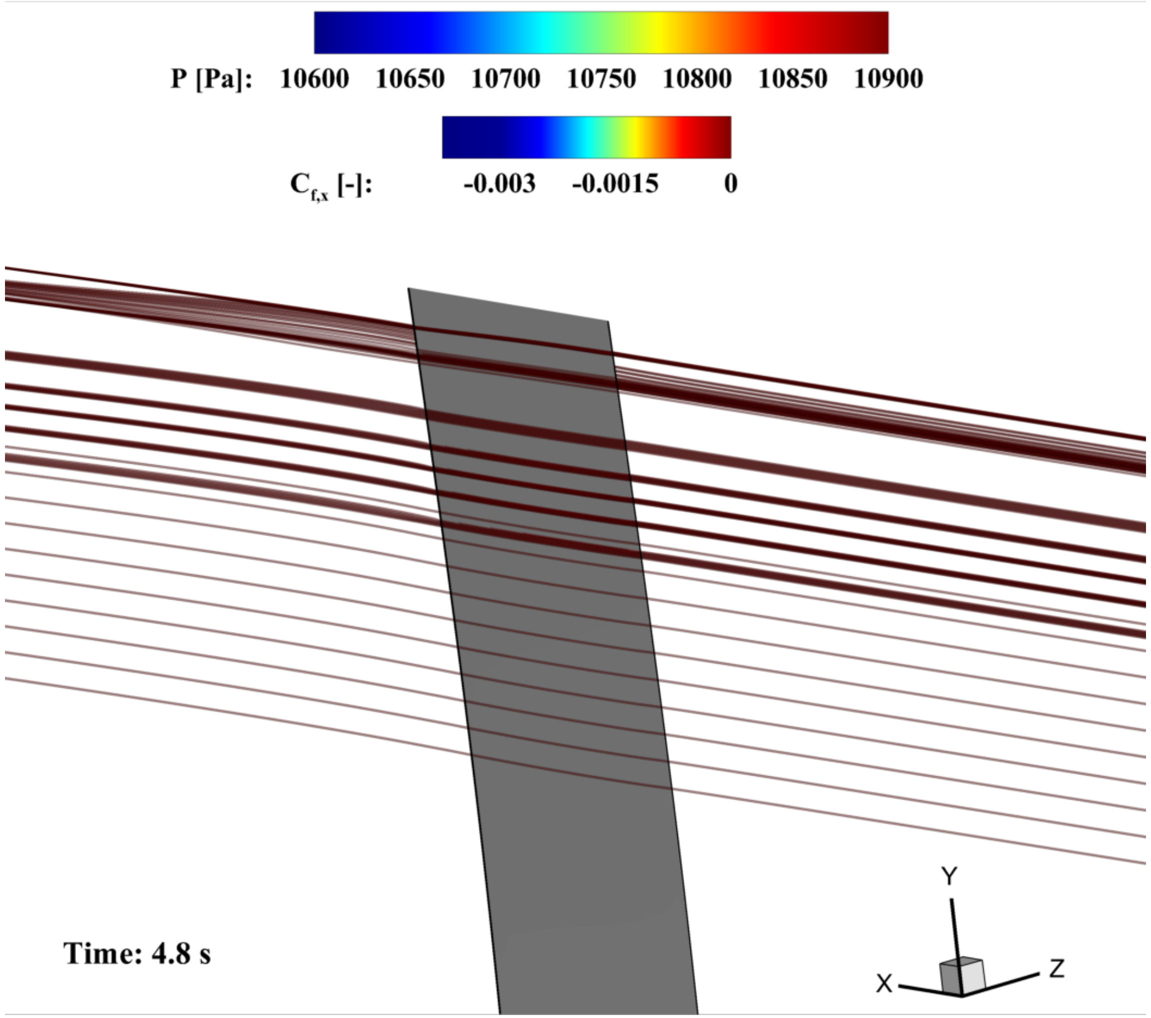
supercritical bifurcation

Not observed experimentally

Thin flat plate wing

LCO flow characteristics

SU2+Metafor

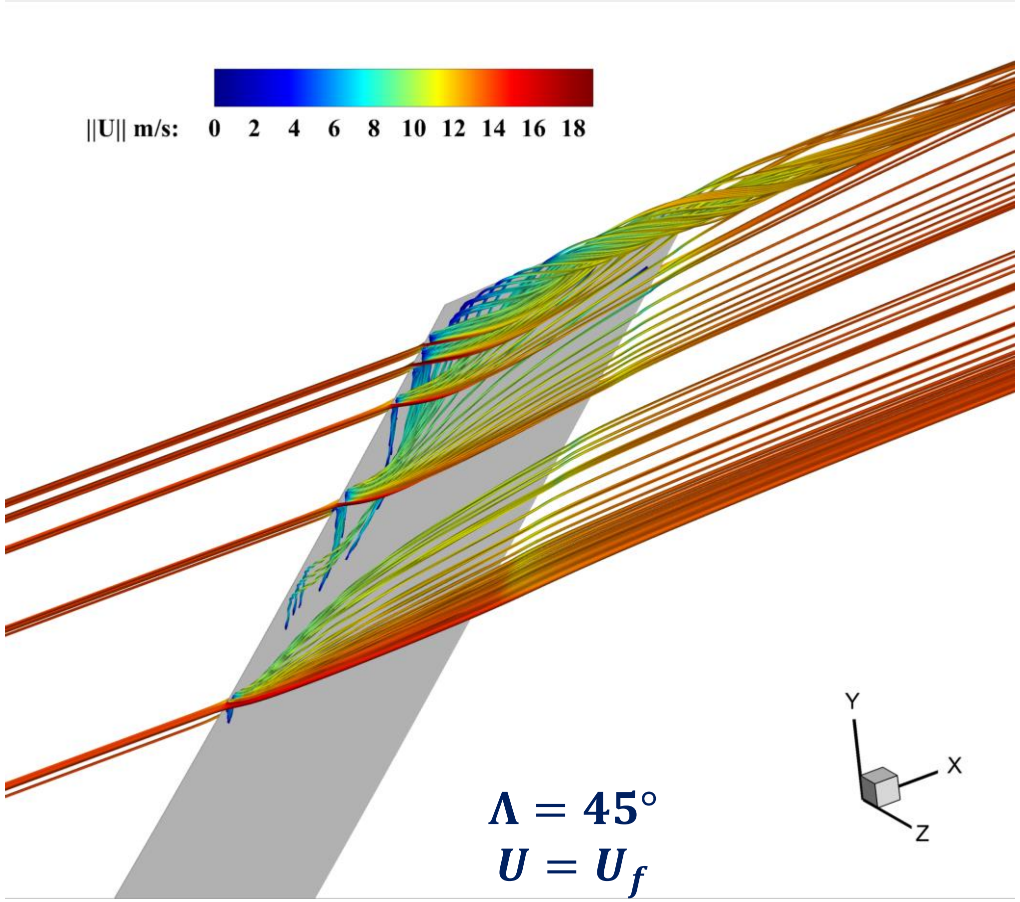


$\Lambda = 0°$
$t^* = 0.1$ s
$U = 1.01\ U_f$

- Periodic formation of a **leading edge recirculation** bubble
  ➔ locally increases the suction
- **Spanwise increase** of the size then collapses due to **tip vortices**
- Relates occurrence of **high-frequency LCO** with the occurrence of the LE recirculation

Thin flat plate wing

Aeroelastic response – swept wing



- Significant spanwise flow component
- Large tip vortices
- **No** LE recirculation detected

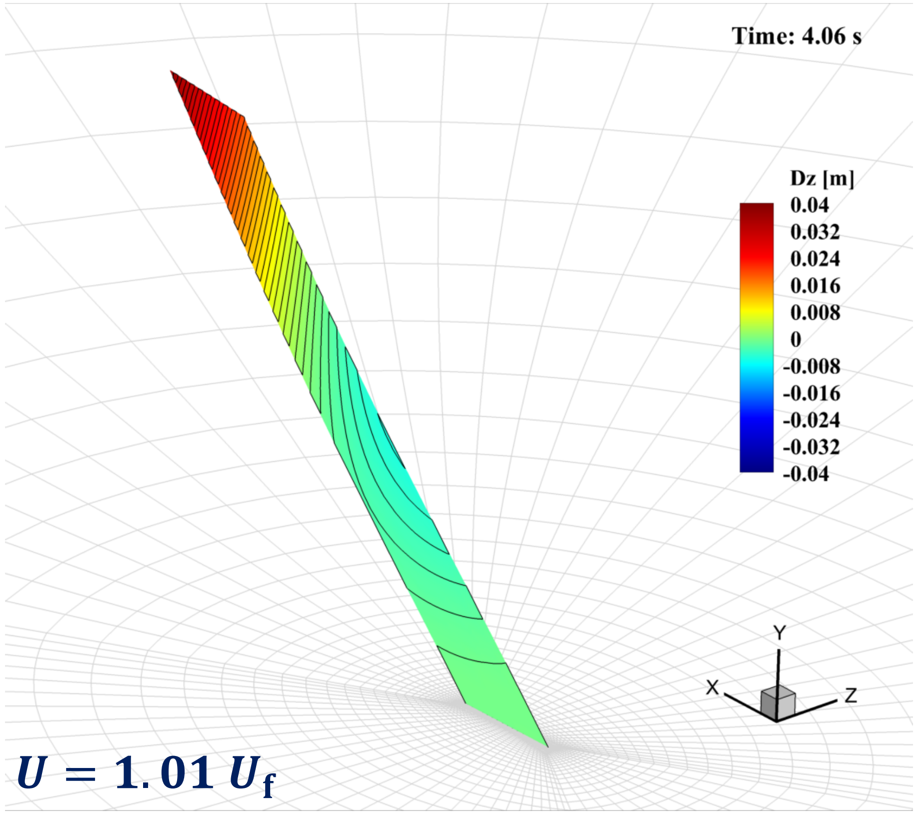
➔ Only **one LCO** branch

Thin flat plate wing

Aeroelastic response – swept wing

$\boldsymbol{\Lambda = 45°}$

Qualitative comparison with the experimental model



Outline

PART I: The FSI problem

- Overview
- Mathematical description and numerical formulation

PART II: CUPyDO

- Data structure and numerical models

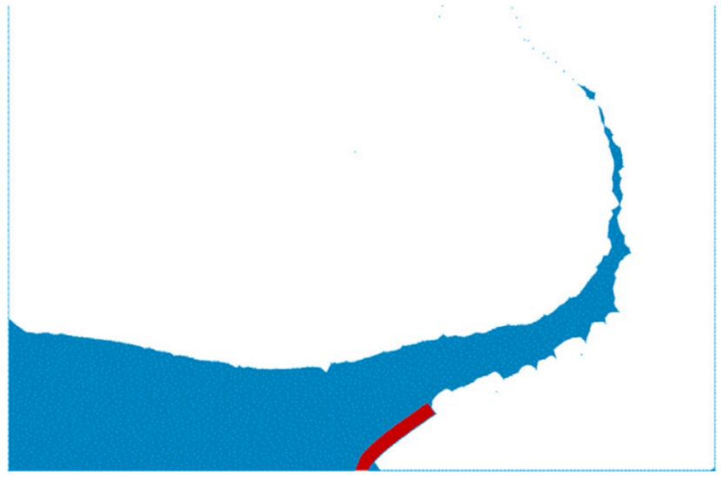
PART III: Verification and applications

- Verification test cases
- Aeroelastic study of a thin flat plate wing

CONCLUSION

Concluding words

Development of CUPyDO
- Innovative implementation of state-of-the-art coupling algos
- Coupling based on Python wrapping
- Maximizes flexibility and modularity
- Minimally intrusive

