Featflow

Fluid-structure interaction with applications

M. Razzaq, S. Turek,
Institute of Applied Mathematics, LS III, TU Dortmund
http://www.featflow.de

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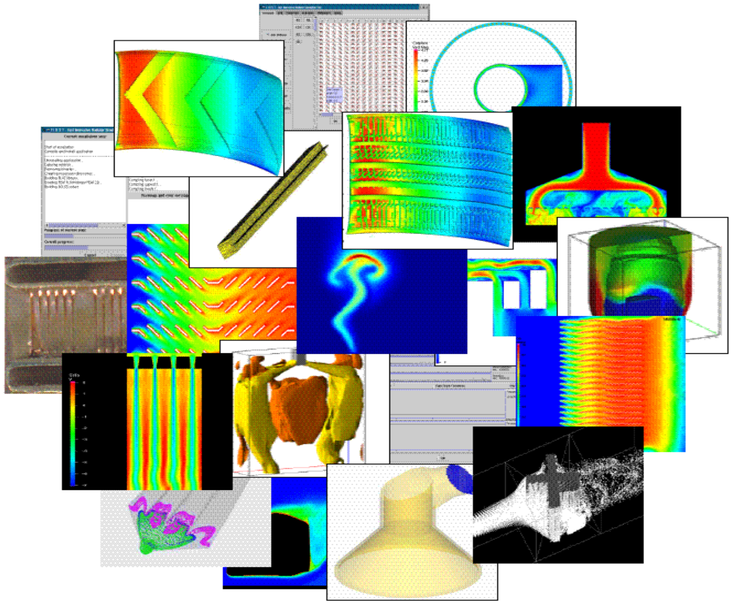

3. FSI applications
   I. Benchmarking and Experimental benchmark
   II. FSI Optimization
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Featflow Preprocessing

- Preprocessing (DeViSoR) Coarse grid editor Grid3.0.21 Java2
  - FeatFlow and Feast preprocessing tool
  - Purpose: creation and modification of geometries for processing within FeatFlow or Feast
- Download for free at http://sun.java.com/
- Written in Java and therefore platform independent
- Maintainer: Thomas Rohkämper <thomas.rohkaemper@tu-dortmund.de>

Modules

1. CC2d code
   I. CC2d is a direct, coupled approach for solving the discrete version of the incompressible NSE for
   II. flows at low and intermediate Reynolds number
   III. for both stationary and non stationary problems
   IV. Nonlinear rheology

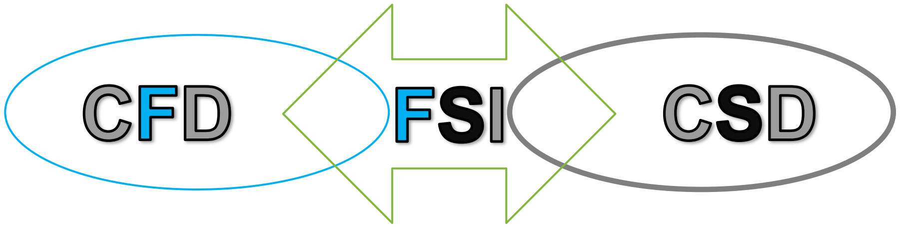
2. PP2d code
   I. PP2d is a pressure projection scheme for solving the discrete version of the incompressible NSE
   II. for flows at intermediate and high Reynolds numbers.
   III. PP2d code is applied to non stationary problems only

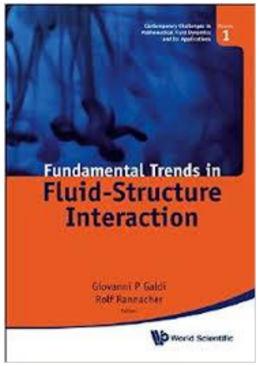
- Postprocessing (GMV, Paraview)

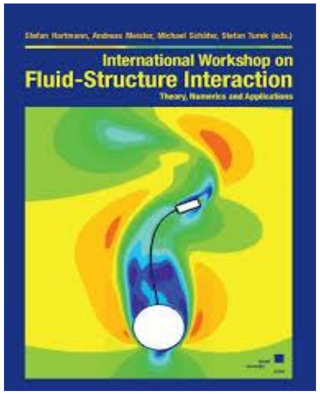
Postprocessing (visualization)

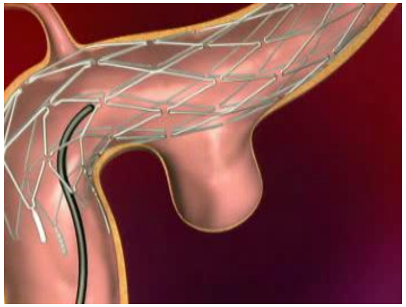
1. Postprocessing (gmvmpeg3.0) Genral mesh viewver (GMV)
   I. The current process of generating graphical multimedia output is mainly based on GMV
   II. GMV is freely available for almost all platforms and can be easily applied for the visualization of: vector fields for velocity-like data
   III. scalar data as pressure, streamfunction or temperature
   IV. isolines, isosurfaces, isovolumes, cutlines, cutplanes
   V. dynamic particle tracing
2. Paraview
   I. About ParaView an open-source application for visualising two- and threedimensional data sets, in particular transient data sets
   II. scalable, multi-platform visualization application
   III. support for distributed data sets
   IV. open, flexible, and intuitive user interface
   V. extensible, modular architecture based on open standards
   VI. large user community (academic, government and commercial institutions), reasonable support via mailing list

