AV-Flow: a software library for FSI Problems based on a Variational Transfer IB Method

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Introduction

We present a novel software library (named **AV-flow**) for Fluid-Structure Interaction simulations based on the embedded boundary method.

By taking inspiration from the Immersed Boundary technique introduced by Peskin [1] we employ the Finite-Element method for discretizing the equations of the solid structure and the Finite-Difference method for discretizing the fluid flow.

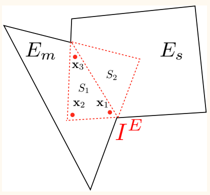
The code is optimised for modern hybrid high-performance computing platforms such as the Cray XC50 system at the Swiss National Supercomputing Centre CSCS.

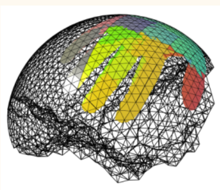
L^2 - projection

For coupling the fluid and the solid subproblems a volume L^2 - projection is adopted.

Such approach allows to transfer data between non-conforming grids randomly distributed among processors without requiring a priori information on the relation between the different meshes.

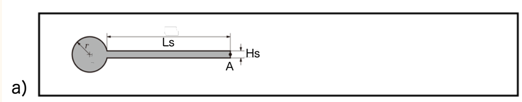
To this aim, Lagrangian basis functions are attached to the Finite Difference discretization [2].





Turek-Hron FSI benchmark

In this section we present results related to the Turek-Hron FSI benchmark which considers the incompressible flow of a Newtonian fluid around an elastic solid structure composed of a disk and a rectangular trailing beam.

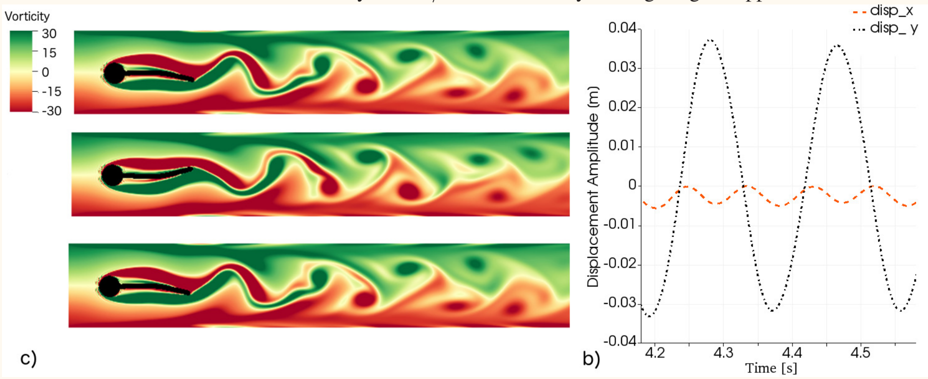


$L_f[m]$	$H_f[m]$	$L_s[m]$	$H_s[m]$	$r[m]$
2.5	0.41	0.35	0.02	0.05

The disk center is positioned at $C = (0.2\,m, 0.2\,m)$ (measured from the left bottom corner of the channel). The fluid properties are $\rho_f = 1000\,kg/m^3$ and $\mu = 1\,Pa \cdot s$ which lead to a Reynolds number of 200.

A nearly incompressible Saint-Venant Kirchhoff model is adopted: $\widehat{\mathbf{P}} = \widehat{\mathbf{F}}(\lambda \ \mathrm{tr}(\widehat{\mathbf{E}})\boldsymbol{I} + 2\mu\widehat{\mathbf{E}}) + \kappa \det(\widehat{\mathbf{F}})(\det(\widehat{\mathbf{F}})-1)\mathbf{F}^{-T}$ with $\mu = 2.0\,MPa$, $\lambda = 4.7\,MPa$ and $\kappa = 10\,MPa$.