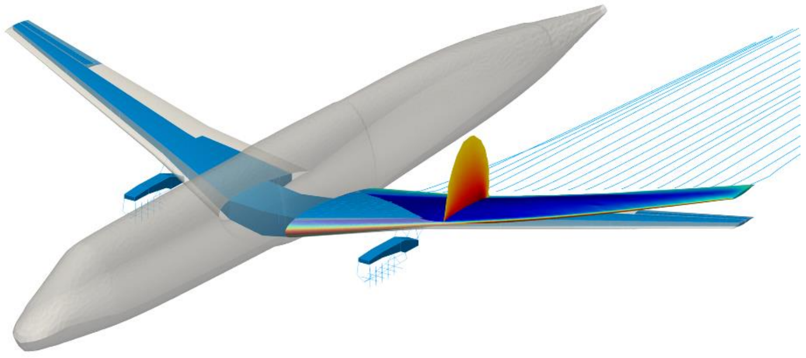


Dam break against elasto-plastic obstacle (PFEM+Metafor)
M.L. Cerquaglia

Application of CUPyDO…

… in this thesis
- Demonstrated the accuracy, flexibility and efficiency

… in other research projects
- FSI with free-surface flows and strong added-mass effect
- Steady aeroelasticity of composite wings in transonic regime
- Validation of lower-fidelity method for flutter calculation
- Adjoint formulation for steady FSI (unsteady is ongoing)



Aeroelastic study of the EBW (FLOW+Modali)
A. Crovato

Future perspectives

Development
- **Extend** the list of coupled solvers (e.g. OpenFOAM, TACS)
- **Vectorial** coupling (>< staggered)
- Improve/extend non-matching mesh **interpolation**
- **Scalability** on massively distributed resources

Applications
- More general **multiphysics** applications (e.g. add electro-magnetic field)
- **Unsteady adjoint FSI** using harmonic balance
- FSI with **very large** solid motion

Acknowledgements

Funding entity

RÉGION WALLONNE

Computational resources

C.E.C.I

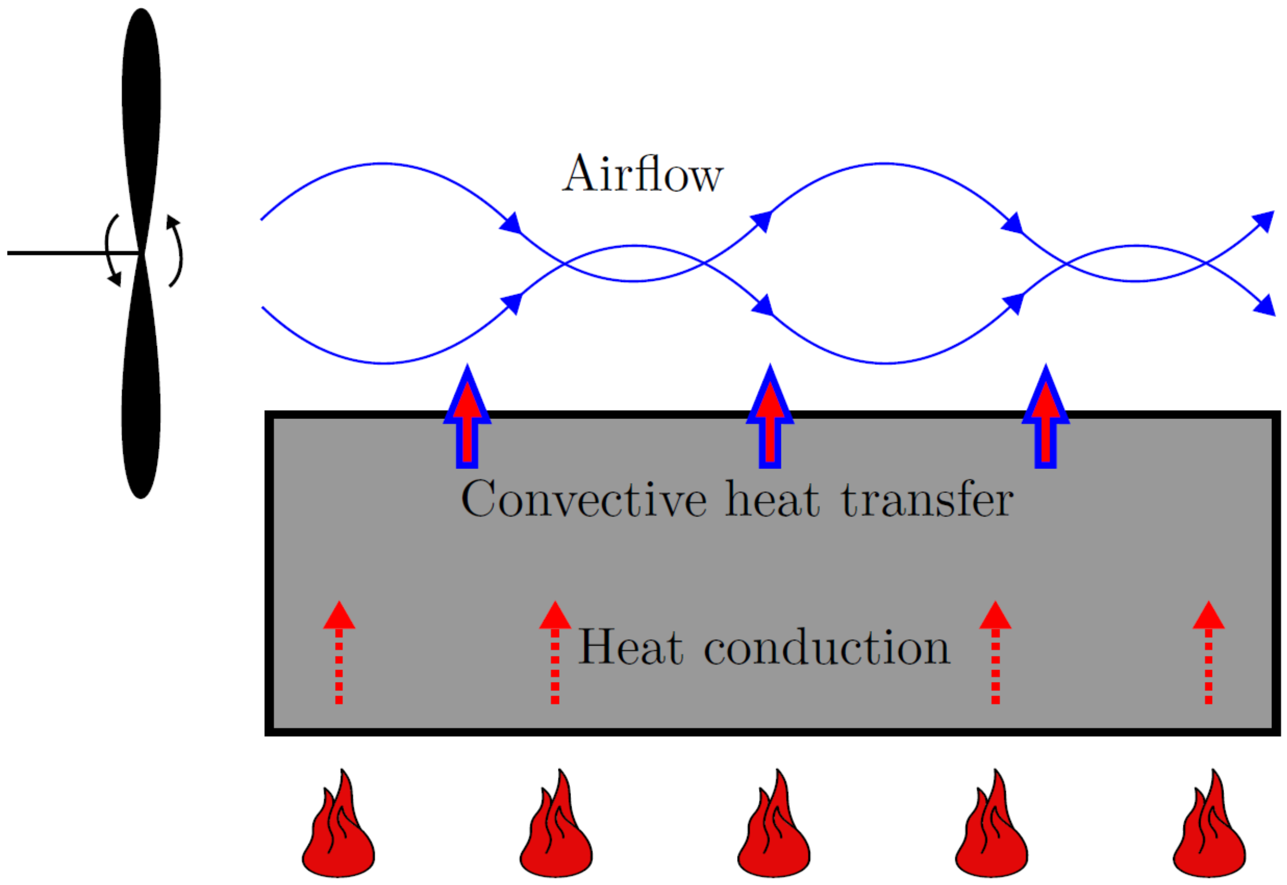
Research stay + SU2

Stanford University

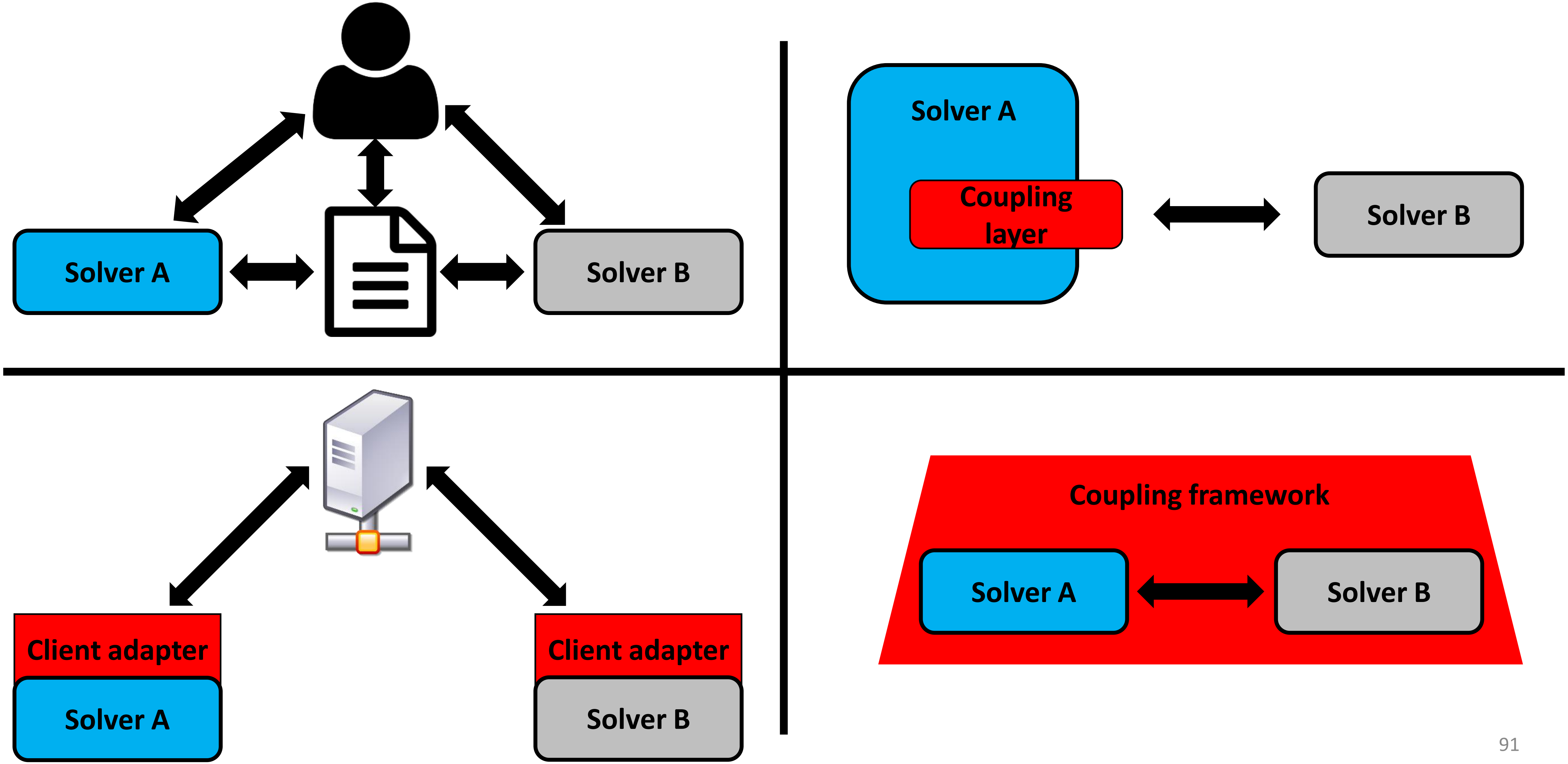
aerospacedesignlab

Additional support

Thermal coupling: conjugate heat transfer (CHT)