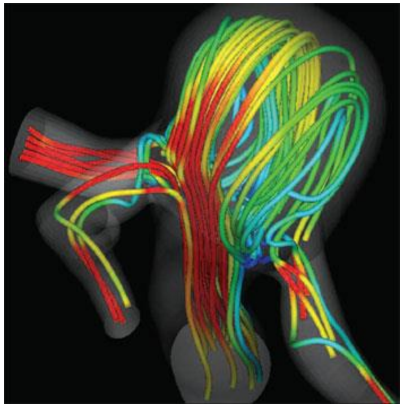
Motivation, aim











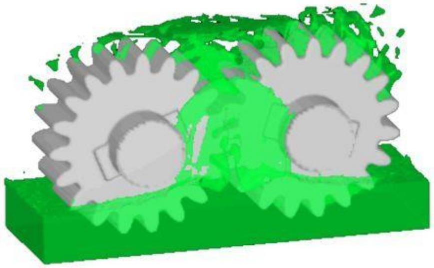
Aim:

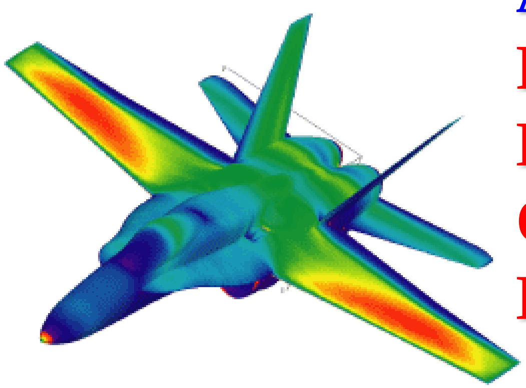
FSI-model

Benchmark

Optimization

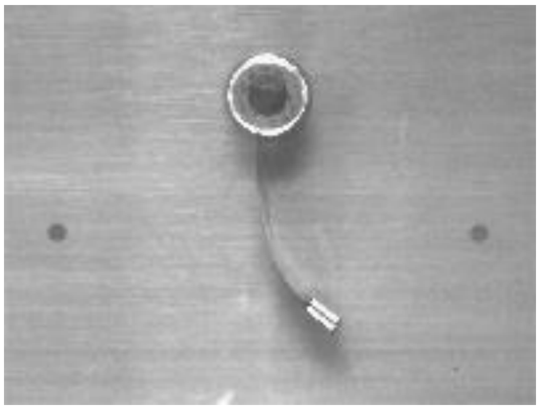
Extensions



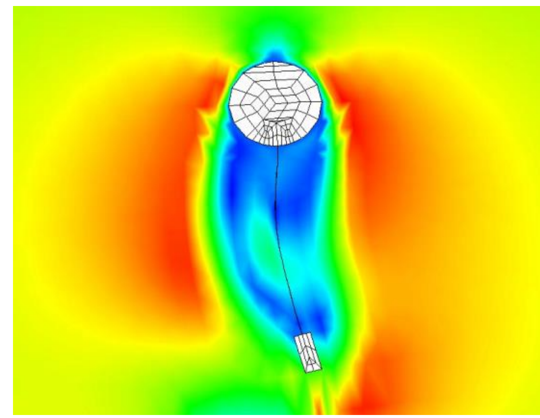


Overview

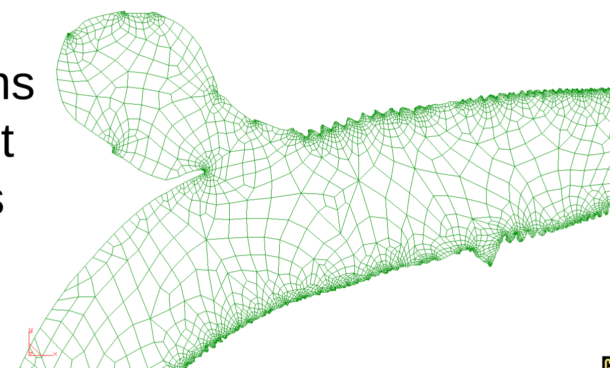
- Model for bioengineering
- Numerical methods
- Validation/Benchmarking
- Example application



