TOPOLOGY OPTIMIZATION OF BINARY STRUCTURES UNDER DESIGN-DEPENDENT FLUID-STRUCTURE INTERACTION LOADS

R. Picelli, S. Ranjbarzadeh, R. Sivapuram, R.S. Gioria, E.C.N. Silva

rpicelli@usp.br – Research Fellow
Graduate Program in Mechanical Engineering
University of São Paulo, Brazil

Research Centre for Gas Innovation
cleaner energy for a sustainable future

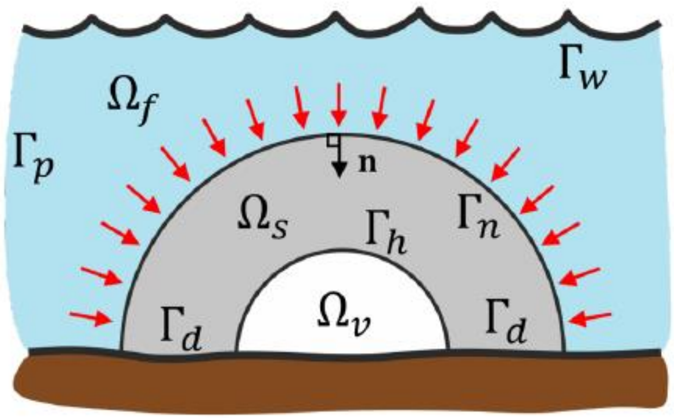
Acknowledgement:
FAPESP

TOP Webinar 8
December 17th , 2020

Contents

- Introduction – Fluid-structure interaction (FSI) in topology optimization (TO)
- Topology optimization of binary structures (TOBS)
- A new recipe for FSI design
- Results
- Conclusions

Introduction



[1] Picelli et al. (2019)

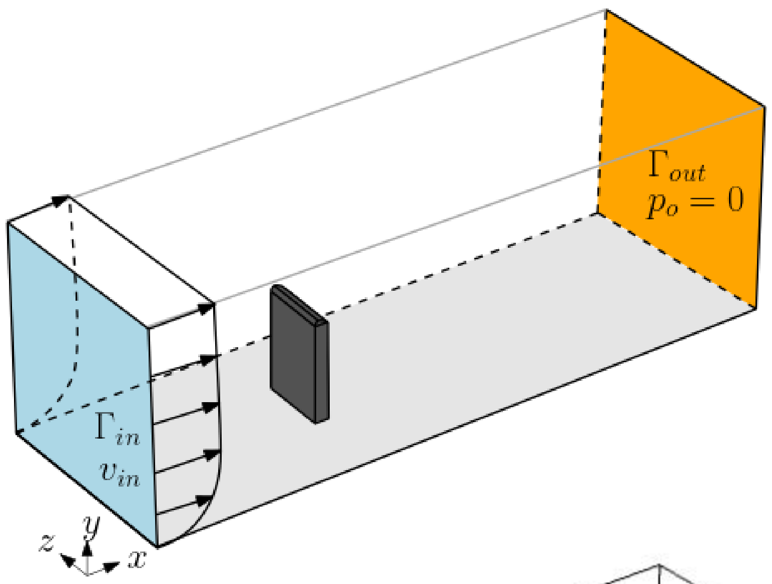
- Multiphysics
  - Hydrostatic fluid pressure
  - Thermoelastic design
  - Acoustic-structure interaction
  - Fluid flow optimization
  - Acoustics
  - …

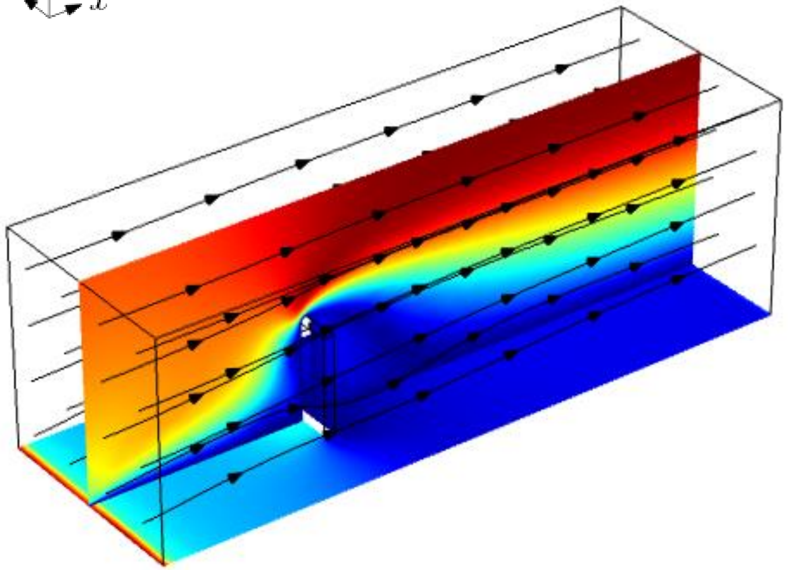
www.marinetechnologynews.com/news/sales-forum-subsea-announced-557928

Underexplored and challenging!

Introduction

- Multiphysics
  - Hydrostatic fluid pressure
  - Thermoelastic design
  - Acoustic-structure interaction
  - Fluid flow optimization
  - Acoustics
  - …
- Fluid-structure interaction (FSI)



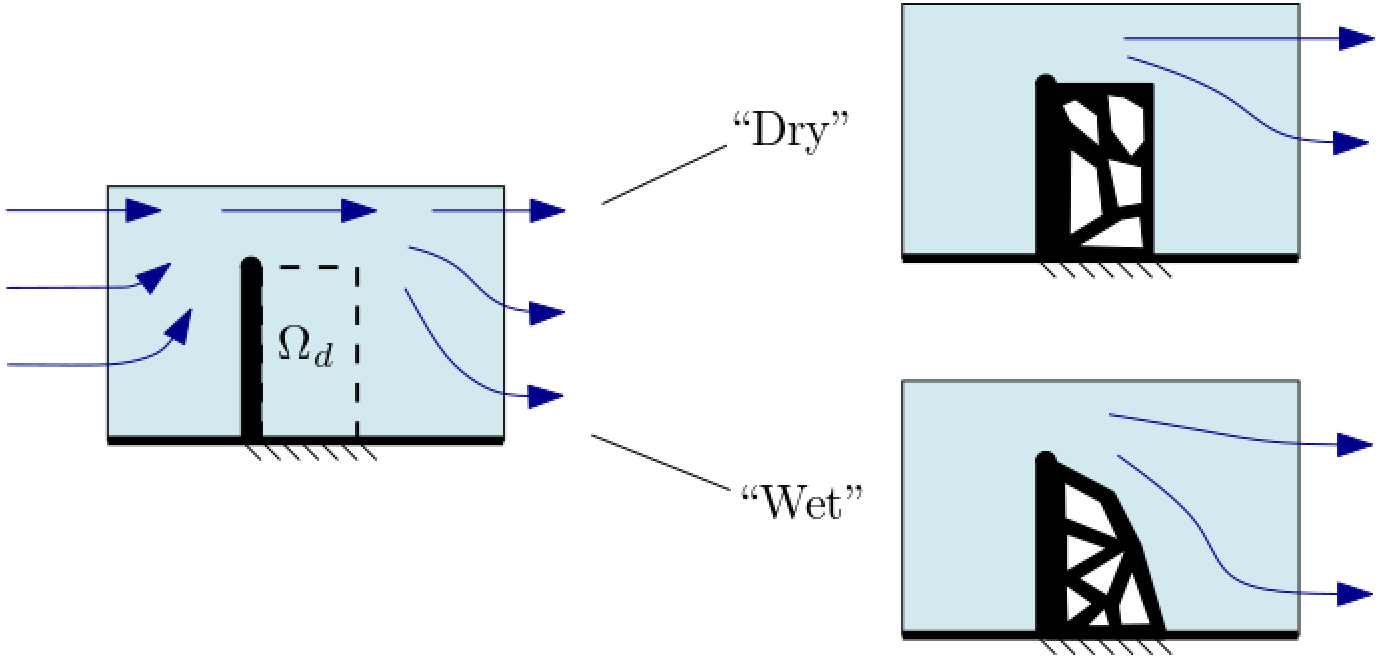


Objectives

- Topology optimization of FSI problems
- Use the TOBS approach
- Create an algorithm to decouple analysis and optimization grid

- Motivation: create a methodology for FSI and other physics design

Topology Optimization in FSI problems

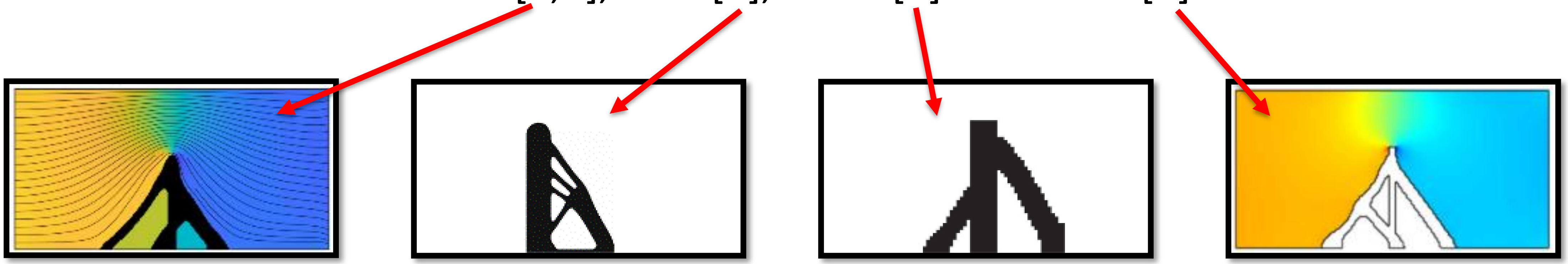


Design-dependent loading problem

[4] Jenkins and Maute (2016)

Topology Optimization in FSI problems

- Scientific and technological challenges
  - FSI design-dependent loading – equilibrium conditions
  - Strongly coupled phenomenon: fluid flow ↔ structural deformation
- Available TO methods: SIMP [2,3], LSM [4], BESO [5] and TOBS [6]