Multi-code coupling architectures



Development of a coupling framework

Review of existing software

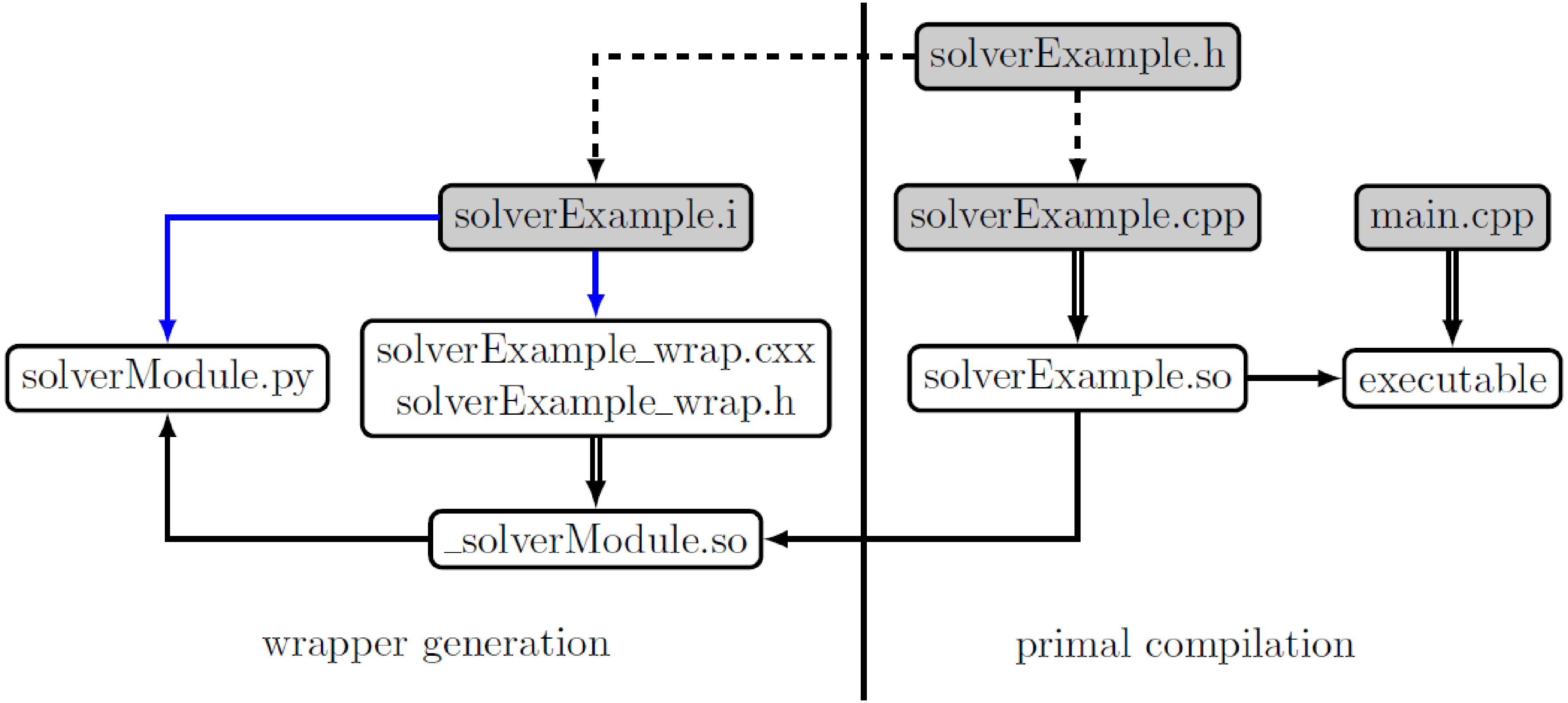
	API level	HPC	Legal	Coup. schemes	Communication	Intrusive
ADVENTURE	med	yes	in-house	yes	TCP/IP	yes
EMPIRE	med	no	open	yes	MPI	yes
MpCCI	med	no	commercial	yes	TCP/IP	yes
OpenPALM	high	yes	open	no	MPI	yes
OASIS	low	yes	open	no	MPI	yes
preCICE	high	yes	open	yes	TCP/IP/MPI	yes
FUNtoFEM	high	yes	open	yes	TCP/IP/MPI	no
CUPyDO	high	yes	open	yes	Direct	no

Development of a coupling framework

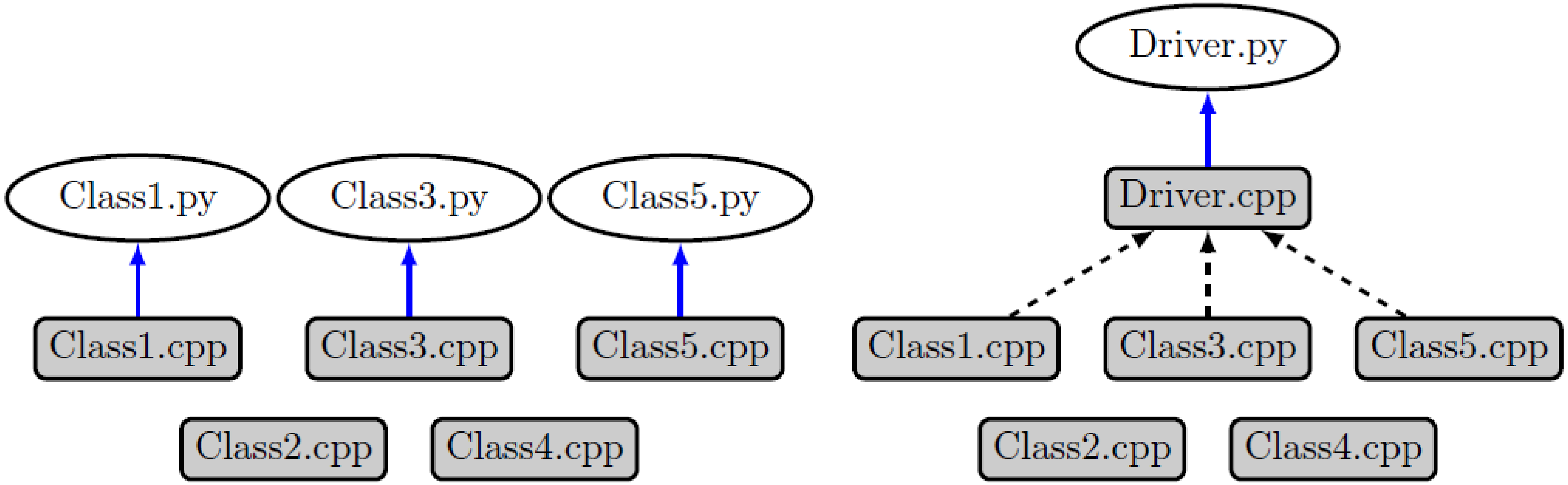
Review of existing software

	API level	HPC	Legal	Coup. schemes	Communication	Intrusive
ADVENTURE	med	yes	in-house	yes	TCP/IP	yes
EMPIRE	med	no	open	yes	MPI	yes
MpCCI	med	no	commercial	yes	TCP/IP	yes
OpenPALM	high	yes	open	no	MPI	yes
OASIS	low	yes	open	no	MPI	yes
preCICE	high	yes	open	yes	TCP/IP/MPI	yes
FUNtoFEM	high	yes	open	yes	TCP/IP/MPI	no
CUPyDO	high	yes	open	yes	Direct	no