FSI experiment vs numerical simulation



(Brain) Aneurysms and stent implants



Fluid structure interaction

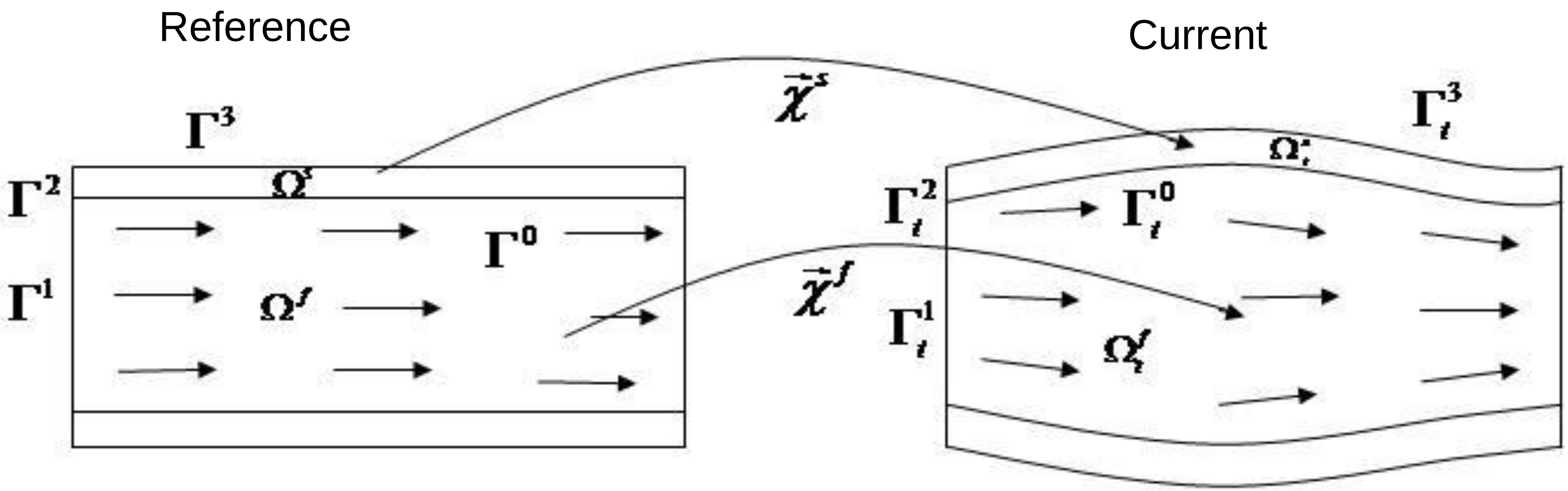
- ➢ large deformation of a structure in internal/external flow
  - aeorelasticity
  - bioengineering
  - polymer, food, paper processing
  - . . .

➢ physical models
- viscous fluid flow
- elastic body under large deformations
- interaction between the two parts

➢ numerical tasks involved
- space and time discretization
- nonlinear system
- large linear systems

➢ testing and validation
- accuracy, efficiency, robustness
- benchmarking

FSI problem formulation



Structure part

$$\chi^s : \Omega^s \times [0,T] \mapsto \Omega_t^s$$

$$u^s = \chi^s(X,t) - X, \quad v^s = \frac{\partial u^s}{\partial t}$$

$$\mathrm{F} = \mathrm{I} + \mathrm{Grad}\, u^s, \quad J = \det \mathrm{F}$$

Fluid part

$$\chi^f : \Omega^f \times [0,T] \mapsto \Omega_t^f$$

$$u^f = \chi^f(X,t) - X$$

$$v^f : \Omega_t^f \times [0,T] \mapsto R^n$$

Governing equations

Structure part

$$\frac{\partial v^s}{\partial t} = \operatorname{div}\left(J\sigma^s \mathrm{F}^{-T}\right) + f \quad \text{in } \Omega^s$$

$$\det(\mathrm{F}) = 1 \quad \text{in } \Omega^s$$

$$u^s = 0 \quad \text{on } \Gamma^2$$

$$\sigma^s n = 0 \quad \text{on } \Gamma^3$$

Fluid part

$$\frac{\partial v^f}{\partial t} + \left(\nabla v^f\right) v^f = \operatorname{div} \sigma^f + f \quad \text{in } \Omega_t^f$$

$$\operatorname{div} v^f = 0 \quad \text{in } \Omega_t^f$$

$$v^f = v_0 \quad \text{on } \Gamma_t^1$$

$$\text{or } \sigma^f n = 0 \quad \text{on } \Gamma_t^1$$

interface conditions

$$v^f = v^s \quad \text{on } \Gamma_t^0$$

$$\sigma^f n = \sigma^s n \quad \text{on } \Gamma_t^0$$

ALE Formulation

$$\chi : \Omega \times [0,T] \mapsto \Omega_t \qquad v = \frac{\partial \chi}{\partial t}, \qquad \mathrm{F} = \frac{\partial \chi}{\partial X}, \qquad J = \det \mathrm{F}$$

$$\zeta_R : R \times [0,T] \mapsto R_t \qquad R_t \subset \Omega_t \ \ \forall t \in [0,T], \ v_R = \frac{\partial \zeta_R}{\partial t} \ \ \mathrm{F}_R = \frac{\partial \zeta_R}{\partial X} \qquad J_R = \det \mathrm{F}_R$$

$$\frac{\partial}{\partial t} \int_{R_t} \rho \, dv + \int_{\partial R_t} \rho (v - v_R) \cdot n_{R_t} \, da = 0$$

$$\frac{\partial}{\partial t}(\rho J_R) + \operatorname{div}\left(\rho J_R (v - v_R) \mathrm{F}_R^{-T}\right) = 0$$

Lagrangian description

$$\zeta_R = \chi \Rightarrow \mathrm{F}_R = \mathrm{F}, \ \ J_R = J, v_R = v$$

$$\frac{\partial}{\partial t}(\rho J) = 0$$

Eulerian description

$$\zeta_R = \mathrm{Id} \Rightarrow \mathrm{F}_R = \mathrm{I}, \ \ J_R = 1, v_R = 0$$