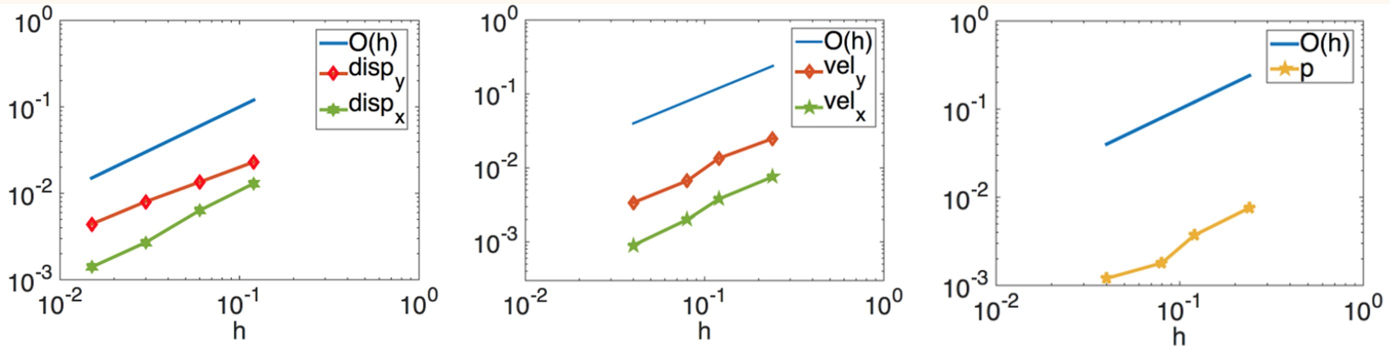
Periodic boundary conditions are imposed along the inlet and the outlet of the fluid channel together with no-slip boundary conditions on the top and on the bottom. Moreover, at the inlet a Poiseuille flow with a centerline velocity of $1\,m/s$ is enforced by a fringe region appended downstream.



The amplitude of the last period of oscillation is in the range of $0.03\,m$ for the vertical displacement and of $0.0025\,m$ for the horizontal displacement; the frequency of the y-displacement is about $6\,s^{-1}$, and the frequency for the x-displacement is about $12\,s^{-1}$. All values are in good agreement with the original benchmark results [3]. The vorticity in the fluid ranges from $-30\,s^{-1}$ to $30\,s^{-1}$.

Convergence Studies

Relative errors in the L^2 norm for the Turek-Hron Benchmark.



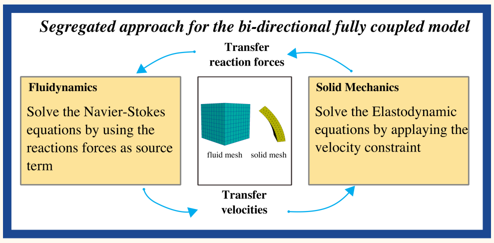
Immersed Boundary Method

$$(\widehat{\rho}_{s0} - \rho_f)\frac{\partial^2 \widehat{\mathbf{u}}_s}{\partial t^2} - \widehat{\nabla}_{\widehat{x}} \cdot \widehat{\mathbf{P}} = \mathbf{0} \quad \text{on} \quad \widehat{\Omega}_s$$

$$\rho_f \frac{\partial \mathbf{v}_f}{\partial t} + \rho_f (\mathbf{v}_f \cdot \nabla)\,\mathbf{v}_f + \nabla p_f - \mu \Delta \mathbf{v}_f = \mathbf{f}_{\text{fsi}} \quad \text{on} \quad \Omega$$

$$\nabla \cdot \mathbf{v}_f = 0 \quad \text{on} \quad \Omega$$

$$\mathbf{v}_f = \frac{\partial \mathbf{u}_s}{\partial t} \quad \text{on} \quad \Gamma_{\text{fsi}}$$



Software Libraries

IMPACT employed to solve the non-dimensional Navier-Stokes equations [4].
PASSO providing various solvers for non-linear problems.
MOONoLiTH used for detecting the overlapping region between the fluid and the solid grid.
MOOSE used for discretizing the solid problem and embedding all the libraries.

References

[1] Peskin, C.S., J. Comp. Phys. 10.2 (1972): 252-271. [2] Fackeldey, K., et al., Multiscale Modeling and Simulation, 9.4 (2011) 1459-1494. [3] Turek, S., and Jaroslav H., Springer Berlin Heidelber. [4] Krause, Rolf, and Patrick Zulian, SIAM J. Scientific Computing 38.3 (2016): C307-C333. [5] Henniger, R., et al., J. Comp. Phys. 220.10 (2010).