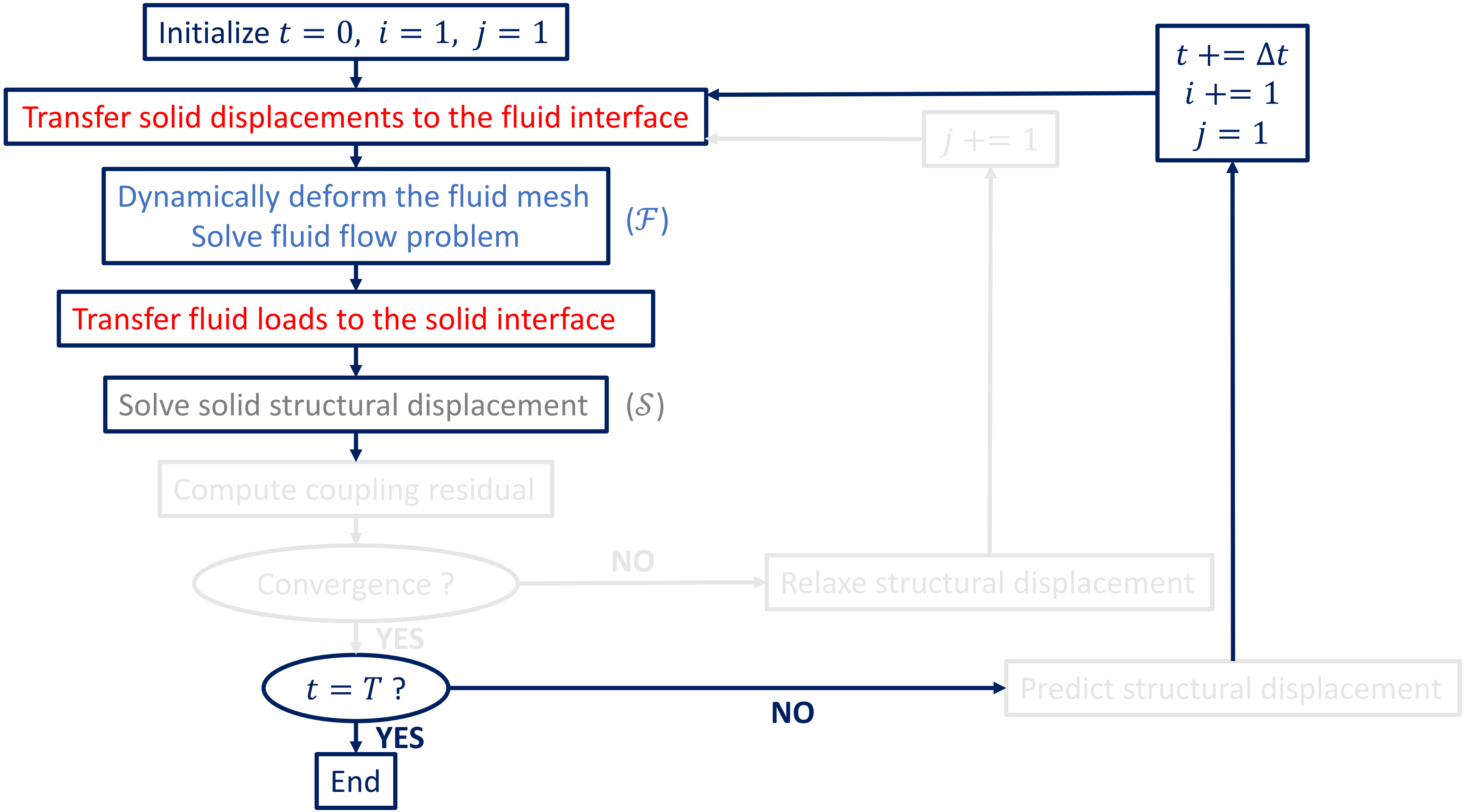
Python wrapper generation



Class architecture

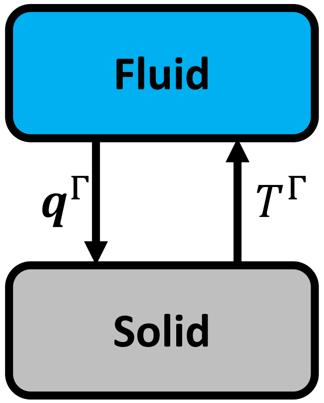


Weak coupling algorithm



Thermal coupling schemes

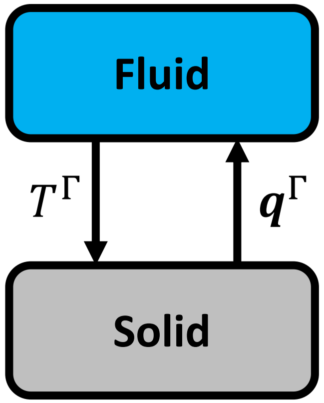
$$\mathrm{Bi} = \frac{hL}{\lambda}$$



FFTB

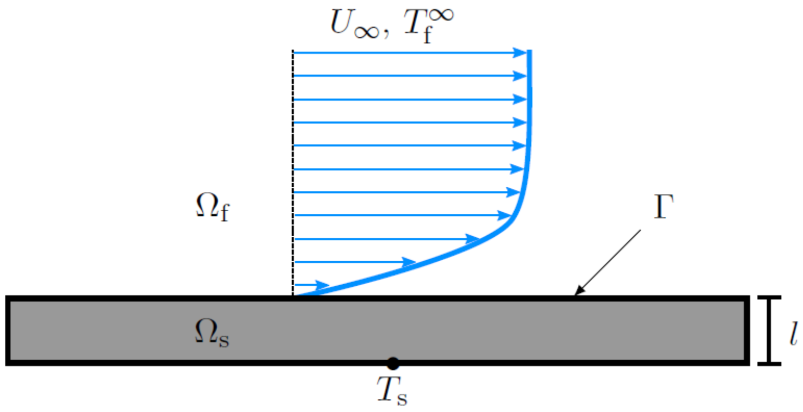
Stable for $\mathrm{Bi} < 1$

TFFB



Stable for $\mathrm{Bi} > 1$

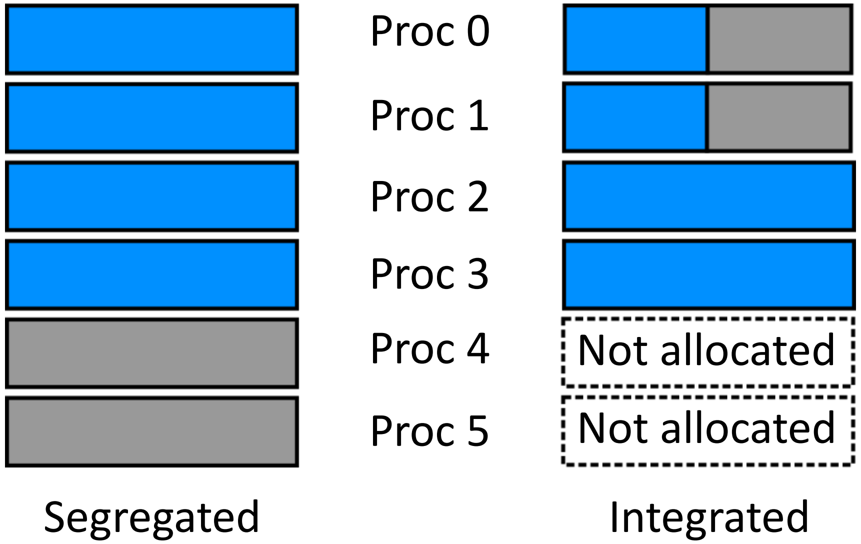
Stability analysis for simple 1D CHT problem



Use of **numerical heat transfer coefficient** to stabilize or accelerate the convergence (hFFB, hFTB)

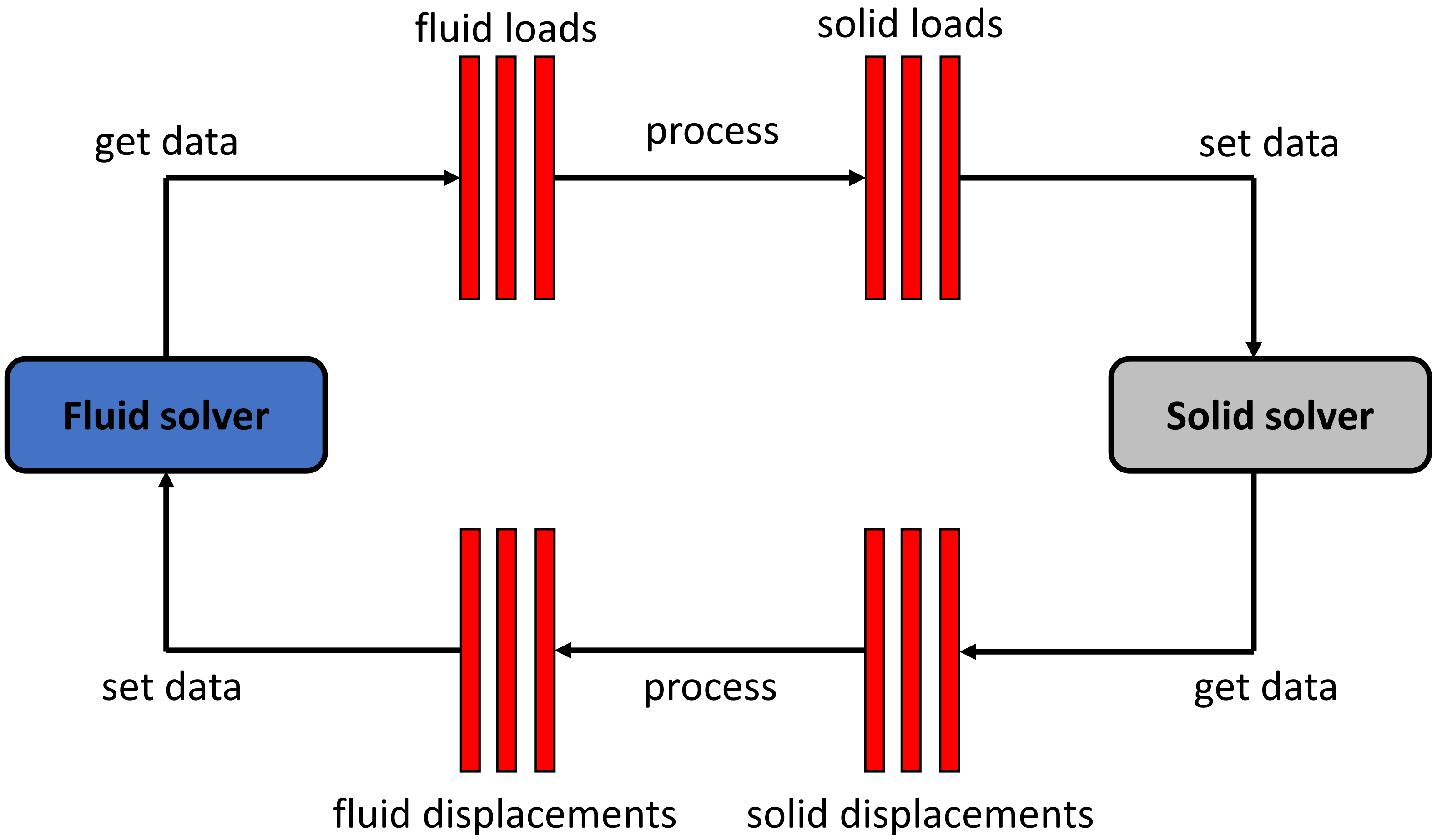
Stability based on **numerical vs physical Bi**