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho v) = 0$$

ALE uniform formulation

$$\Omega = \Omega^f \cup \Omega^s \qquad u : \Omega \times [0,T] \to R^3, \quad v : \Omega \times [0,T] \to R^3,$$

$$\frac{\partial u}{\partial t} = \begin{cases} v & \text{in } \Omega^s \\ \Delta u \ \ (\text{mesh deformation operator}) & \text{in } \Omega^f \end{cases}$$

$$\beta \frac{\partial v}{\partial t} = \begin{cases} \operatorname{div}\left(J\sigma^s \mathrm{F}^{-T}\right) & \text{in } \Omega^s \\ -\beta(\nabla v)\mathrm{F}^{-1}\left(v - \frac{\partial u}{\partial t}\right) + \operatorname{div}\left(J\sigma^f \mathrm{F}^{-T}\right) & \text{in } \Omega^f \end{cases}$$

$$0 = \begin{cases} J - 1 & \text{in } \Omega^s \\ \operatorname{div}\left(Jv\mathrm{F}^{-T}\right) & \text{in } \Omega^f \end{cases}$$

$$\mathrm{J}\sigma^f F^{-T} N = \mathrm{J}\,\sigma^s F^{-T} N \quad \text{on } \Gamma^0$$

$$v = v_B \quad \text{on } \Gamma^1$$

$$u = 0 \quad \text{on } \Gamma^2$$

$$\mathrm{J}\,\sigma^s F^{-T} N = 0 \quad \text{on } \Gamma^3$$

Constitutive equations

For fluid

- incompressible Newtonian fluid

$$\sigma^f = -p^f \mathrm{I} + 2\nu^f(\cdot)\mathrm{D},$$

$$\mathrm{D} = \frac{1}{2}\left(\nabla v^f + \left(\nabla v^f\right)^T\right)$$

The generalized Newtonian

- ✓ Power-law model
- ✓ Yasuda model
- ✓ Carreau model

For solid

- Hyperelastic material
  - A neo-Hookean incompressible $J = \det F = 1$

$$\sigma^s = -p^s \mathrm{I} + \mu^s\left(\mathrm{F}\mathrm{F}^T - \mathrm{I}\right),$$

  - A neo-Hookean incompressible $J = \det F$

$$\sigma^s = \lambda^s\left(J - \frac{1}{J}\right)\mathrm{I} + \frac{\mu^s}{J}\left(\mathrm{F}\mathrm{F}^T - \mathrm{I}\right).$$

  - **Saint Venant Kirchhoff** material

$$\sigma^s = \frac{1}{J}\mathrm{F}\left(\lambda^s(\mathrm{trE})\mathrm{I} + \mu^s\mathrm{E}\right)\mathrm{F}^T$$

$$\mathrm{S}^s = \lambda^s(\mathrm{trE})\mathrm{I} + \mu^s\mathrm{E}, \qquad \mathrm{E} = \frac{1}{2}\left(\mathrm{F}^T\mathrm{F} - \mathrm{I}\right)$$

λ^s is lame coefficient,
μ^s is poisson ratio

Coupling approaches

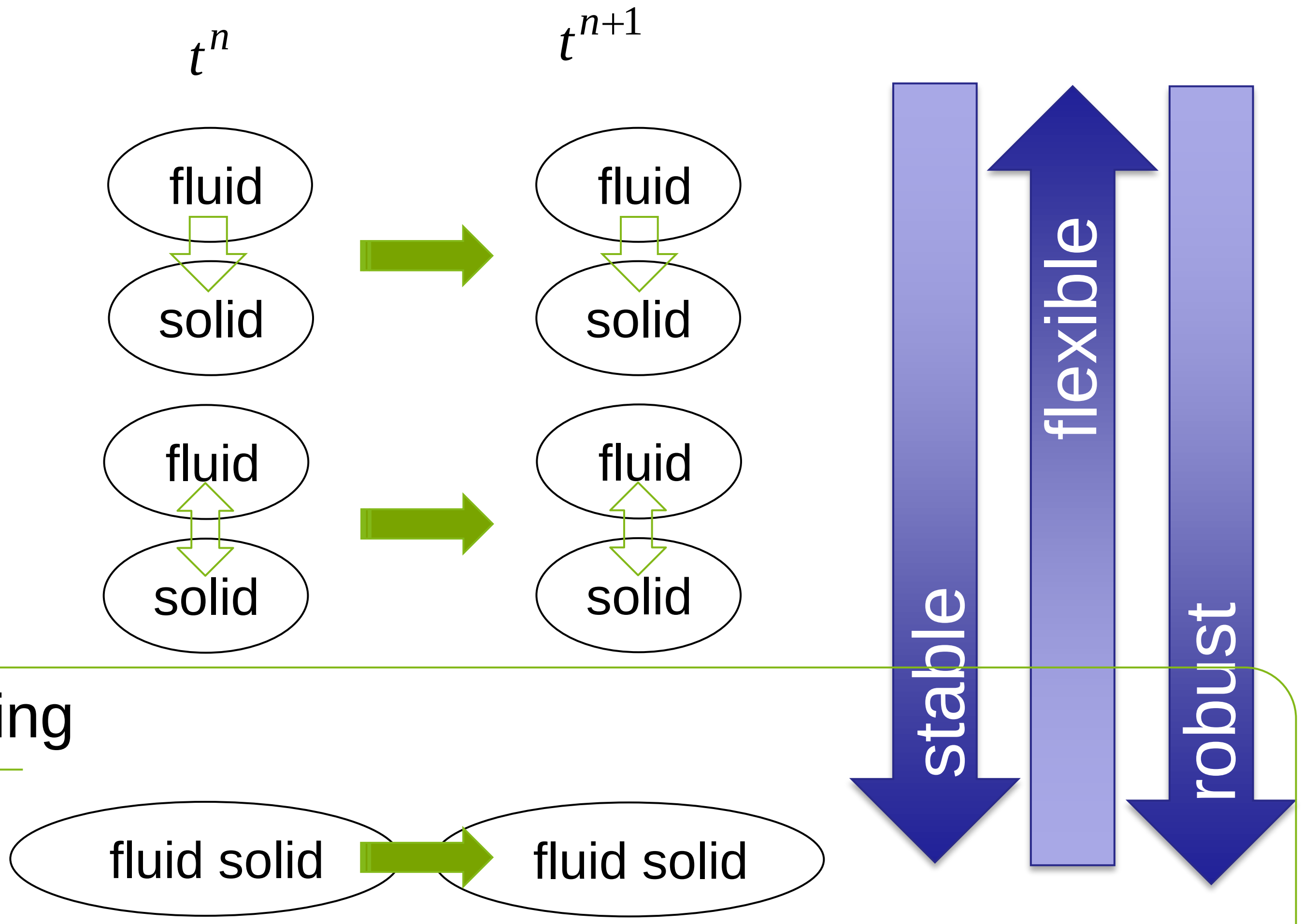
Separated (partitioned)