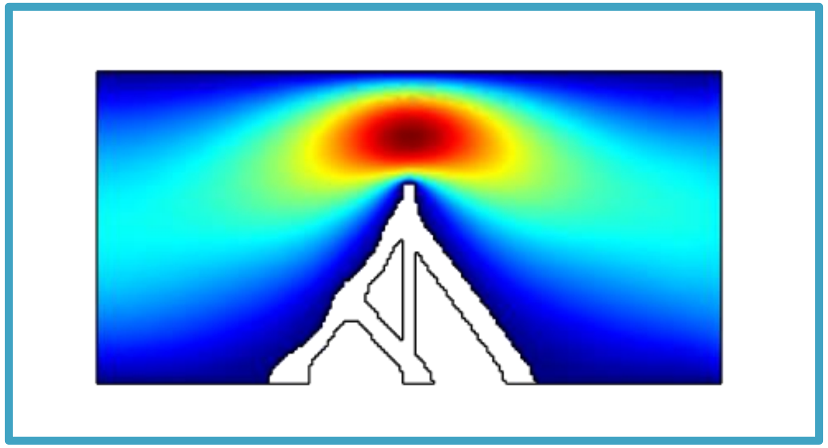


❖ [2] Lungaard et al. (2018); [3] Yoon (2010); [4] Jenkins and Maute (2016); [5] Picelli et al. (2017); [6] Picelli et al. (2020)

Topology Optimization in FSI problems

TOBS approach

FSI simulation



[6] Sivapuram and Picelli (2018), [7] Picelli et al. (2020)

- Binary {0,1} design variables
  - Clear distinction between solid and fluid/void materials
  - Lesser or no effects at all from the material interpolation
  - Multiphysics simulation with separate domains

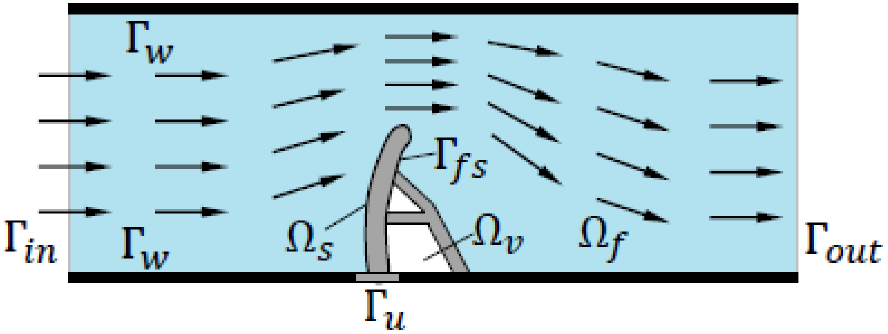
[8] Picelli, R., Ranjbarzadeh, S., Sivapuram, R., Gioria, RS, Silva, ECN, "Topology optimization of binary structures under design-dependent fluid-structure interaction loads" SMO 62:2101–2116 (2020)

Topology Optimization in FSI problems

$$\underset{\mathbf{x}}{\text{Minimize}}\ C(\mathbf{x})$$

$$\text{Subject to } V_i(\mathbf{x}) \leq \overline{V}_i,\ \ i \in [1, N_g]$$

$$x_j \in \{0, 1\},\ \ j \in [1, N_d]$$



Fluid domain(incompressible Navier-Stokes eqs.)

$$\begin{cases} \rho_f\left(\mathbf{v}_f \cdot \nabla \mathbf{v}_f\right) = -\nabla P_f + \mu \nabla^2 \mathbf{v}_f \\ \nabla \cdot \left(\mathbf{v}_f\right) = \mathbf{0} \end{cases}$$

Solid domain (linear elasticity)

Topology Optimization of Binary Structures (TOBS)

- The TOBS method
  - Sequential approximate problems
  - Binary design variables
  - Sensitivity filtering
  - Integer linear programming (ILP)
    - Branch-and-bound algorithm in CPLEX by IBM

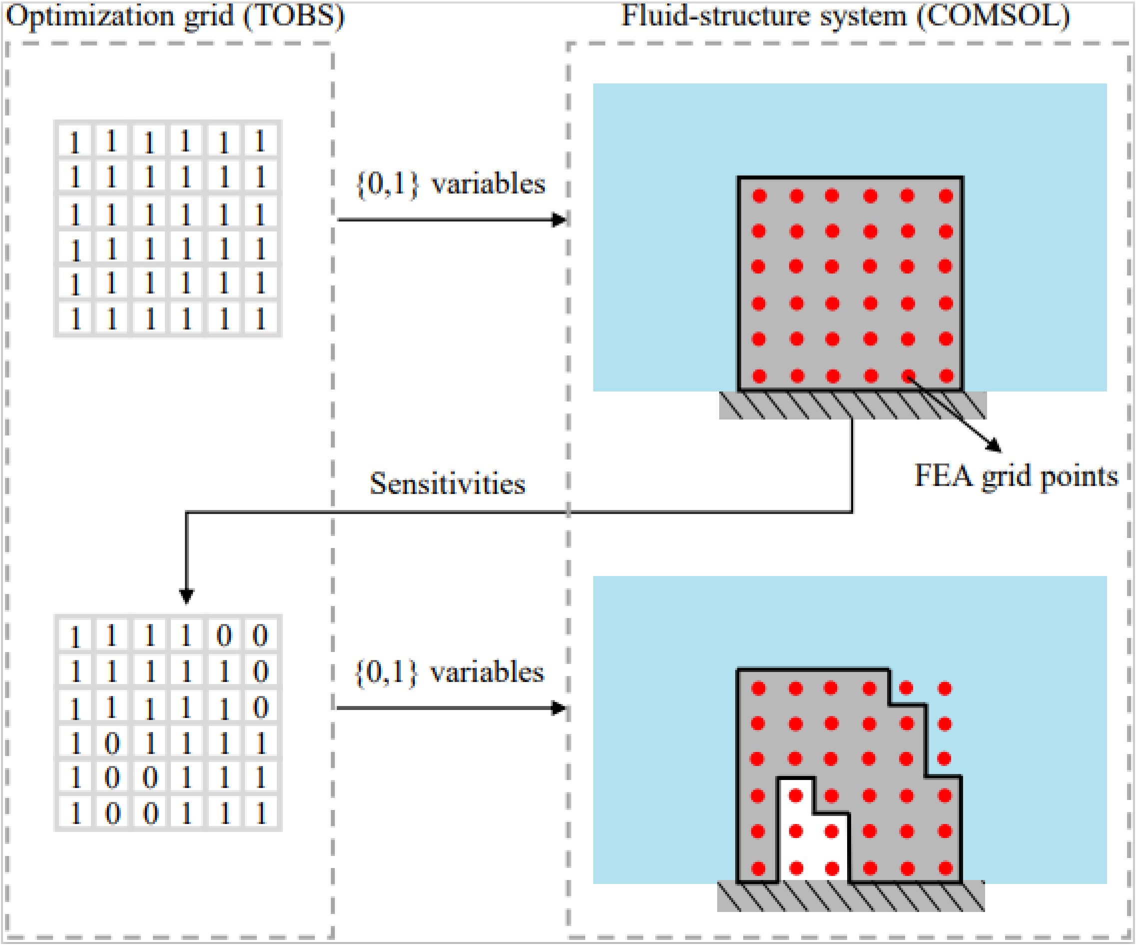
$$
\begin{aligned}
\underset{\Delta \boldsymbol{x}^k}{\text{Minimize}} \quad & \frac{\partial f(\boldsymbol{x}^k)}{\partial \boldsymbol{x}} \cdot \Delta \boldsymbol{x}^k, \\
\text{Subject to} \quad & \frac{\partial g_i(\boldsymbol{x}^k)}{\partial \boldsymbol{x}} \cdot \Delta \boldsymbol{x}^k \leq \overline{g}_i - g_i\left(\boldsymbol{x}^k\right) := \Delta g_i^k, \; i \in [1, N_g], \\
& \left\|\Delta \boldsymbol{x}^k\right\|_1 \leq \beta N_d, \\
& \Delta x_j^k \in \{-x_j^k, 1 - x_j^k\}, \; j \in [1, N_d].
\end{aligned}
$$

Educational paper:
[7] Picelli et al. (2020)

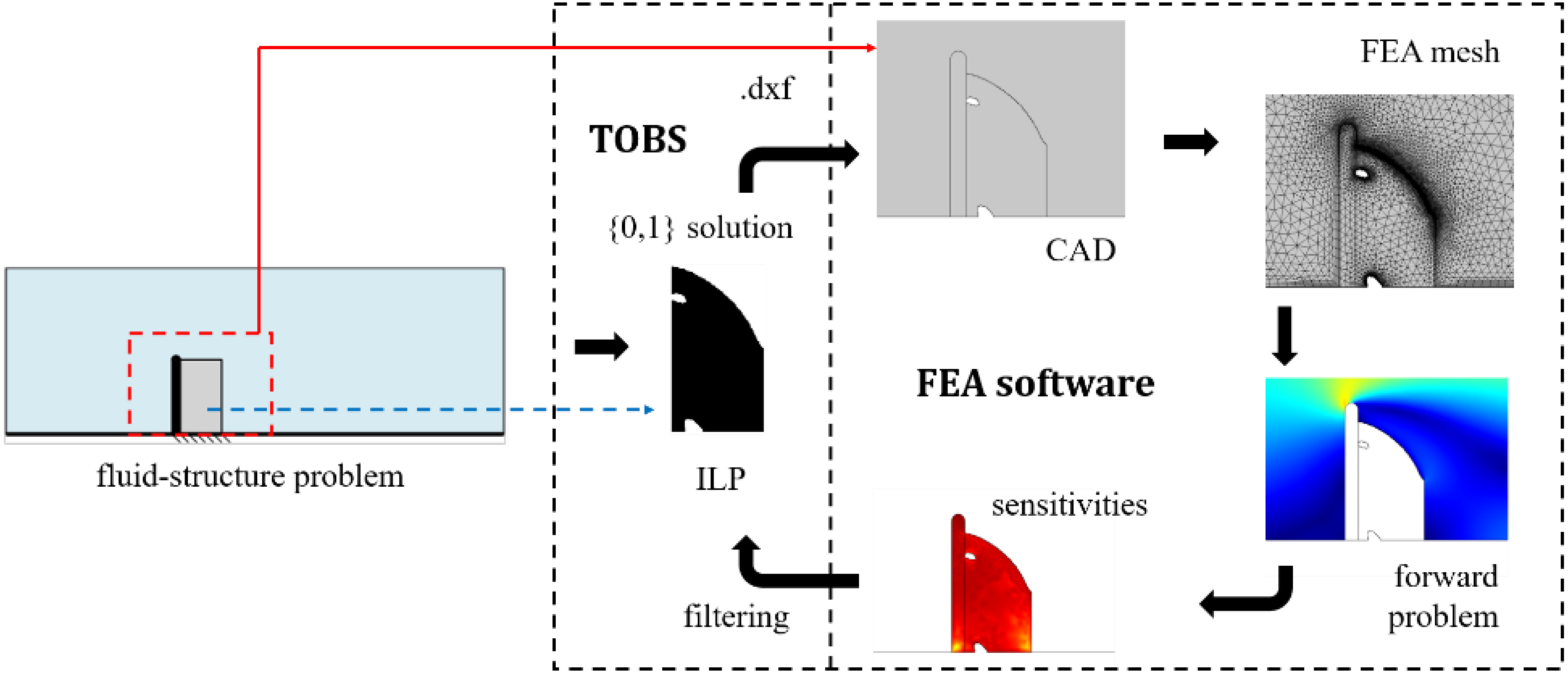
$$
\Delta g_i^k = \begin{cases} -\epsilon_i g_i\left(\boldsymbol{x}^k\right) & : \overline{g}_i < (1-\epsilon_i) g_i\left(\boldsymbol{x}^k\right), \\ \overline{g}_i - g_i\left(\boldsymbol{x}^k\right) & : \overline{g}_i \in \left[(1-\epsilon_i) g_i\left(\boldsymbol{x}^k\right), (1+\epsilon_i) g_i\left(\boldsymbol{x}^k\right)\right] \\ \epsilon_i g_i\left(\boldsymbol{x}^k\right) & : \overline{g}_i > (1+\epsilon_i) g_i\left(\boldsymbol{x}^k\right), \end{cases}
$$