Partitioned solver distribution

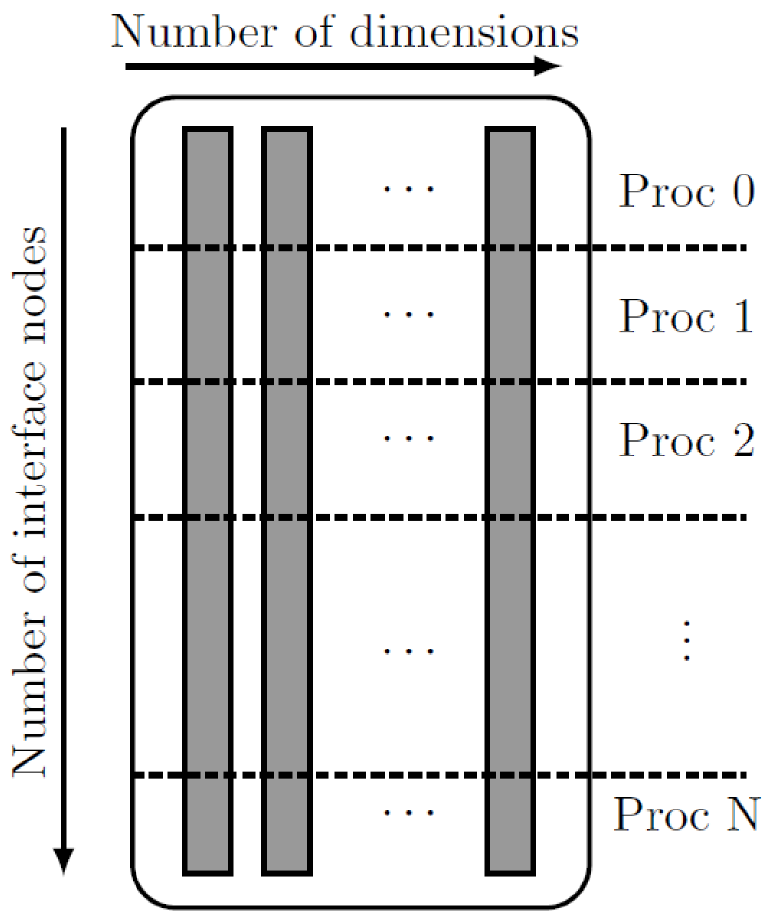


Interface date structure

Used in inter-communications



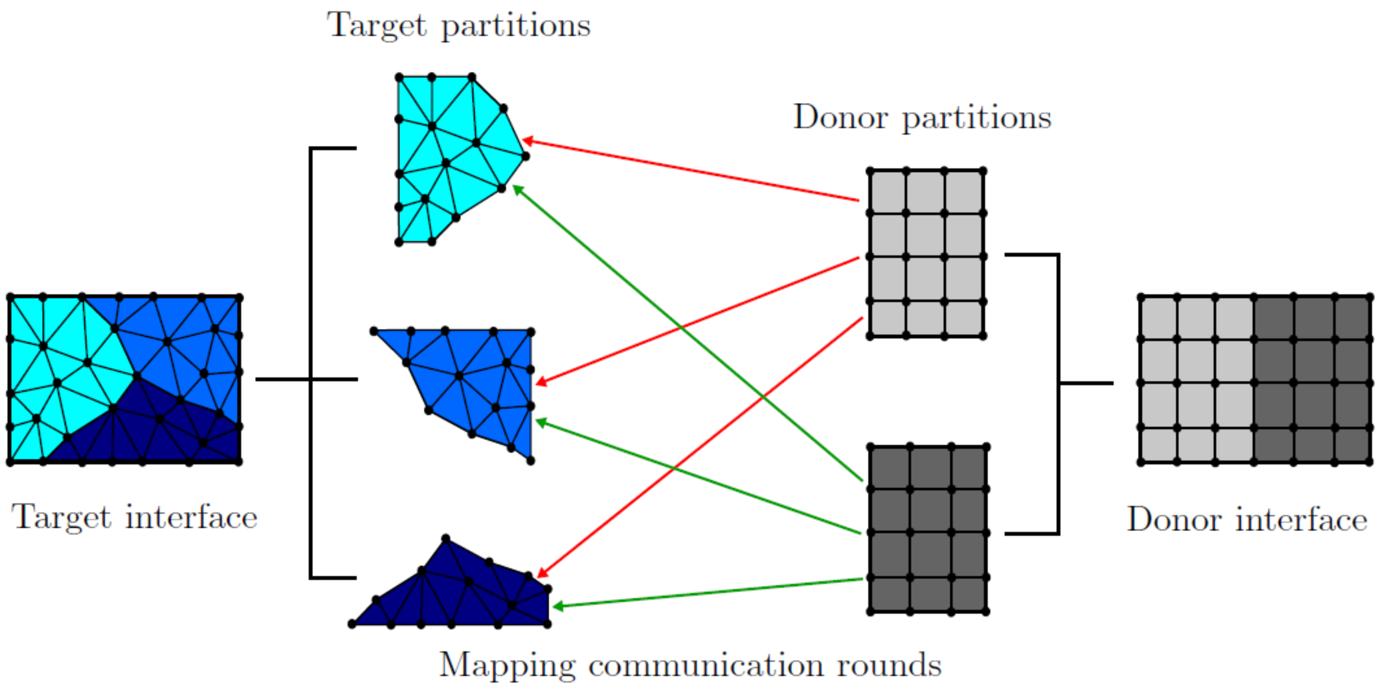
Interface data structure



Interface mesh treatment

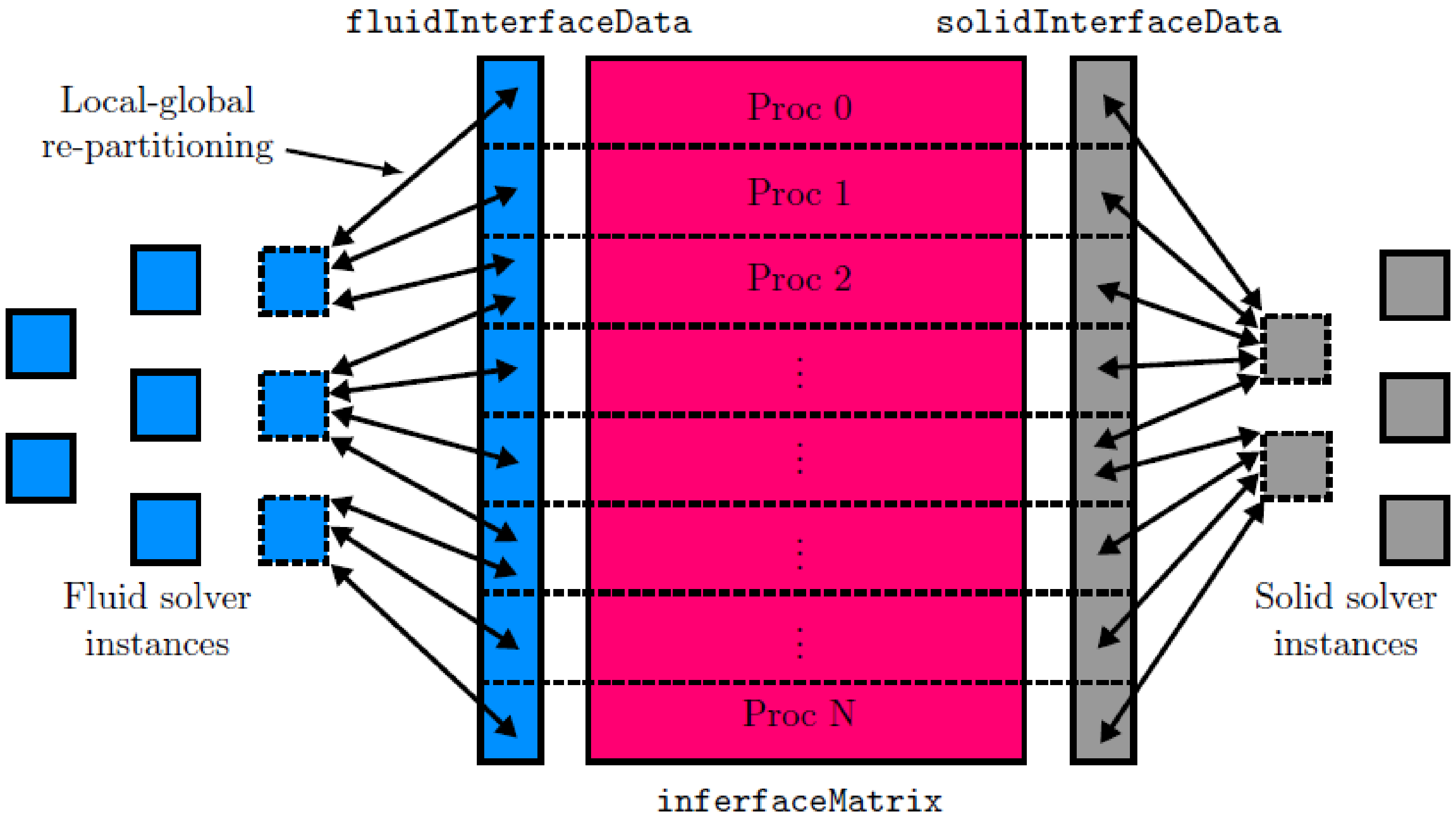
Parallel mapping

- Mapping performed **in parallel** through successive MPI communication **rounds** (donor → target)
- Use of **non-blocking communications**
- Each pair of donor-target fills the corresponding entries of the **matrices**