Weak coupling

Strong coupling

Monolithic coupling

Strong coupling

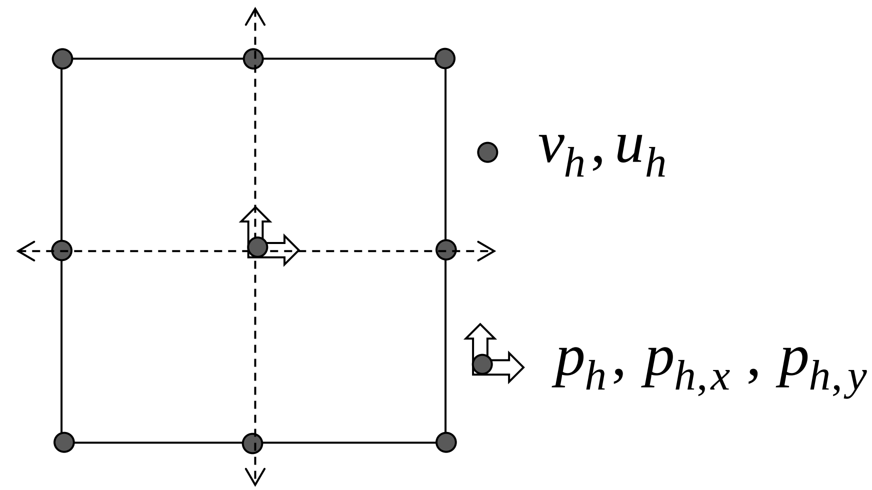


Discretization in space and time

- FEM: high order $Q_2/Q_2/P_1^{disc}$ approximations for deisplacement-velocity-pressure

Advantages: Inf-sup stable for velocity and pressure

$$\sup_{u\in[H_0^1(\Omega)]^2} \frac{\int_\Omega \nabla\cdot u\, q\, dx}{\|u\|_{1,\Omega}} \geq \beta_1 \|q\|_{0,\Omega} \quad \forall q \in L_0^2(\Omega)$$



$$U_h = \{u_h \in [C(\Omega_h)]^2, u_h|_T \in [\mathrm{Q}_2(T)]^2 \,\forall T \in \tau_h, u_h = 0 \text{ on } \Gamma^1\},$$

$$V_h = \{v_h \in [C(\Omega_h)]^2, v_h|_T \in [\mathrm{Q}_2(T)]^2 \,\forall T \in \tau_h, v_h = 0 \text{ on } \Gamma^1\},$$

$$P_h = \{p_h \in L^2(\Omega_h), p_h|_T \in P_1(T) \forall T \in \tau_h\}.$$

- **Discretization in time:** Crank-Nicholson scheme (2nd order) or fractional theta scheme (2nd order better stability)

Discrete Nonlinear System

$$R(\mathrm{X}) = 0 \qquad X = (u_h, v_h, p_h) \in U_h \times V_h \times P_h$$

$$\frac{\partial R}{\partial X}(X) = \begin{pmatrix} M - \frac{k}{2} L^f & \frac{k}{2} M^s & 0 \\ \frac{1}{2}\frac{\partial\left(N_1 + S^s + S^f\right)}{\partial u_h} + k\frac{\partial B}{\partial u_h} p_h & M^s + \beta M^f + \frac{1}{2}\frac{\partial N_2}{\partial v_h} + \frac{k}{2}\frac{\partial\left(N_1 + S_f^2\right)}{\partial v_h} & kB \\ B^{s^T} + \frac{\partial B^{f^T}}{\partial u_h} v_h & B^{f^T} & 0 \end{pmatrix}$$

$$\begin{bmatrix} S_{uu} & S_{uv} & 0 \\ S_{vu} & S_{vv} & kB \\ c_u B_s^T & c_v B_f^T & 0 \end{bmatrix} \begin{bmatrix} u \\ v \\ p \end{bmatrix} = \begin{bmatrix} \mathrm{f_u} \\ \mathrm{f_u} \\ f_p \end{bmatrix}$$