FSI design with geometry trimming

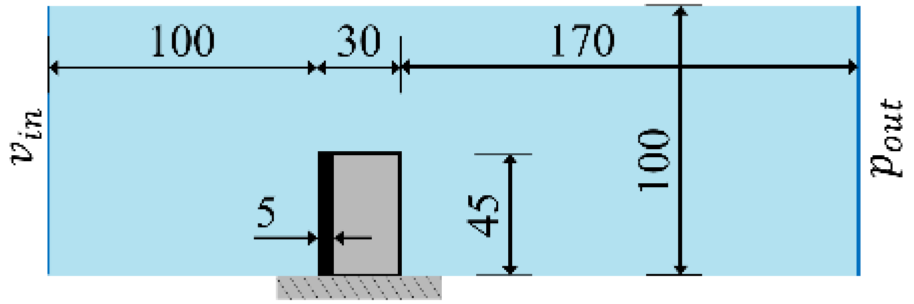
- Decoupling of optimization grid and FEA
  - Optimization module (TOBS)
  - FEA (COMSOL)
- Automatic differentiation
  - SIMP interpolation to aid derivation
- Geometry trimming



FSI design with geometry trimming



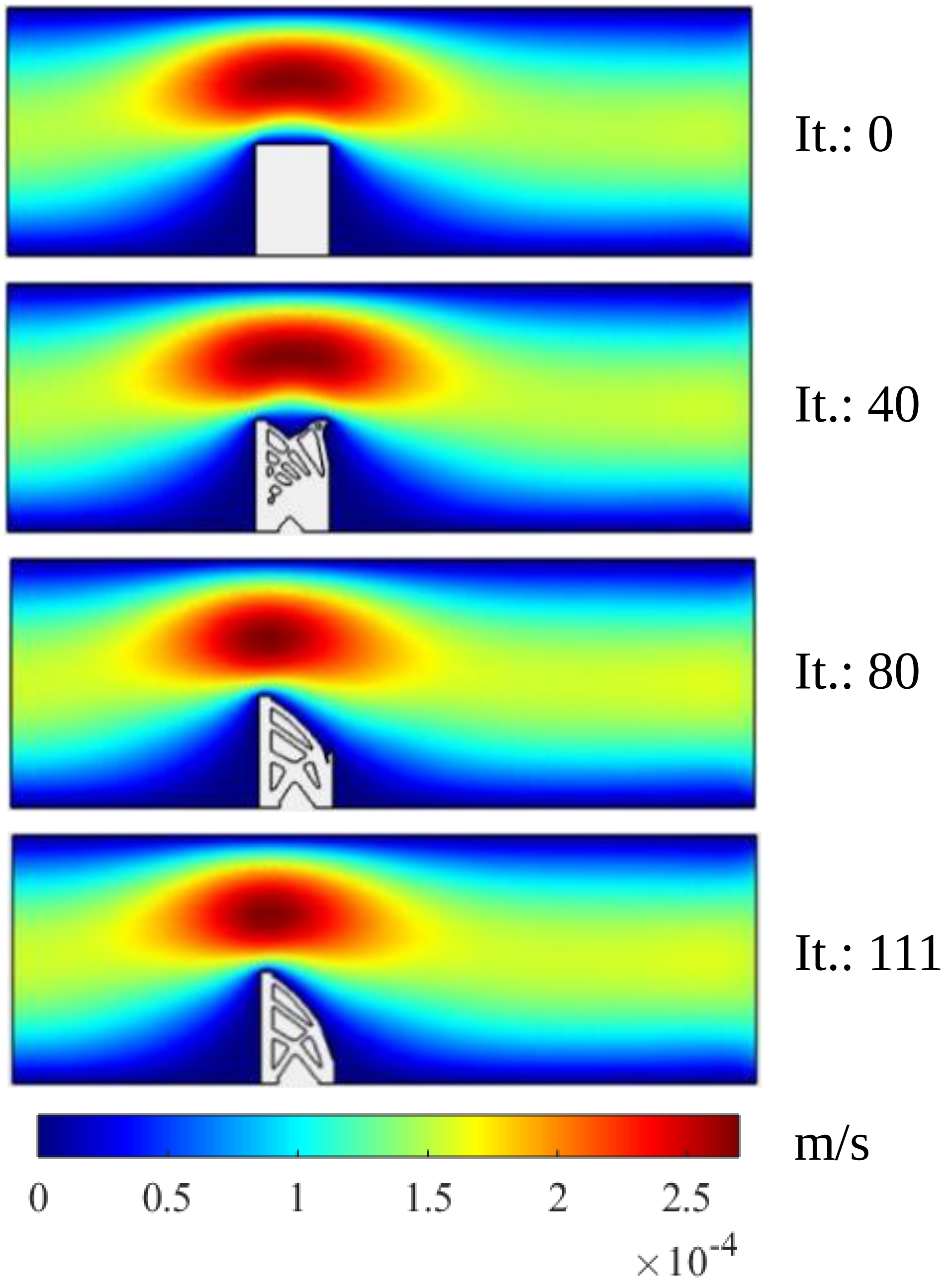
Examples: the wall



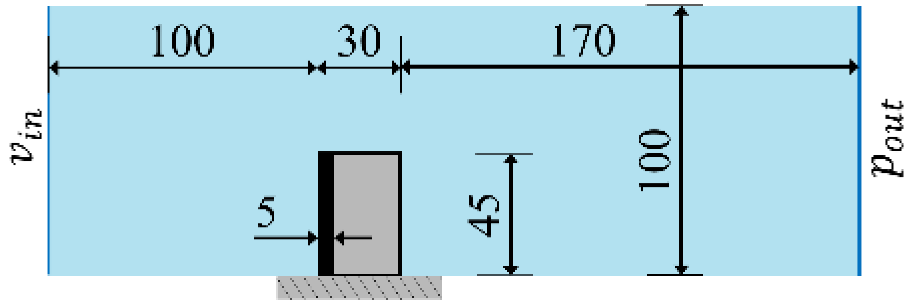
Minimum compliance
$\bar{V} = 35\%$

Solid: $E = 2 \cdot 10^5$ Pa, $\nu = 0.3$
Fluid: water
Re = 0.01

$\epsilon = 0.01$
$\beta = 0.05$



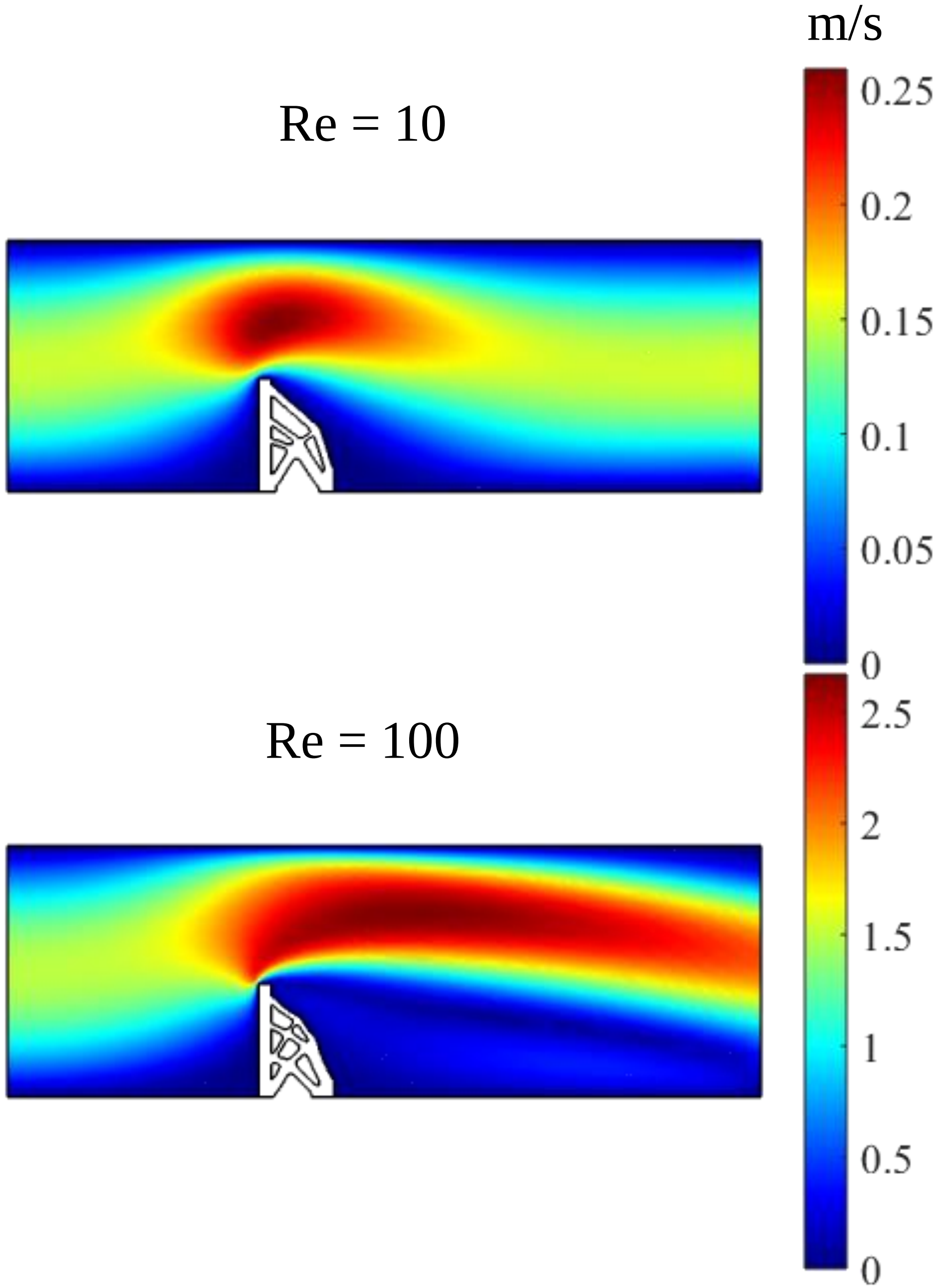
Examples: the wall



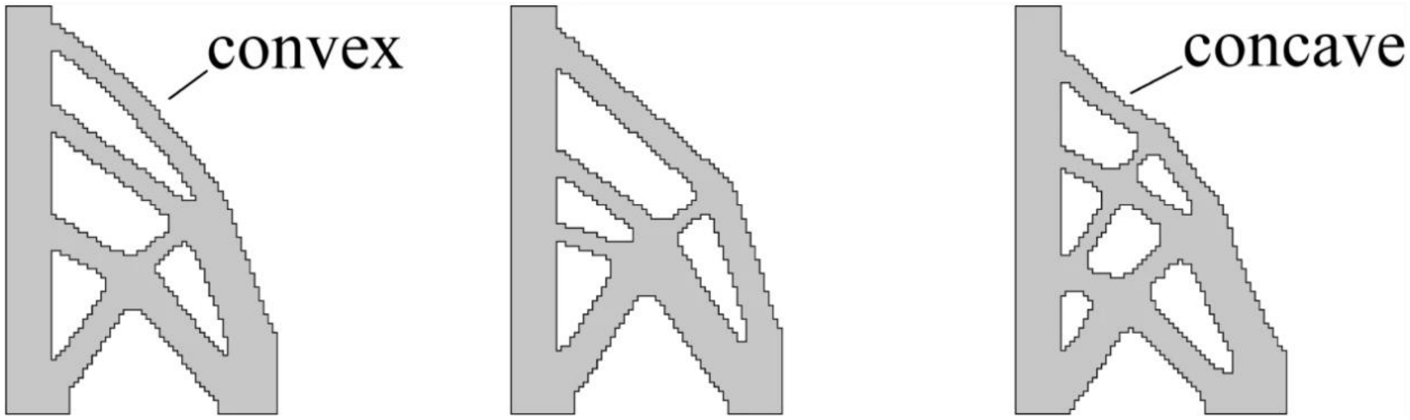
Minimum compliance
$\bar{V} = 35\%$

Solid: $E = 2 \cdot 10^5$ Pa, $\nu = 0.3$
Fluid: water
Re = 0.01

$\epsilon = 0.01$
$\beta = 0.05$

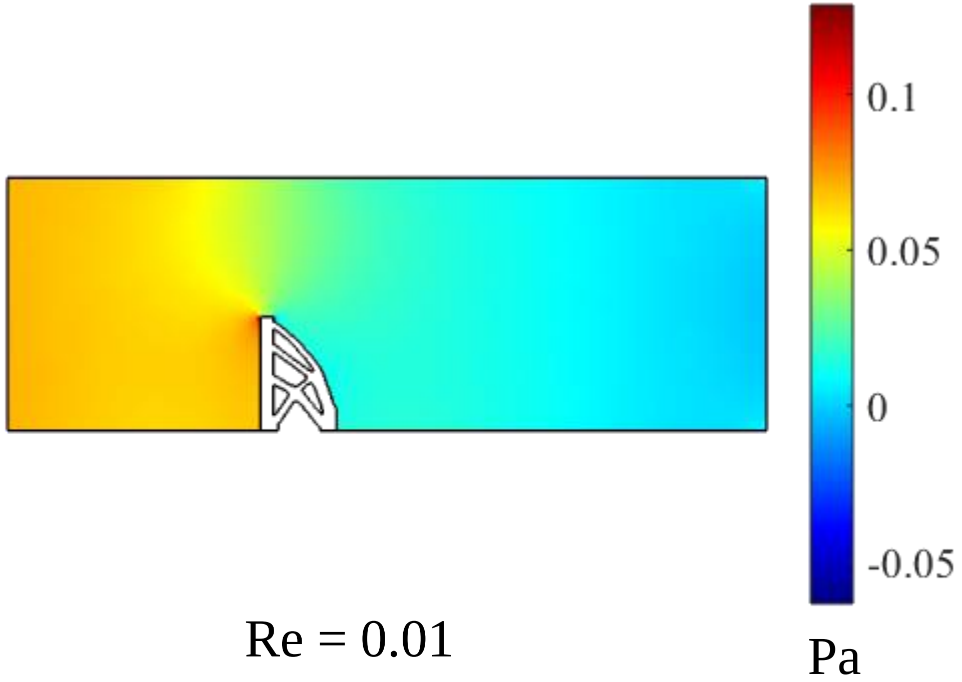


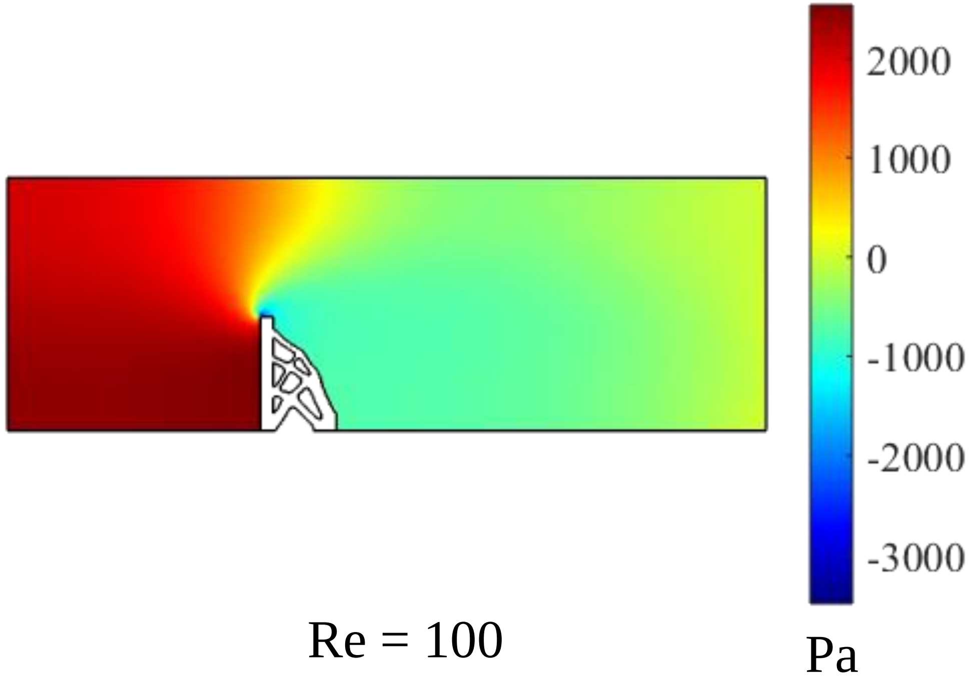
Examples: the wall



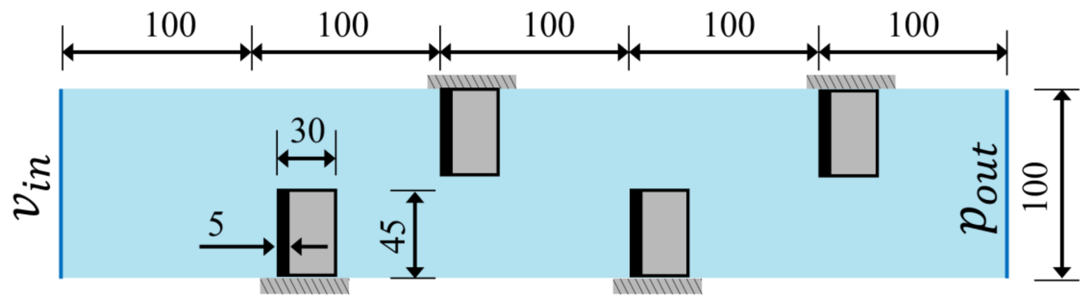
Re = 0.01 Re = 10 Re = 100

Examples: the wall