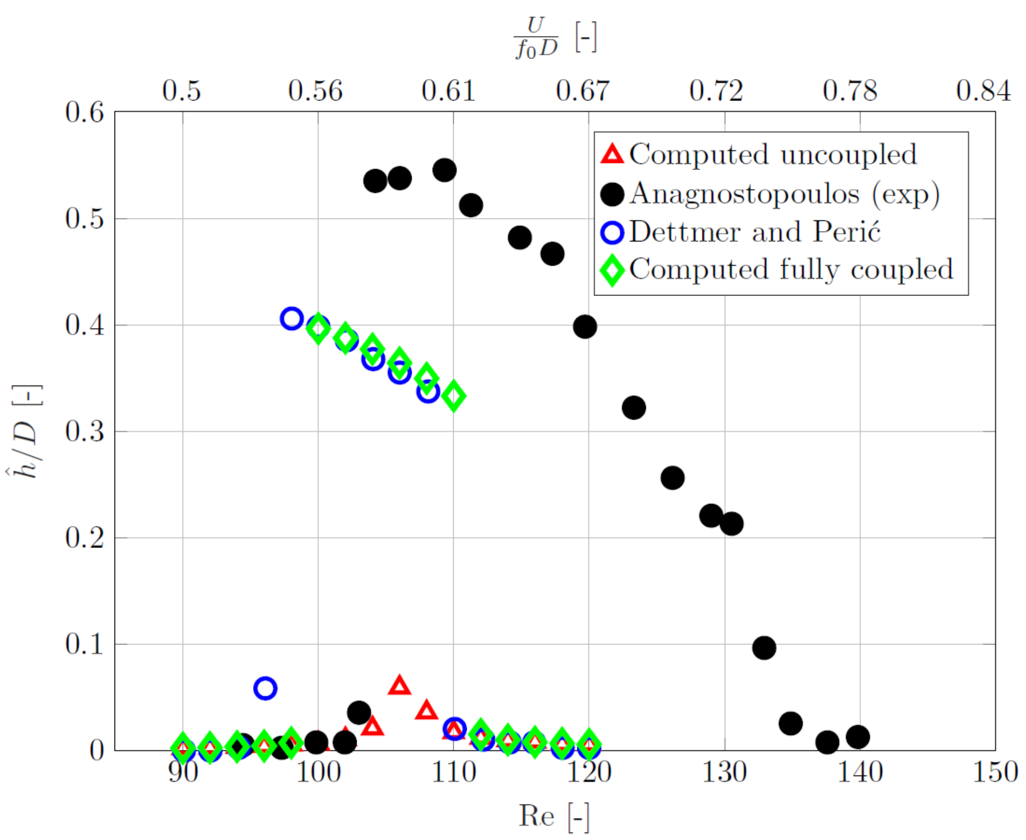


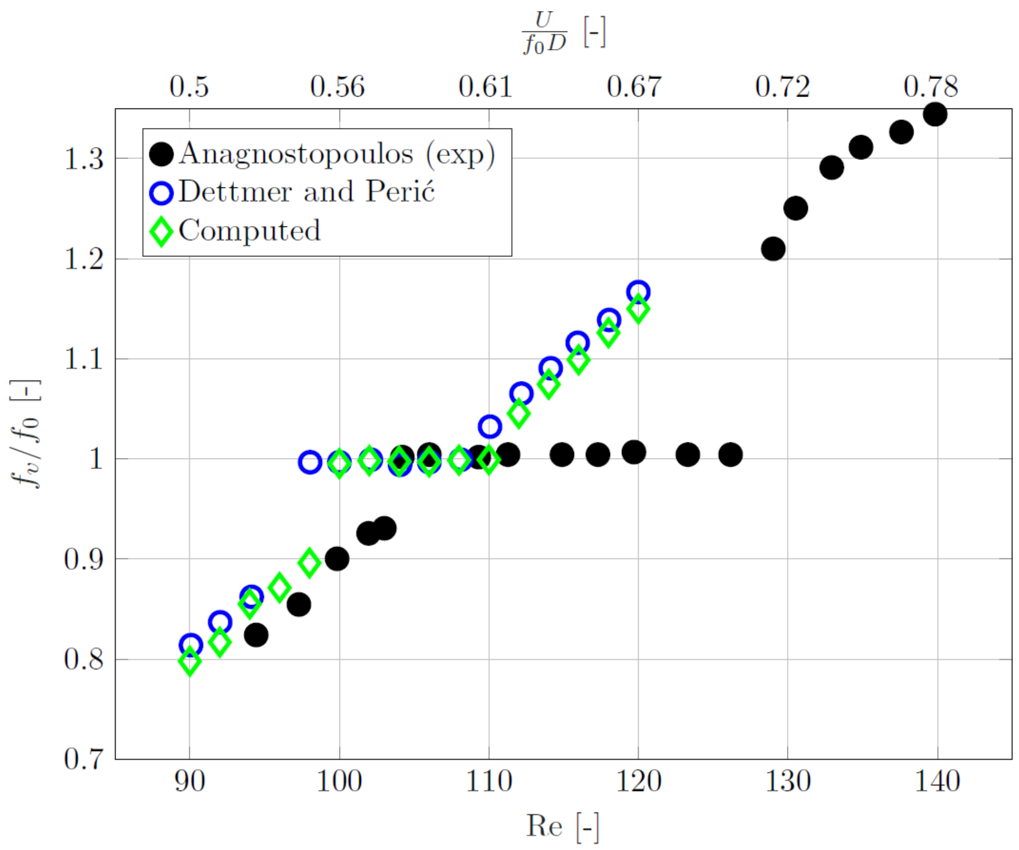
Interface data structure

Interface matrix



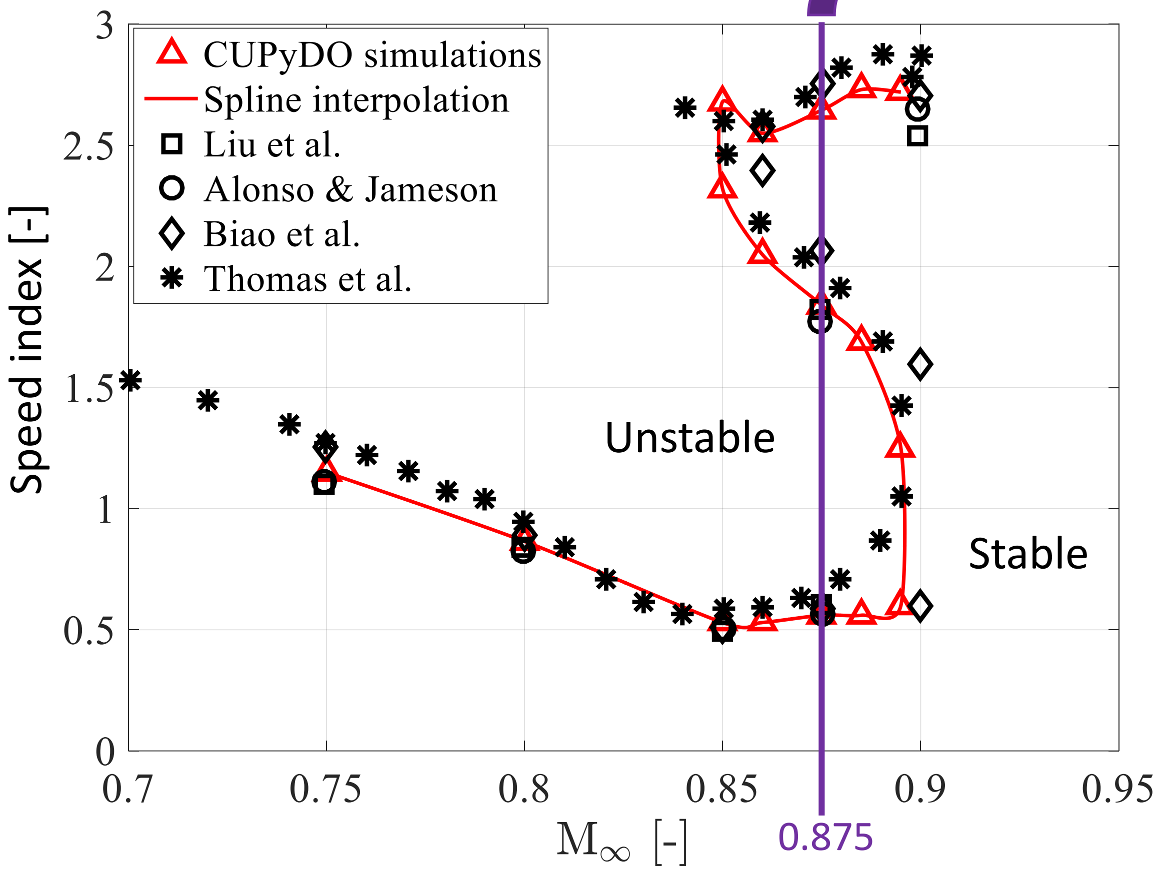
VIV of a rigid cylinder



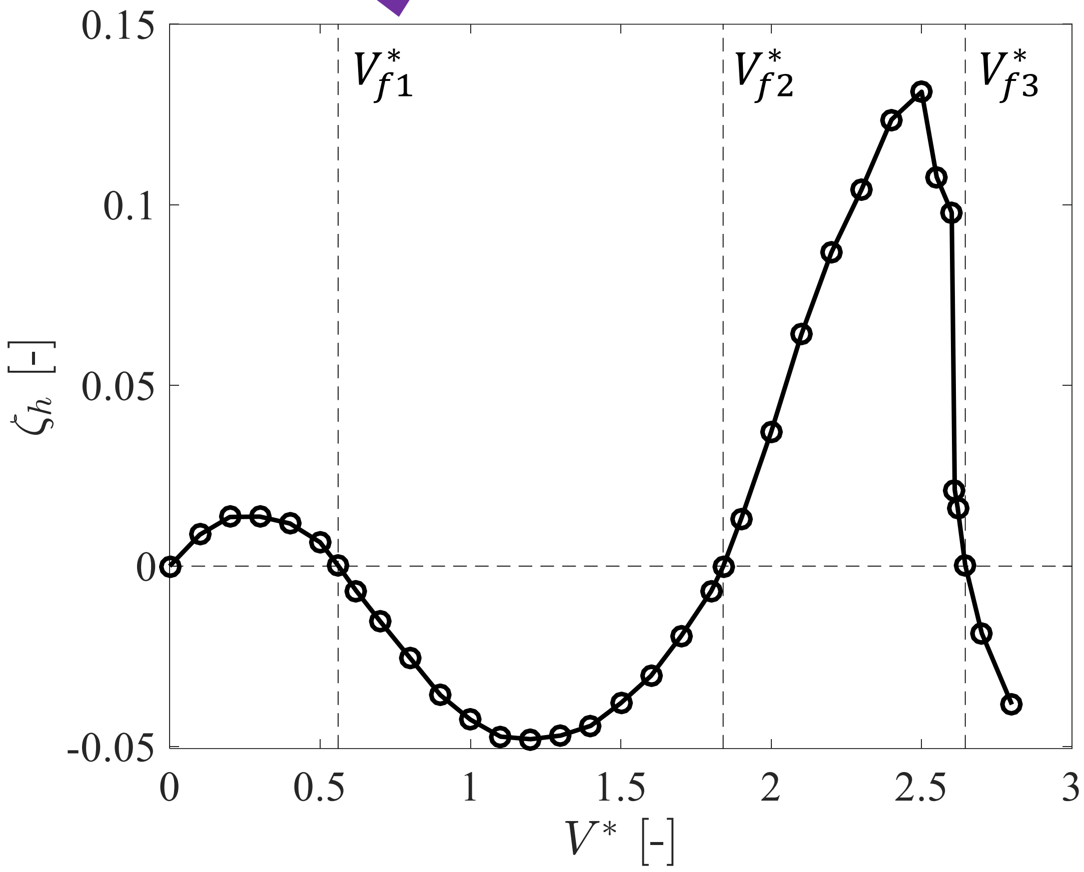


Flutter - Isogai wing section

Flutter boundary

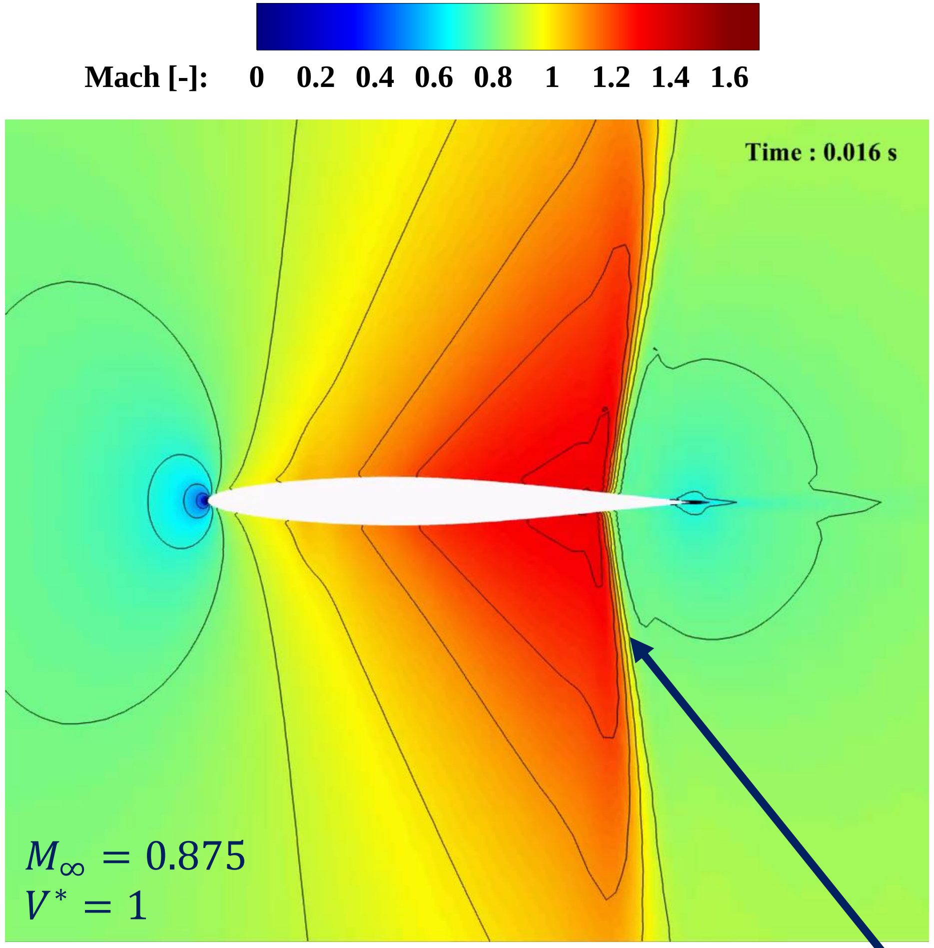


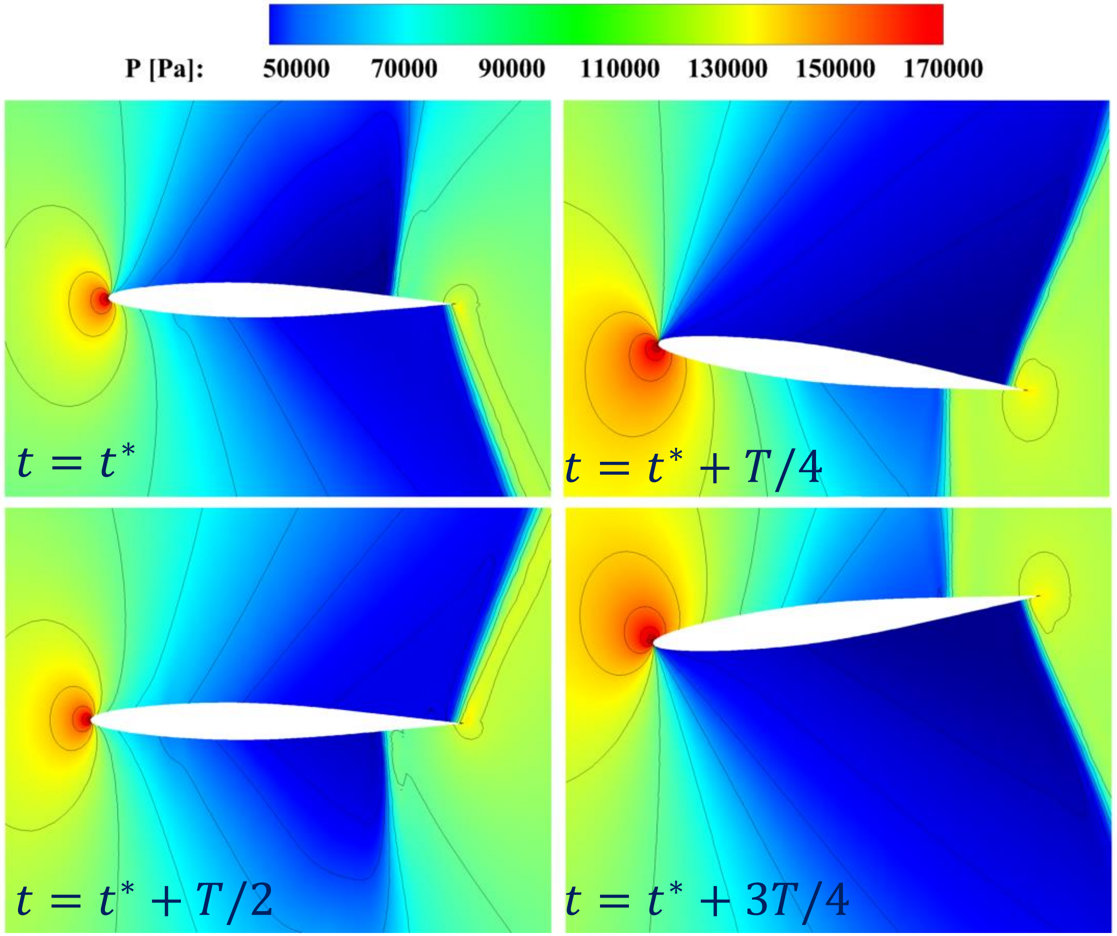
Damping coefficient



Flutter - Isogai wing section

Limit cycle aeroelastic response

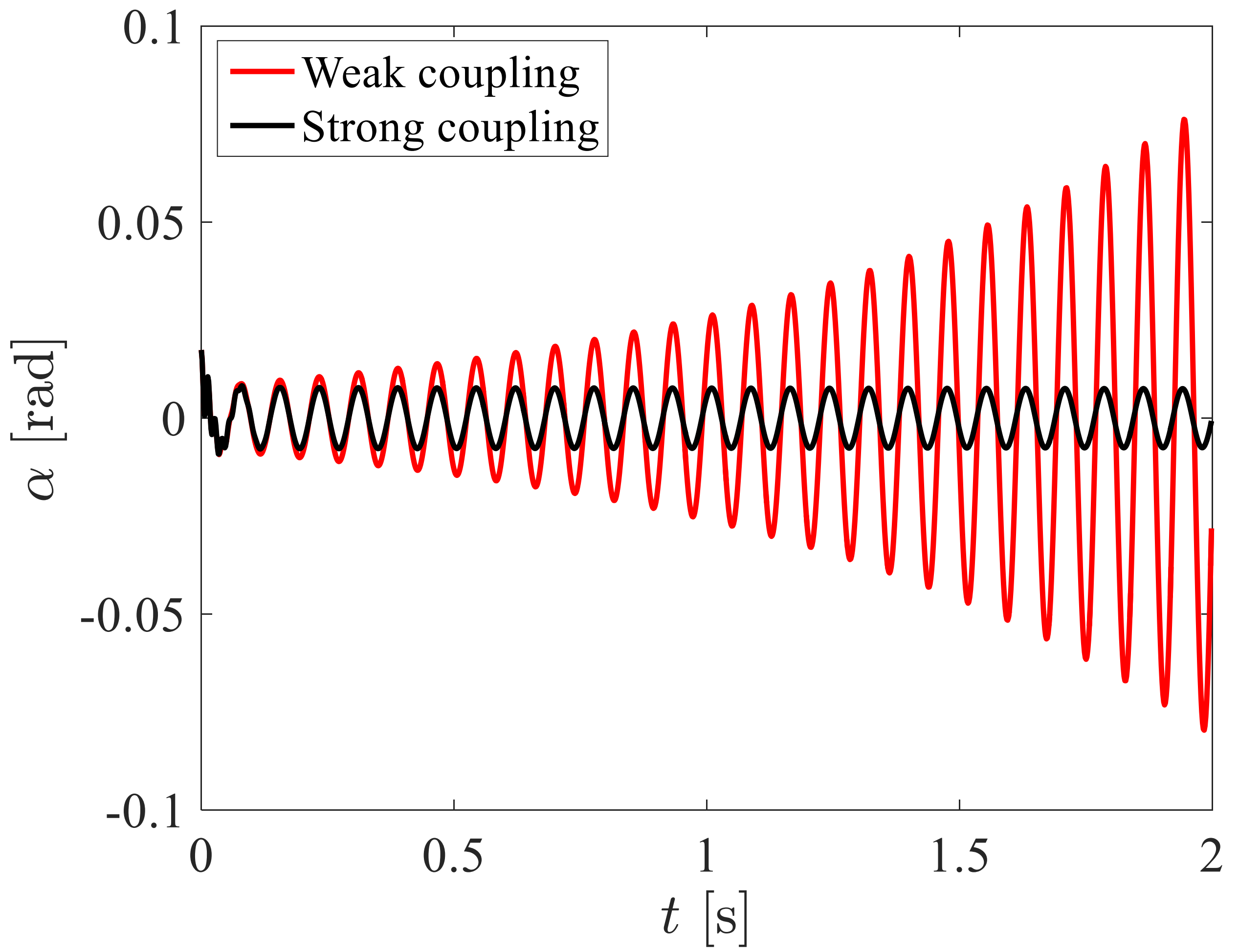




Oscillating shock

Isogai wing section

Weak vs strong coupling



Weak coupling provides **numerically** stable solution, but **physically** unstable response

➔ flutter point is under-predicted compared to strong coupling

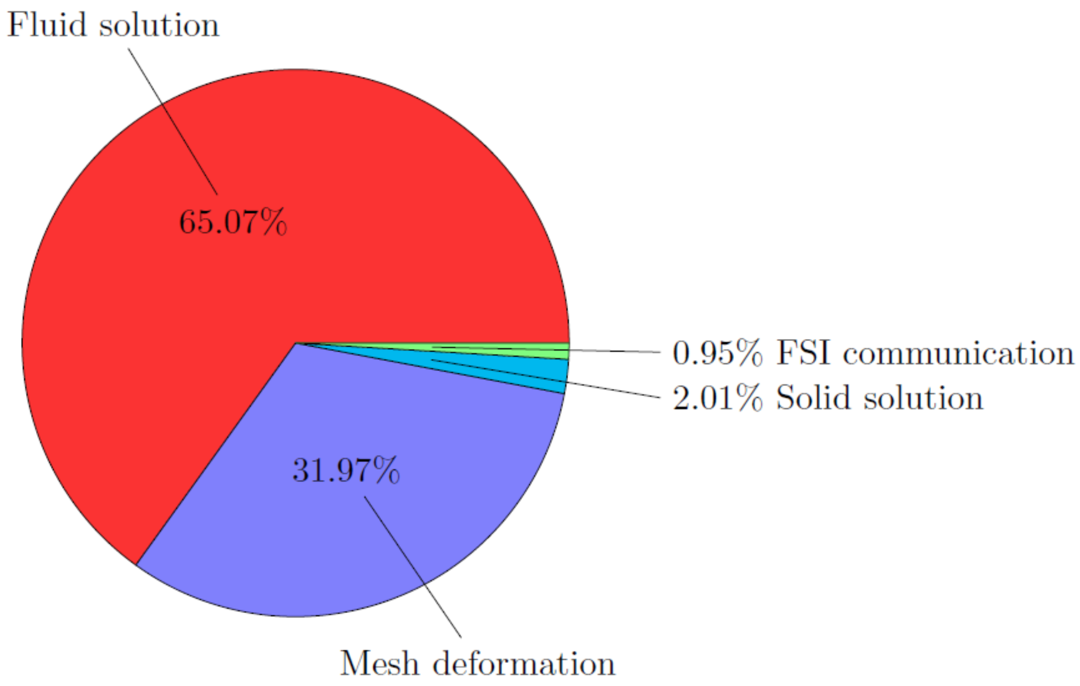
AGARD 445.6

Performance measurement

SU2+Metafor

Mesh size:	248 000 cells