Typical discrete saddle point problem as well known for incompressible NSE

Solution of the nonlinear problem

- Newton method with damping results in iterations of the form

$$R(\mathrm{x}) = 0, \quad \mathrm{x} = (\mathrm{u}, \mathrm{v}, p)$$

$$\mathrm{x}^{\mathrm{n}+1} = \mathrm{x}^{\mathrm{n}} + \omega^{\mathrm{n}} \left[\frac{\partial R(\mathrm{x}^{\mathrm{n}})}{\partial \mathrm{x}} \right]^{-1} R(\mathrm{x}^{\mathrm{n}})$$

- Inexact Newton: on matrix level (after discretization)

→ The Jacobian matrix is **approximated** using finite differences as

$$\left[\frac{\partial R(\mathrm{x}^{\mathrm{n}})}{\partial x} \right]_{ij} \approx \frac{R_i(\mathrm{x}^{\mathrm{n}} + \varepsilon \mathrm{x}_{\mathrm{j}}^{\mathrm{n}} \mathrm{e}_j) - R_i(\mathrm{x}^{\mathrm{n}} - \varepsilon \mathrm{x}_{\mathrm{j}}^{\mathrm{n}} \mathrm{e}_j)}{2\varepsilon \mathrm{x}_{\mathrm{j}}^{\mathrm{n}}}$$

Solution of the linear problem

- standard geometric multigrid approach
- smoother by local MPSC-Ansatz (Vanka-like smoother)

  coupled monolithic multigrid solver

$$\begin{bmatrix} u^{l+1} \\ v^{l+1} \\ p^{l+1} \end{bmatrix} = \begin{bmatrix} u^{l} \\ v^{l} \\ p^{l} \end{bmatrix} - \omega \sum_{\text{Patch}\Omega_i} \begin{bmatrix} S_{uu|\Omega_i} & S_{uv|\Omega_i} & 0 \\ S_{vu|\Omega_i} & S_{vv|\Omega_i} & kB_{|\Omega_i} \\ c_u B^T_{s|\Omega_i} & c_v B^T_{f|\Omega_i} & 0 \end{bmatrix}^{-1} \begin{bmatrix} \text{def}_u^l \\ \text{def}_v^l \\ def_p^l \end{bmatrix}$$

- full inverse of the local problems by LAPACK (39 x39 systems)
- full Q_2 and P_1^{disc} (canonical) FEM prolongation P, restriction $\mathrm{R} = \mathrm{P}^T$

Very accurate, flexible and highly efficient FSI solver

(→ FSI Benchmarks)

Towards testing your code

1st step:

Identification of appropriate FSI settings for numerical benchmarking and calculate

If done

2nd step

Extension to FSI-Optimisation benchmark settings

- Data files are available on

http://featflow.de/beta/en/benchmarks.html

Key question: FSI benchmarking

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- *Accurate and robust description of the interaction mechanisms*

  w.r.t.

  highly dynamical ,

  nonlinear behavior ,

  and significant geometry changes?

- That includes:
  - Quality of different discretization techniques (FEM, FV, FD, LBM, resp., beam, shell, volume elements) for FSI?
  - Robustness and numerical efficiency of the integrated solver components?
  - Coupling mechanisms (partitioned/monolithic, weak/strong)?

Requirements for <u>numerical</u> FSI

- *Realistic materials*
  - **incompressible Newtonian fluid**, laminar flow regime
  - **elastic solid**, large deformations
- *Comparative evaluation*
  - setup with periodical oscillations
  - non-graphically based quantities
- *Computable configurations*
  - laminar flow
  - reasonable aspect ratios
  - simple geometry (2D)
- Mainly based on validated CFD benchmarks, but also close to experimental set-up

Material parameters

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solid

ρ^s density

ν^s Poisson ratio

μ^s shear modulus

fluid

ρ^f density

ν^f kinematic viscosity

Parameter	polybutadiene & glycerine	**polypropylene & glycerine**
$\rho^s[10^3\mathrm{kg/m^3}]$ ν^s $\mu^s[10^6\mathrm{kg/ms^2}]$	incompressible 0.91 0.50 0.53	compressible 1.1 0.42 317
$\rho^f[10^3\mathrm{kg/m^3}]$ $\nu^f[10^{-3}\mathrm{m^2}/s]$	1.26 1.13	1.26 1.13

Oriented materials

Parameter	FSI1	FSI2	FSI3
$\rho^s[10^3\mathrm{kg/m^3}]$ ν^s $\mu^s[10^6\mathrm{kg/ms^2}]$	1 0.4 0.5	1 0.4 0.5	1 0.4 2.0
$\rho^f[10^3\mathrm{kg/m^3}]$ $\nu^f[10^{-3}\mathrm{m^2}/s]$	1 1	1 1	1 1
$\bar{U}[\mathrm{m/s}]$	0.2	1	2