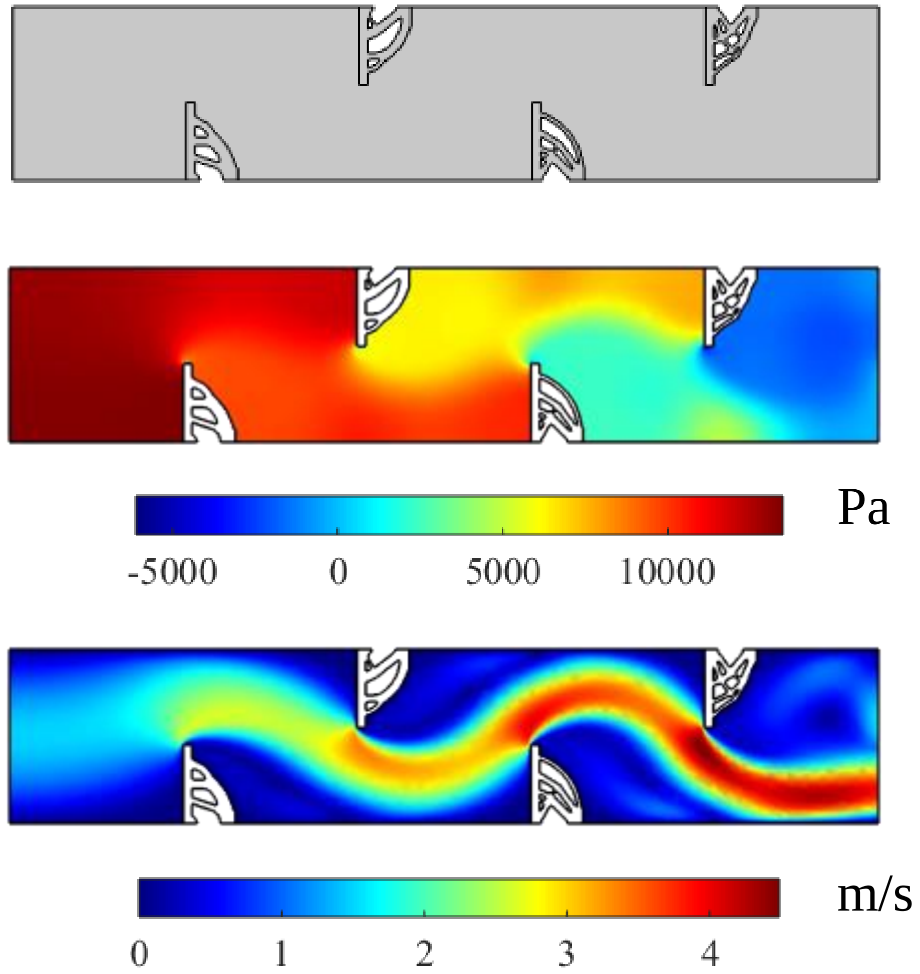
Examples: the seal



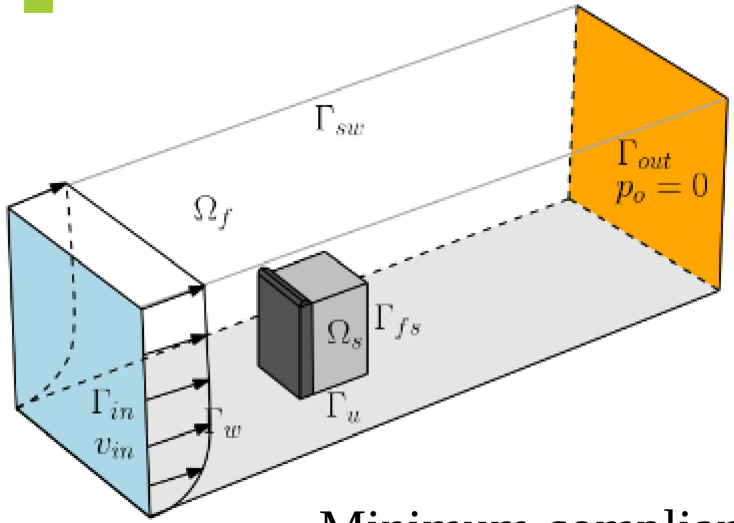
Minimum compliance
$\bar{V}$ = 35%

Solid: $E = 2 \cdot 10^5$ Pa, $\nu = 0.3$
Fluid: water
Re = 0.01

$\epsilon = 0.01$
$\beta = 0.05$



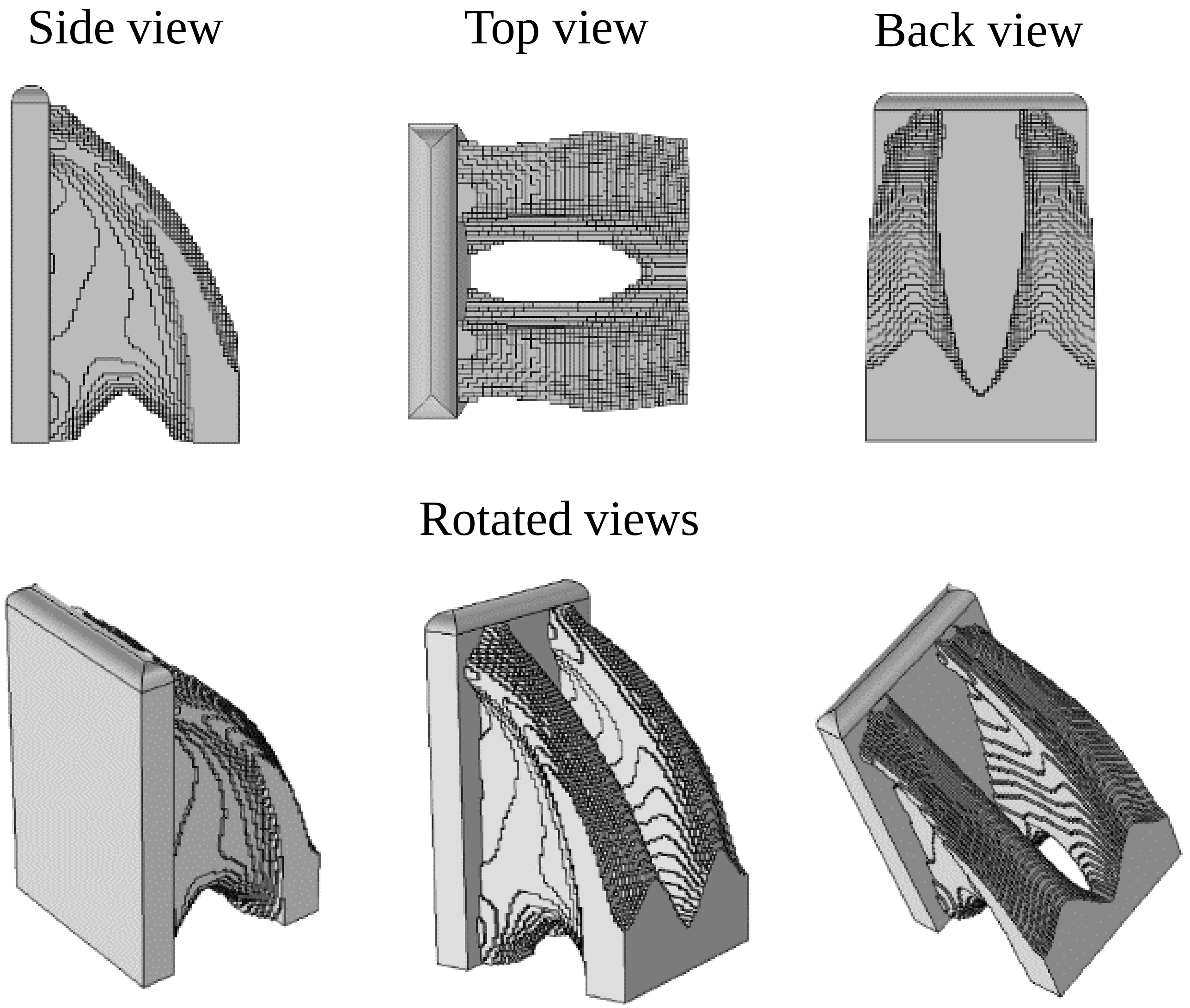
Examples: the 3D wall



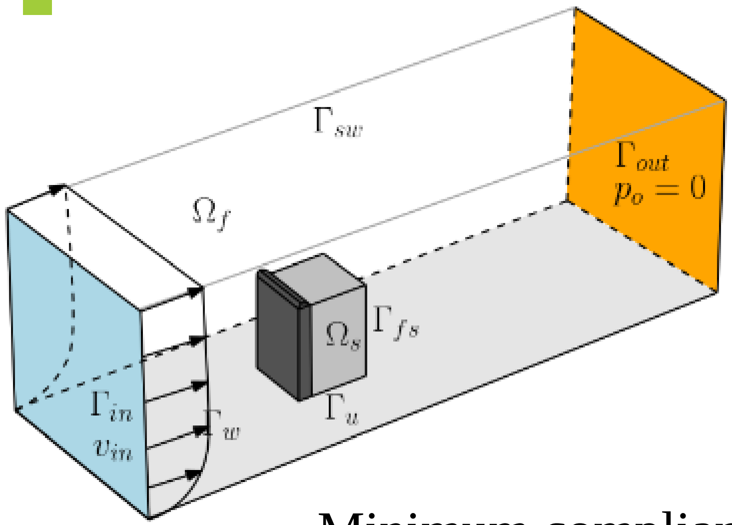
Minimum compliance
$\bar{V}$ = 35%

Solid: $E = 2 \cdot 10^5$ Pa, $\nu = 0.3$
Fluid: water
Re = 0.01

$\epsilon = 0.01$; $\beta = 0.05$



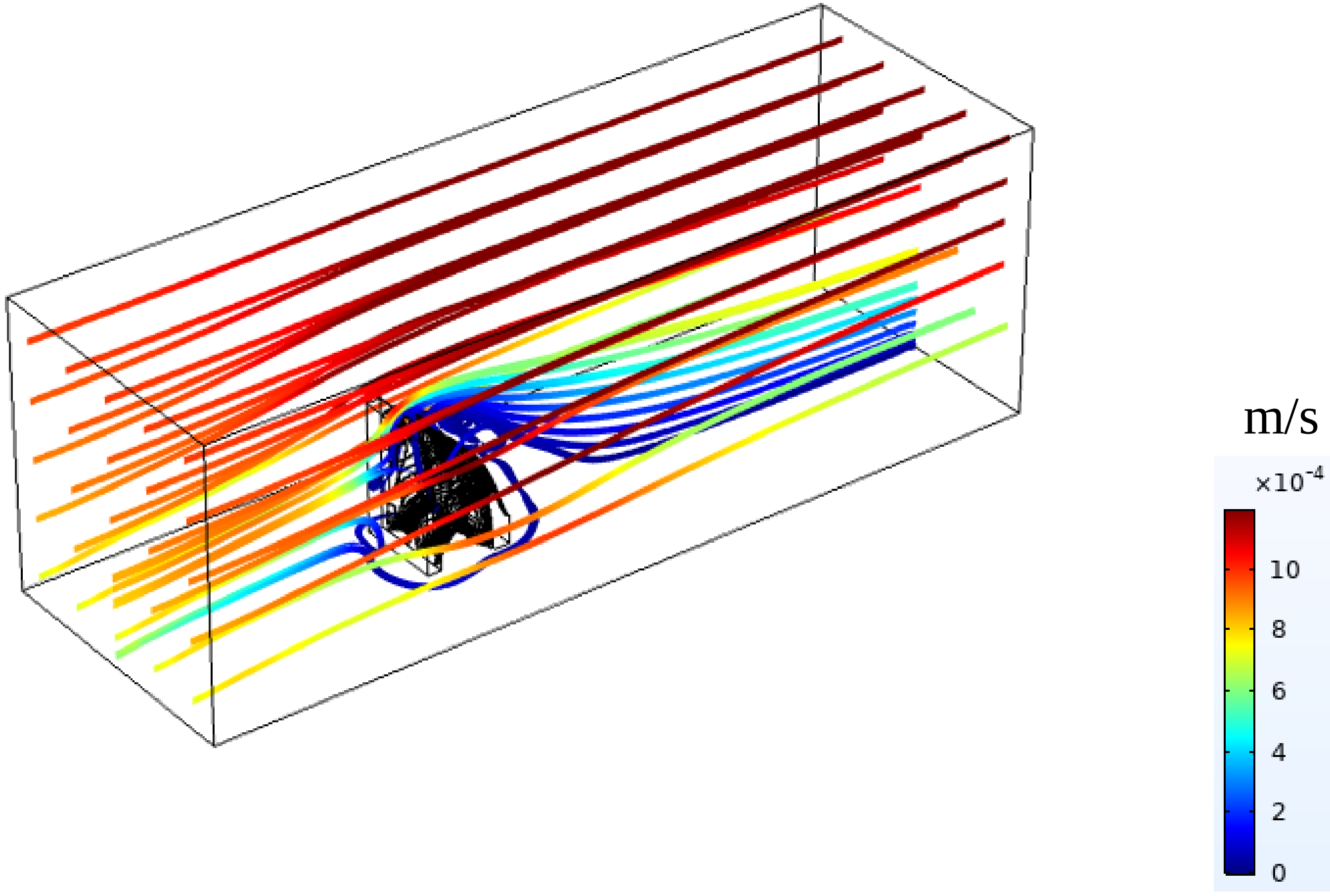
Examples: the 3D wall



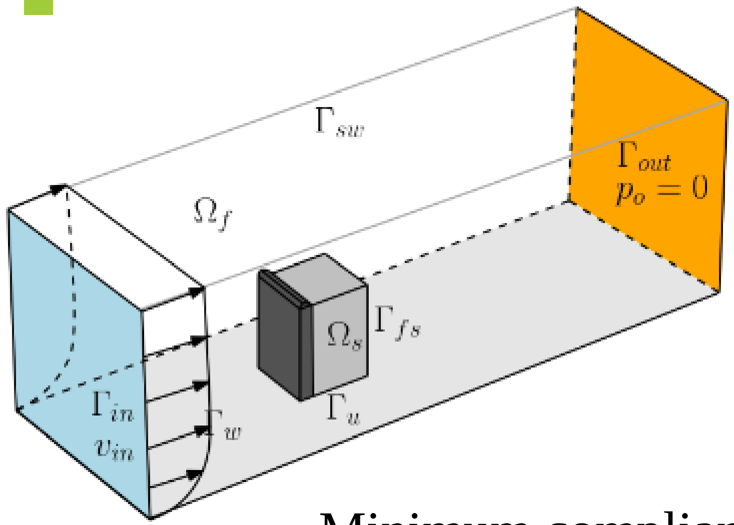
Minimum compliance
$\bar{V}$ = 35%

Solid: $E = 2 \cdot 10^5$ Pa, $\nu = 0.3$
Fluid: water
Re = 0.01

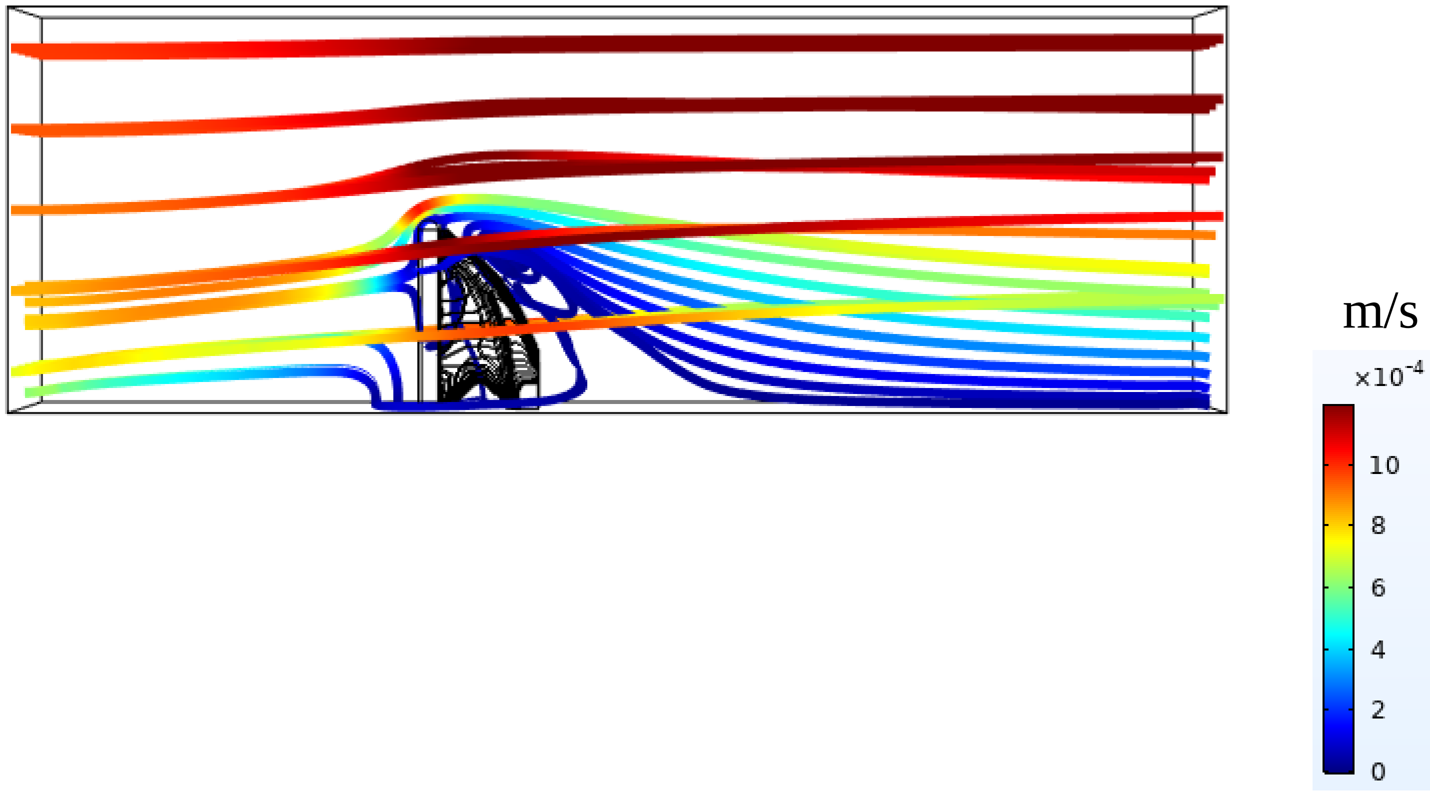
$\epsilon = 0.01$; $\beta = 0.05$



Examples: the 3D wall



Minimum compliance
$\bar{V}$ = 35%



Solid: $E = 2 \cdot 10^5$ Pa, $\nu = 0.3$
Fluid: water
Re = 0.01

$\epsilon = 0.01$; $\beta = 0.05$

Conclusions

- Compliance minimization of structures under fluid-structure interaction loads was successfully solved