Physical time step:	10^{-3} s
Coupling tolerance:	10^{-7} m
Mean number of FSI iterations:	3
Number of threads:	16 fluid – 1 solid

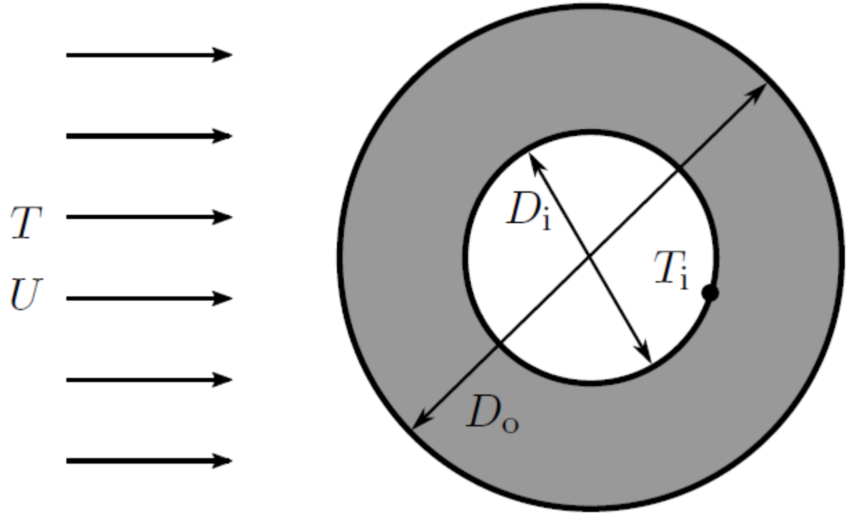
➔typical computing time: **12h for one cycle of the response**



Heated hollow cylinder in cross-flow

Coupled model

SU2+GetDP



$\mathrm{Re} = 40$
$\mathrm{M} = 0.38$
$\mathrm{Pr} = \frac{\nu}{\alpha} = 0.72$

Case A: $\frac{\lambda_s}{\lambda_f} = 4$ ➔ $\overline{\mathrm{Bi}} < 1$

Case B: $\frac{\lambda_s}{\lambda_f} = \frac{1}{4}$ ➔ $\overline{\mathrm{Bi}} > 1$

Flow: viscous laminar flow
Solid: linear FE model (heat equation)

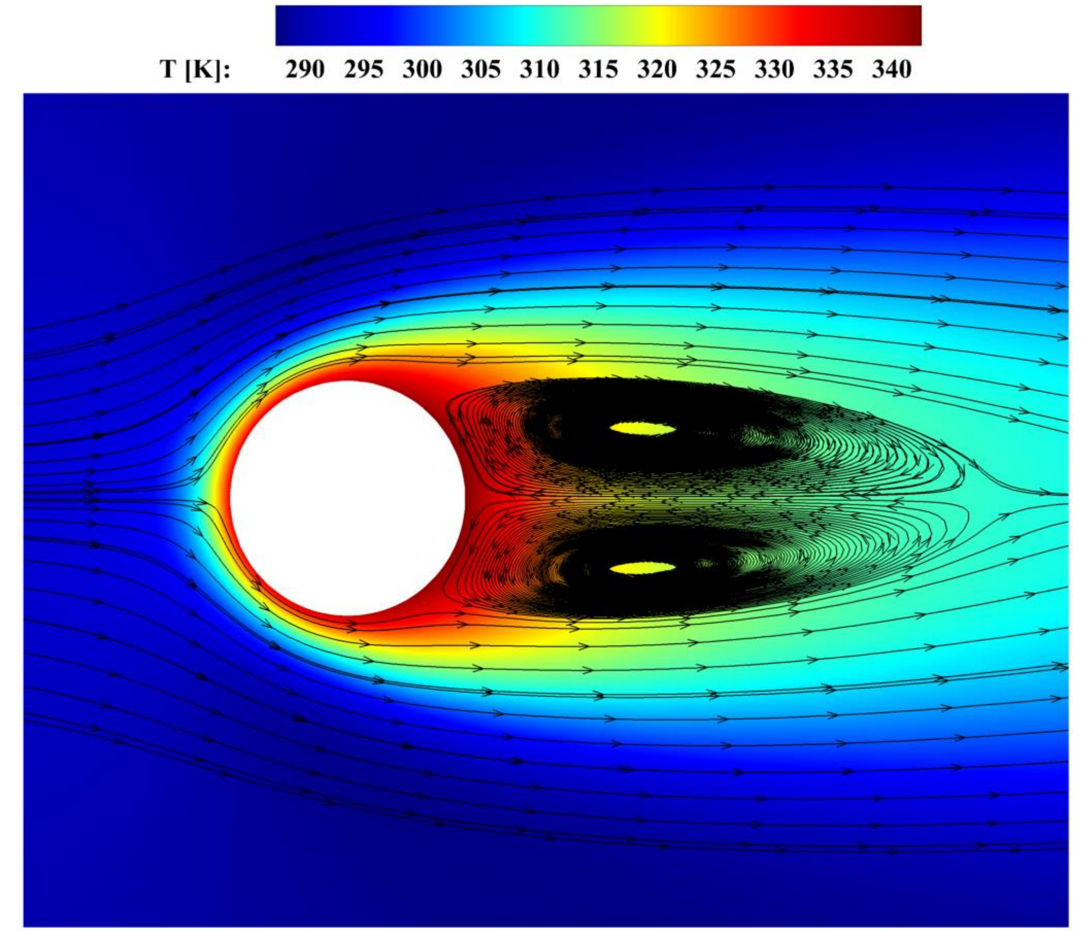
Interface: matching discretization

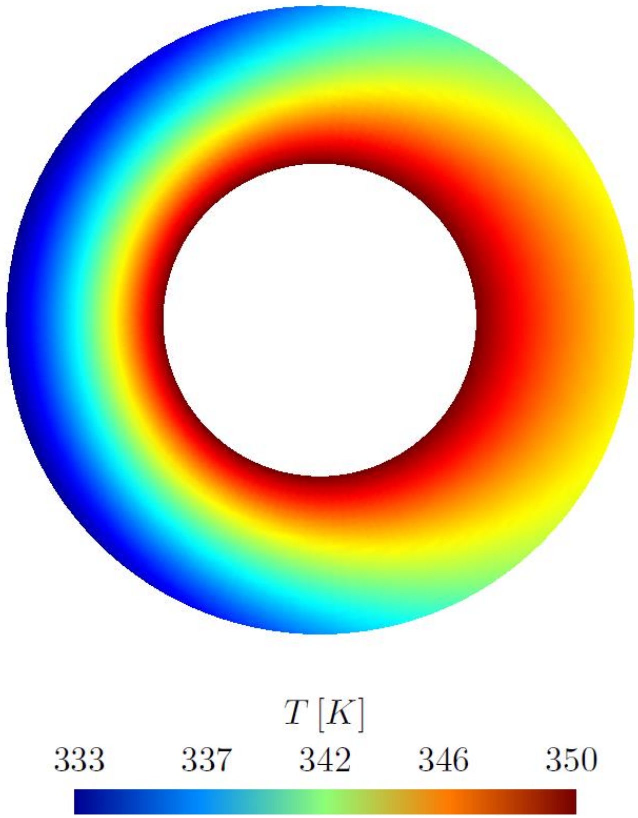
- The steady state thermal equilibrium is sought
- Assessment of the available coupling schemes

