Aortic Valve Hemodynamics Using Variational Transfer Immersed Boundary Method

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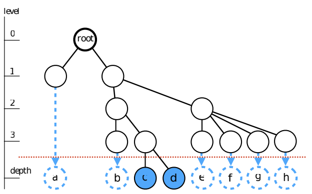
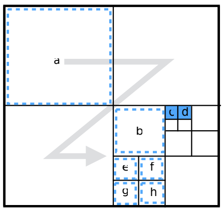
Introduction and Aim

Heart valves are an indispensable feature in the circulation of blood through a healthy organism. However, valves can develop dysfunctions. In particular, the Aortic Valve can suffer from stenosis due to calcification which leads to locally increased flow velocities, a higher pressure drop across the valve and regurgitation (backflow).

We present a numerical tool that allows us to investigate the interaction of the blood flow with the surrounding tissue in hope of characterising it and explaining the cause of the mentioned pathologies in a quantitative and reproducible way. To this end we make use of the concept of the Immersed Boundary Method (C.S. Peskin [a]) and discretize fluid and solid with finite differences and finite elements, respectively.

MOONoLith

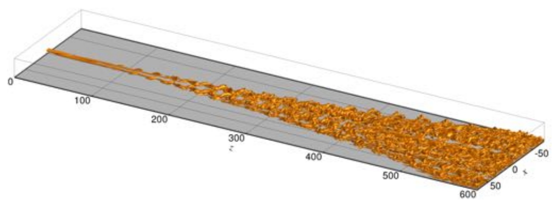




Solid tissue and fluid interact through the MOONoLith library [c], a parallel framework for the variational transfer of discrete fields.

Intersection pairs of meshes are identified in parallel on all processes by a three phase process, during which bounding volumes are setup and exchanged to eliminate trivial negatives (broad phase), setup a tree-search graph based on the bounding volumes in order to obtain a look-up table which contains information on which processes contain non-empty partitions (middle phase), and finally setting up our quadrature on the basis of the intersection polytopes along with eliminating duplicate element pair in our tree (narrow phase).

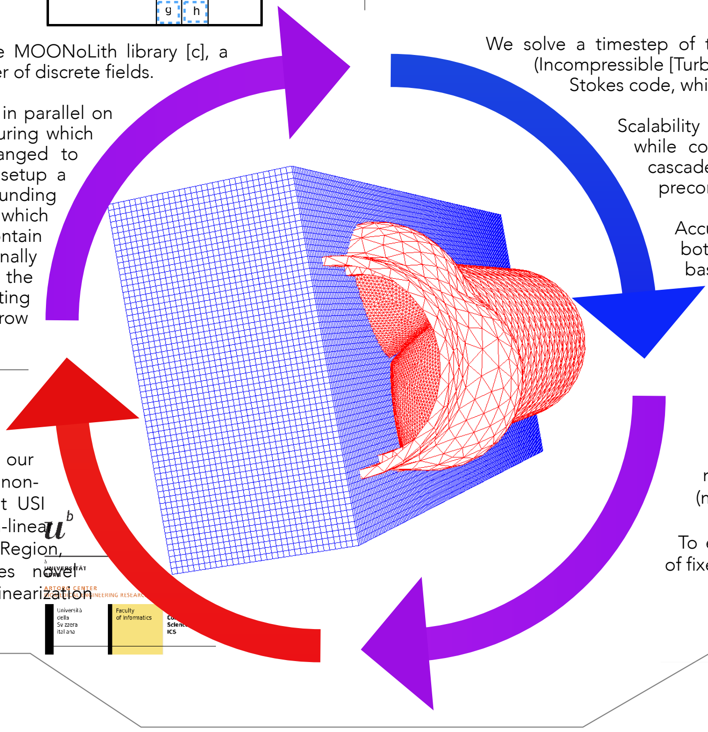
IMPACT



We solve a timestep of the fluid with the proven highly scalable IMPACT (Incompressible [Turbulent] flow on Massively PAralel CompuTers) Navier-Stokes code, which was developed at ETH Zurich [b].