- The TOBS approach is suitable for the problem
- A new methodology of decoupling analysis and simulation was proposed in the context of binary design variables
- Future work should increase the complexity of the FSI simulation

References

- [1] R Picelli, A Neofytou and H A Kim. Topology optimization for design-dependent hydrostatic pressure loading via the level-set method. Structural and Multidisciplinary Optimization, 60(4):1313-1326, 2019.
- [2] C Lundgaard, J Alexand, M Zhou, C Andreasen, and O Sigmund. Revisiting density-based topology optimization for fluid-structure-interaction problems. Structural and Multidisciplinary Optimization, 58:969-995, 2018.
- [3] G H Yoon. Topology optimization for stationary fluid-structure interaction problems using a new monolithic formulation. International Journal for Numerical Methods In Engineering, 82:591-616, 2010.
- [4] N Jenkins and K Maute. An immersed boundary approach for shape and topology optimization of stationary fluid-structure interaction problems. Structural and Multidisciplinary Optimization, 54:1191-1208, 2016.
- [5] R Picelli, W M Vicente, and R Pavanello. Evolutionary topology optimization for structural compliance minimization considering design-dependent fsi loads. Finite Elements in Analysis and Design, 135:44-55, 2017.
- [6] R Picelli, R Sivapuram. Topology optimization of binary structures using Integer Linear Programming. Finite Elements in Analysis and Design, 139:49-61, 2020.
- [7] R Picelli, R Sivapuram and Y M Xie. A 101-line MATLAB code for topology optimization using binary variables and integer programming. Structural and Multidisciplinary Optimization, online, published 27 September 2020.
- [8] R Picelli, S Ranjbarzadeh, R Sivapuram, R S Gioria, and E C N Silva. Topology optimization of binary structures under design-dependent fluid-structure interaction loads. Structural and Multidisciplinary Optimization, 62:2101-2116, 2020.