Heated hollow cylinder in cross-flow

Temperature field – $\overline{\mathrm{Bi}} < 1$

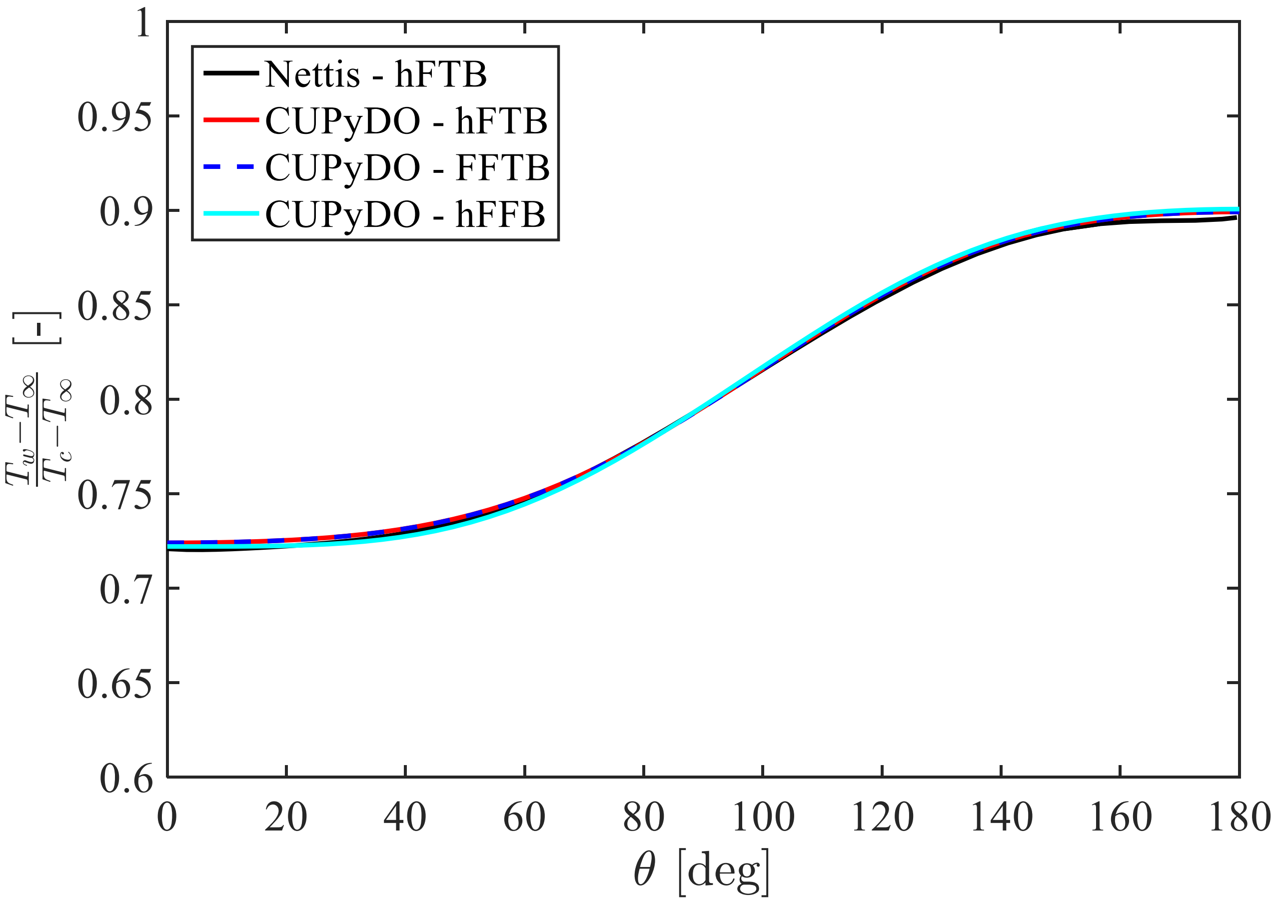
SU2+GetDP

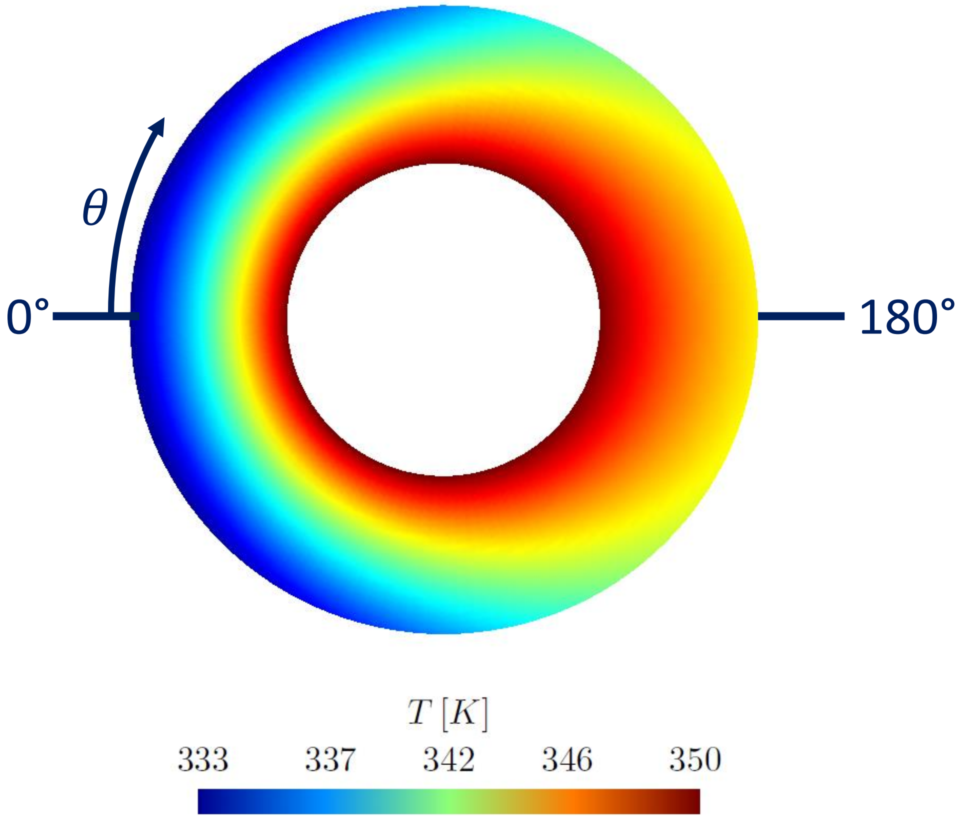




Heated hollow cylinder in cross-flow

Temperature distribution – $\overline{\mathrm{Bi}} < 1$





Heated hollow cylinder in cross-flow

Performance of coupling schemes

SU2+GetDP

	$\overline{\mathbf{Bi}} < \mathbf{1}$	$\overline{\mathbf{Bi}} > \mathbf{1}$
FFTB	8	Unstable
TFFB	Unstable	8
hFTB	8	Unstable
hFFB	33	11

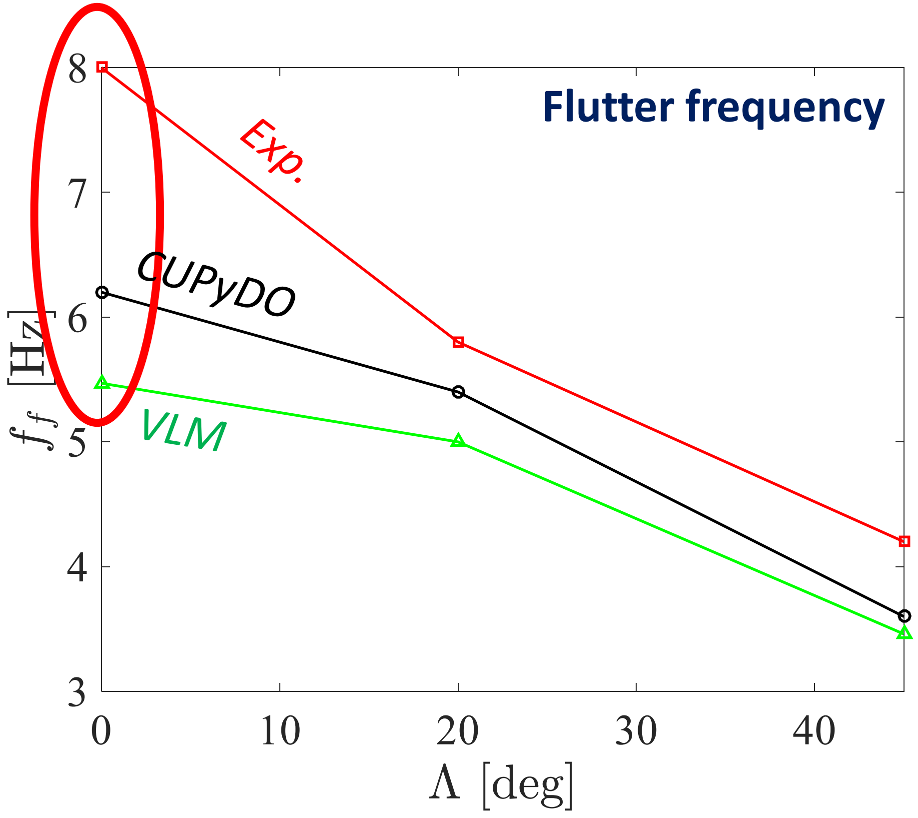
- Expected behavior for FFTB and TFFB (cf. 1D stability analysis)
- Numerical h.t.c. can stabilize the FB scheme for $\overline{\mathrm{Bi}} < 1$, requires more iterations
- Numerical h.t.c. cannot stabilize the TB scheme for $\overline{\mathrm{Bi}} > 1$
- Using numerical h.t.c. does not improve the convergence rate for stable cases

Thin flat plate wing

Flutter speed and frequency

Experimental model **($\Lambda = 0°$) at flutter speed**
Snapchot of the **mean deflection**

G. Dimitriadis



mean deflection → stiffening →increased frequency

Computation time
VLM : a few seconds
CUPyDO: 12h for one cycle

Thin flat plate wing

LCO flow characteristics