Scalability is achieved with geometric data decomposition, while convergence is guaranteed with an iterative solver cascade with highly efficient commutation-based preconditioners for each Poisson equation.

Accuracy is ensured with high order finite differences in both time (3rd) and space (6th), as well as an accuracy based PI(D) type time-step control.



MOOSE

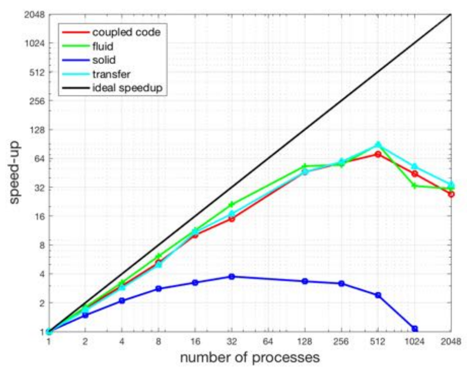
Our libraries are embedded in the open-source multiphysics simulation framework MOOSE (mooseframework.org, Idaho Nat'l Labs).

To ensure convergence, we perform a small number of fixed-point iterations in each time-step.

PASSO

We solve the elastodynamic equation for our tissue with the PASSO library for parallel non-linear solvers. This package developed at USI Lugano [e] contains various solvers for non-linear problems including Newton, Trust-Region, Multigrid solvers and more. It features novel parallelization strategies with respect to linearization and builds upon the PETSc library.

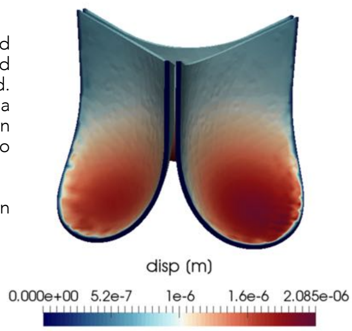
Scaling

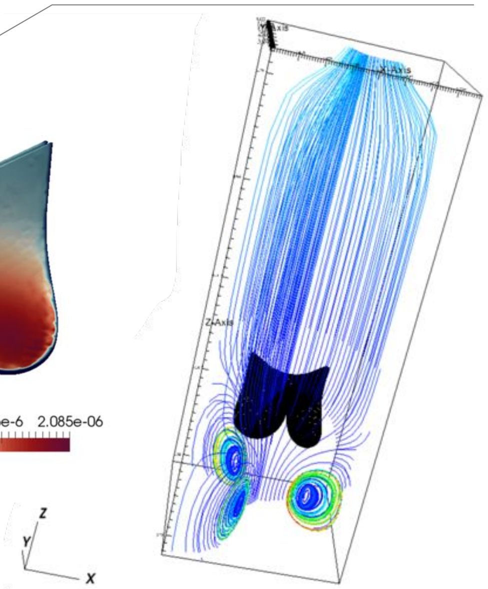


AV-FLOW

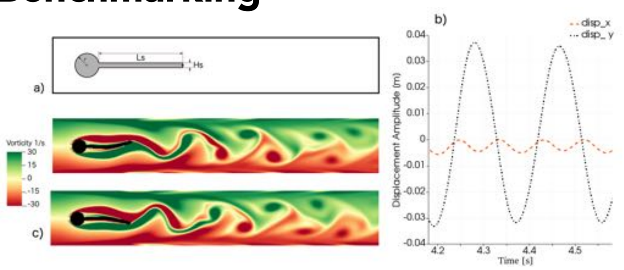
Three-dimensional flow around aortic valves was performed and feasible results were observed. The flow field around a bioprosthetic valve inside an aortic root phantom remains to be studied.

The complete setup can be seen in the above picture.





Benchmarking



We benchmarked our simulation framework with the 2D benchmark proposed by S. Turek and J. Hron [d]. We were able to observe good accordance of our results to literature.

Platform for Advanced Scientific Computing

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