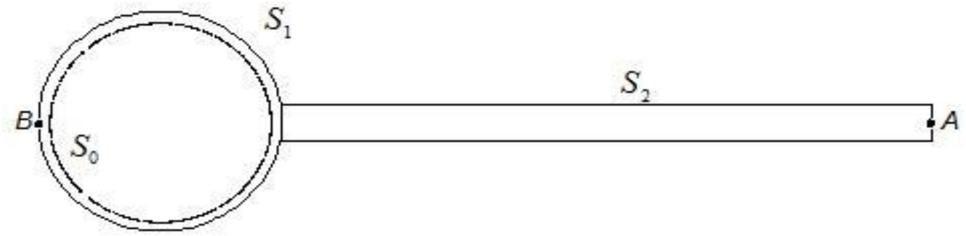
Parameter	FSI1	FSI2	FSI3
$\beta = \frac{\rho^s}{\rho^f}$ $\mathrm{Ae} = \frac{\mathrm{E}^s}{\rho^f \bar{U}^2}$	1 0.4	1 0.4	1 0.4
$\mathrm{Re} = \frac{\bar{U}d}{\nu^f}$ $\bar{U}[\mathrm{m/s}]$	20 0.2	100 1	200 2

Quantities of interest

- The position $A(t)=(x(t), y(t))$ of the end of the structure
- Pressure difference between the points *A(t)* and *B*

$$\Delta p^{AB}(t) = p^{B}(t) - p^{A(t)}(t)$$

- Forces exerted by the fluid on the *whole body*, i.e. lift and drag forces acting on the cylinder and the structure together



$$(F_D, F_L) = \int_S \sigma\, n dS = \int_{S_1} \sigma^{f} n dS + \int_{S_2} \sigma^{f|S} n dS = \int_{S_0} \sigma\, n dS$$

- Frequency and maximum amplitude
- Compare results for *one* full period and 3 different levels of spatial discretization *h* and 3 time step sizes Δt

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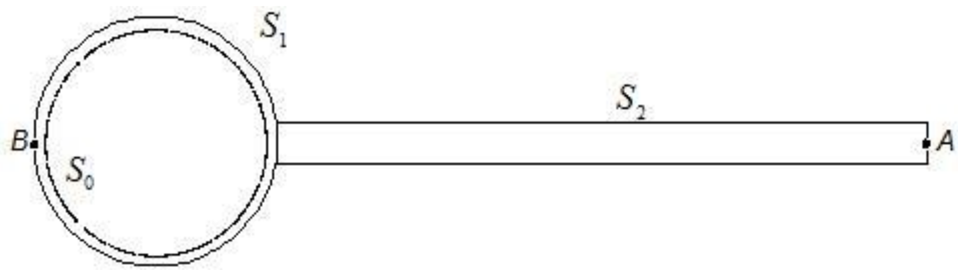
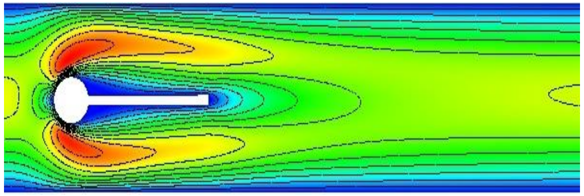
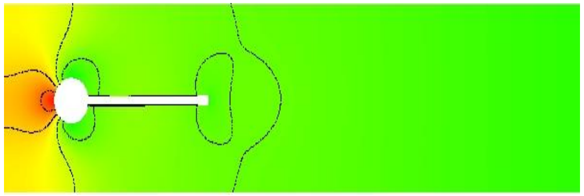
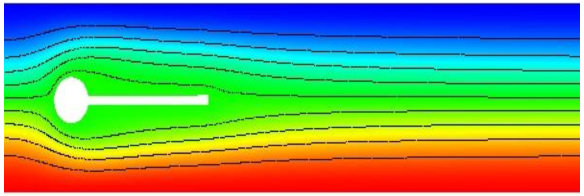
Parameter	FSI1	FSI2	FSI3
$\rho^s [10^3 \mathrm{kg/m^3}]$	1	1	1
ν^s	0.4	0.4	0.4
$\mu^s [10^6 \mathrm{kg/ms^2}]$	0.5	0.5	2.0
$\rho^f [10^3 \mathrm{kg/m^3}]$	1	1	1
$\nu^f [10^{-3} \mathrm{m^2}/s]$	1	1	1
$\bar{U} [\mathrm{m}/s]$	0.2	1	2



$$(F_D, F_L) = \int_S \sigma\, n dS = \int_{S_1} \sigma^f n dS + \int_{S_2} \sigma^{f|S} n dS = \int_{S_0} \sigma\, n dS$$