Research Centre for Gas Innovation

cleaner energy for a sustainable future

THANK YOU

rpicelli@usp.br

Twitter: @PicelliRenato
ResearchGate – Renato Picelli
Google Scholar – Renato Picelli

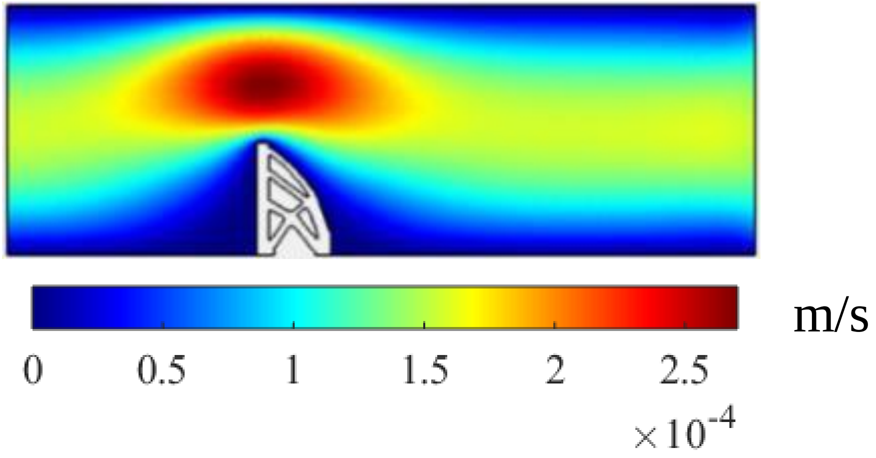
FAPESP
[2018/05797-8]

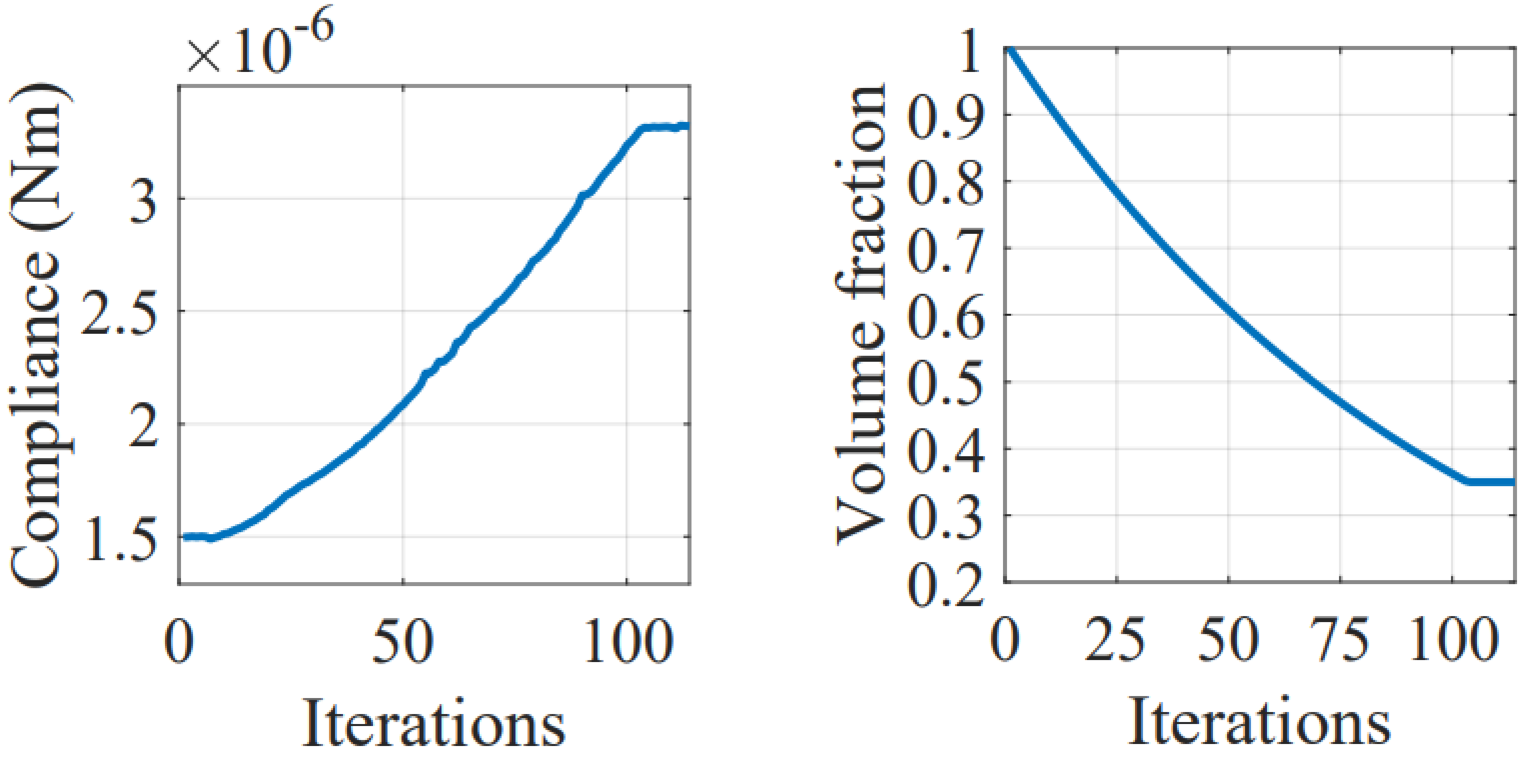
Design method sheet

Design method specifications

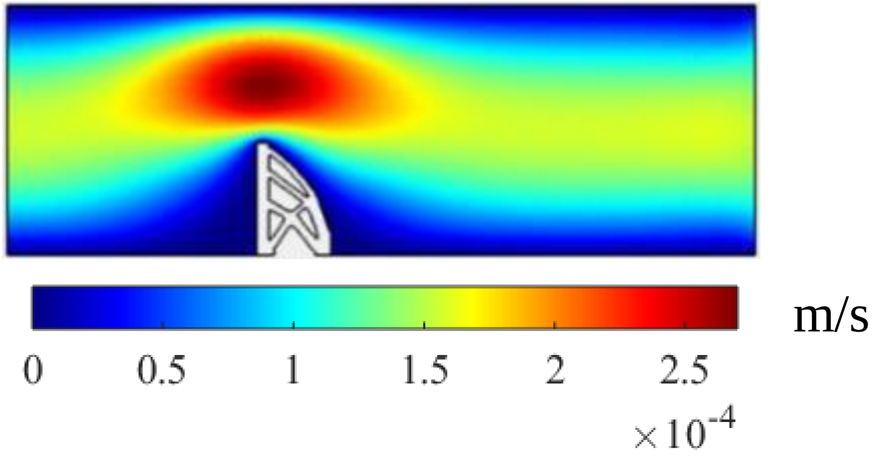
- Topology optimization variables
  - [ ] density-based interpolation
  - [x] binary {0,1}
  - [ ] boundary description (level set)
- Governing equations
  - [ ] monolithic (mixed model)
  - [x] separate
- Mesh type
  - [ ] remeshing
    - [x] global
    - [ ] local (XFEM)
  - [ ] fixed grid
- Sensitivity analysis
  - [ ] element-based
    - [ ] material interpolation
    - [ ] discrete
  - [ ] point-based
    - [x] material interpolation
    - [ ] shape sensitivities

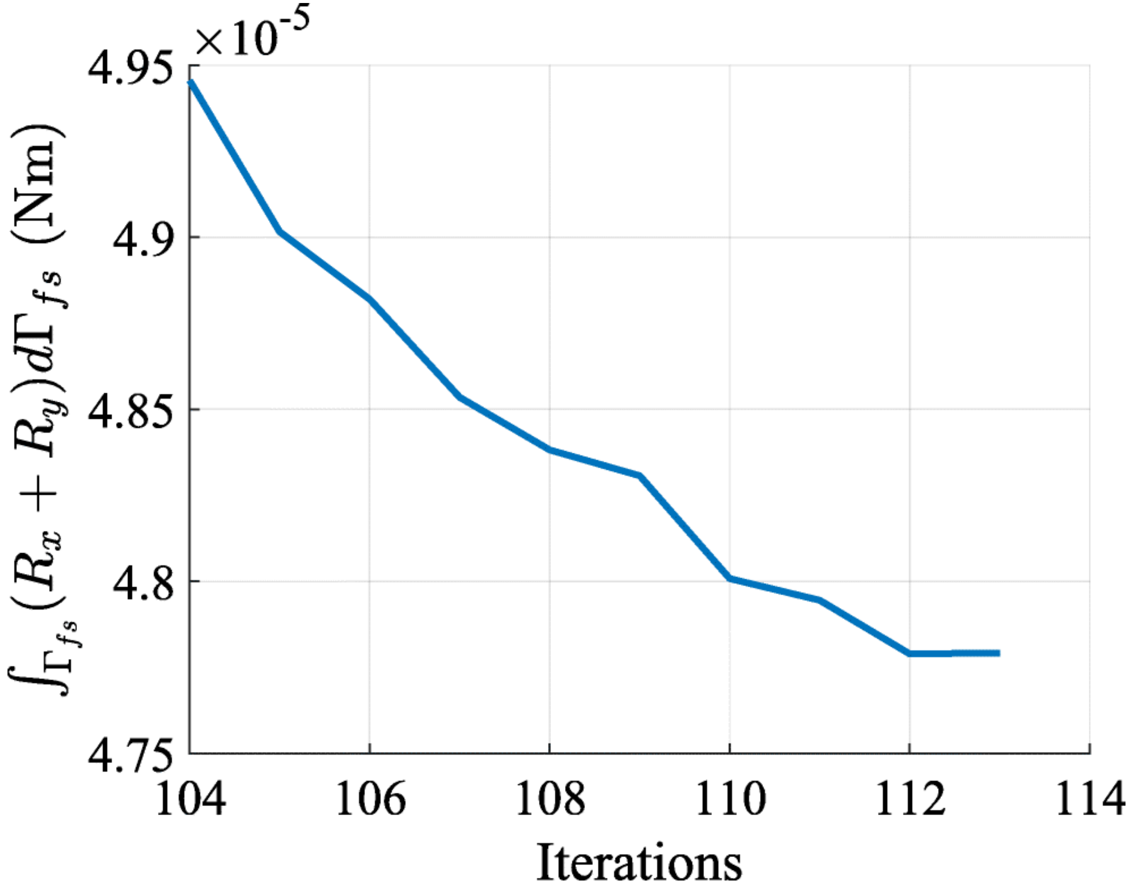
Examples: the wall





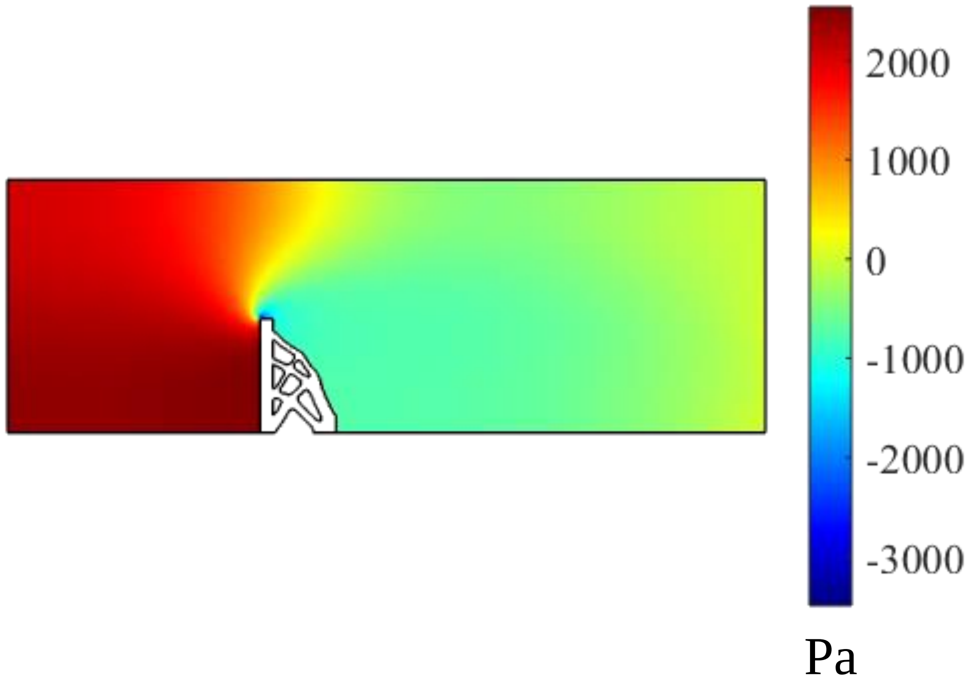
Examples: the wall



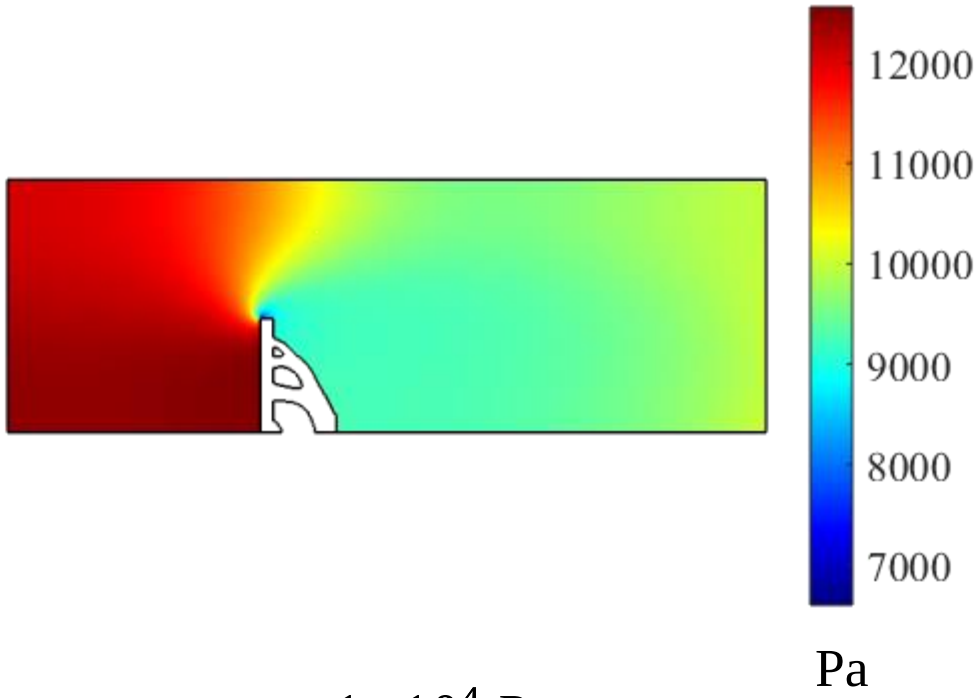


Examples: the wall, reference pressure

Re = 100

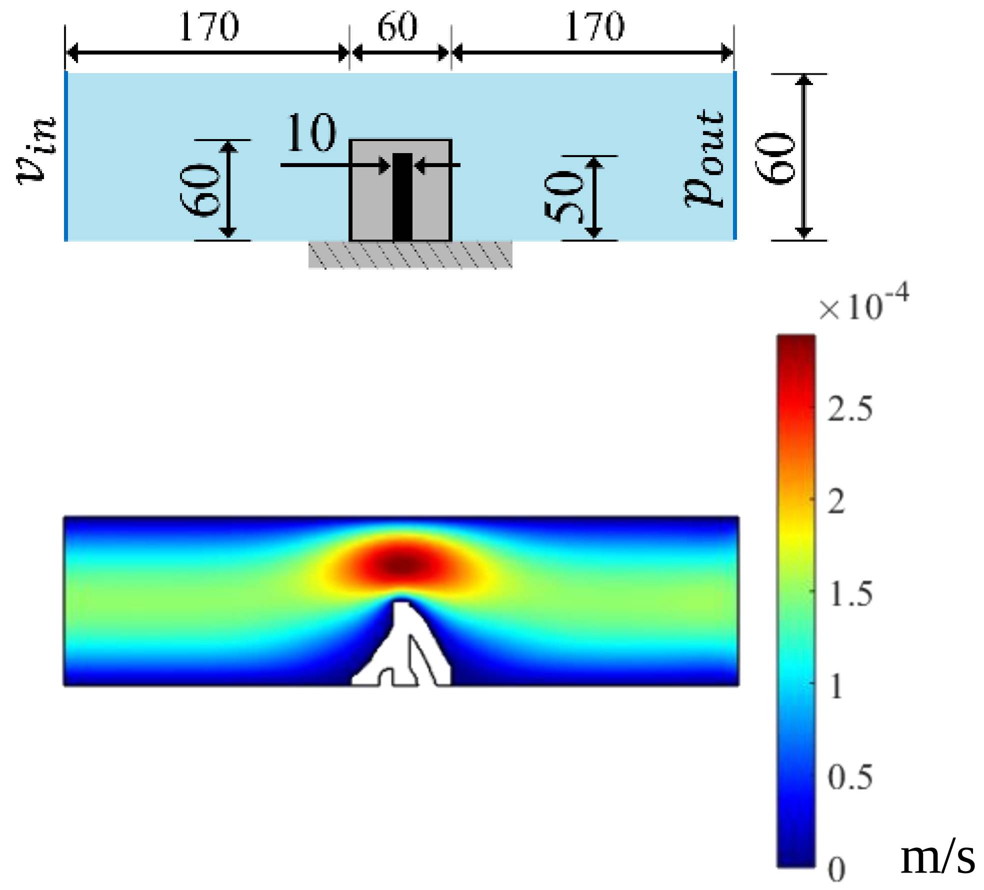


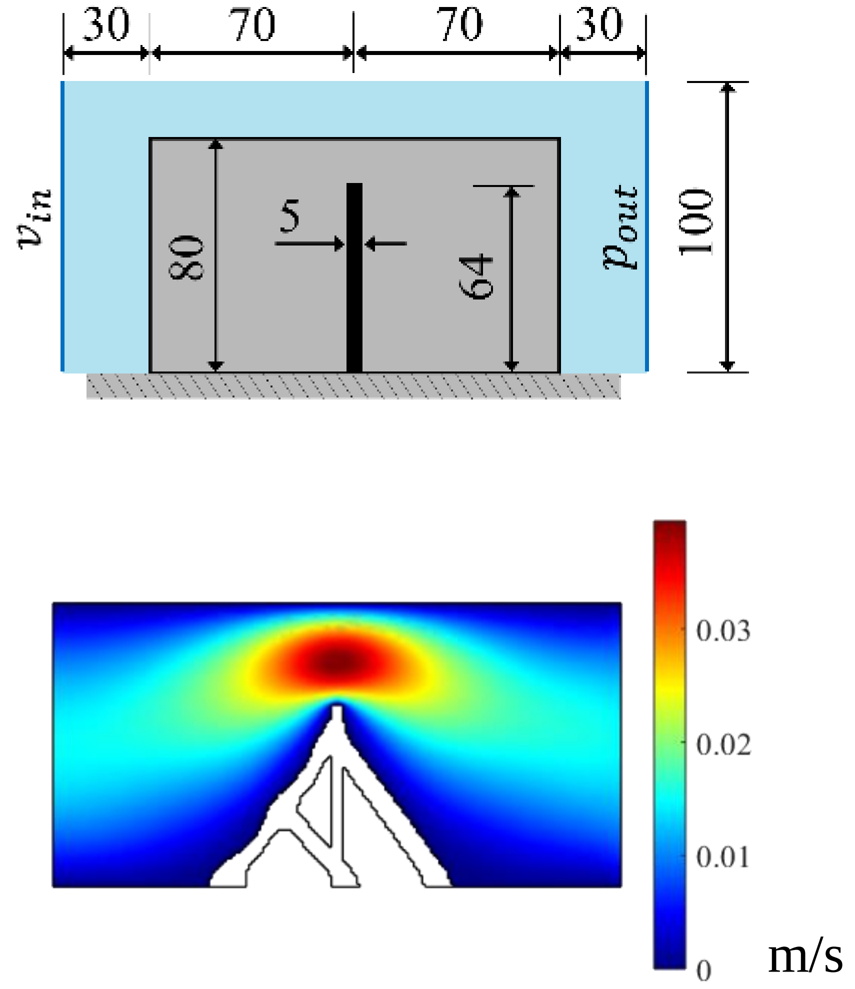
$p_0 = 0$



$p_0 = 1 \cdot 10^4$ Pa

Other examples





ILP – Computational time

Mesh size	Iterations	FEA (sec)	ILP (sec)
50×50	83	3.926	6.366
100×100	95	39.330	9.510
200×200	170	547.264	59.041
400×400	234	9429.989	129.589

R Sivapuram and R Picelli. Topology design of binary structures subjected to design-dependent thermal expansion and fluid pressure loads. Structural and Multidisciplinary Optimization, 61:1877–1895, 2020.