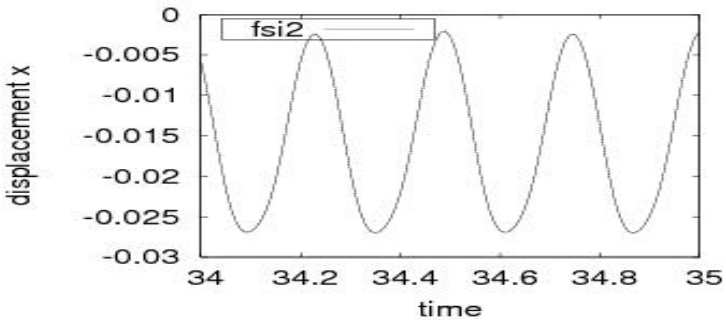


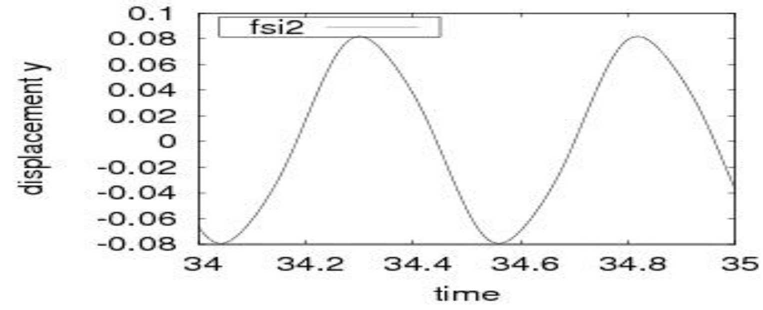


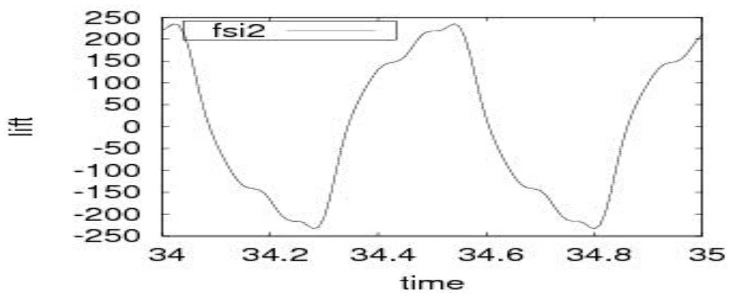


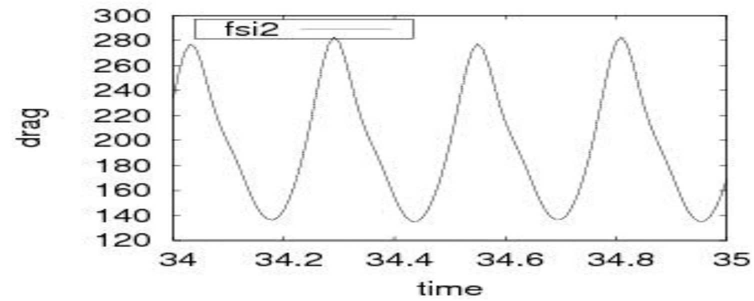
	ux of A $[\times 10^{-5} \mathrm{m}]$	uy of A $[\times 10^{-4} \mathrm{m}]$	drag	lift
FSI1	2.270493	8.208773	14.2942	0.76374

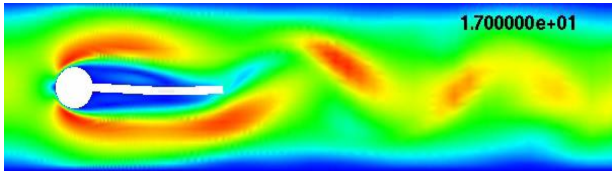
FSI2: large deformations, periodical oscillations

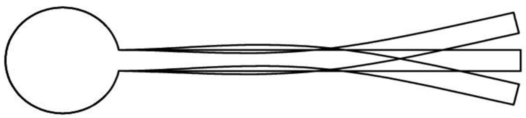






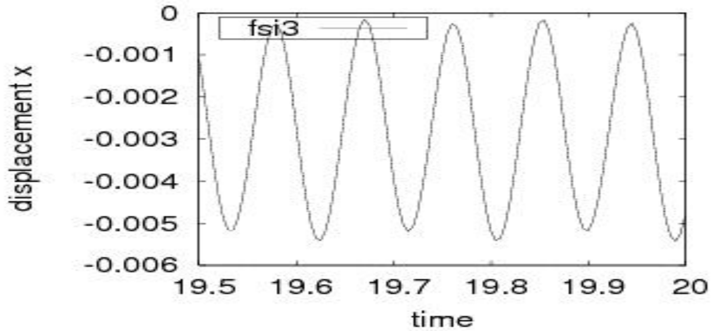


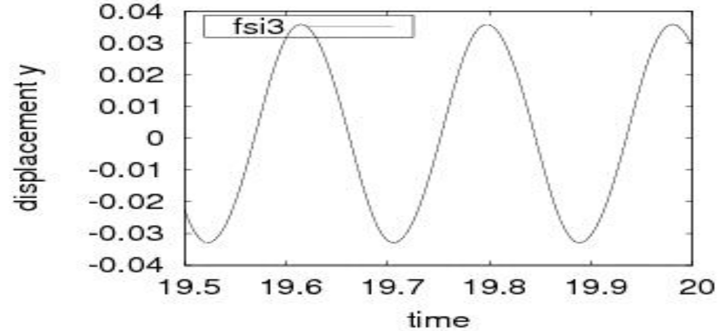


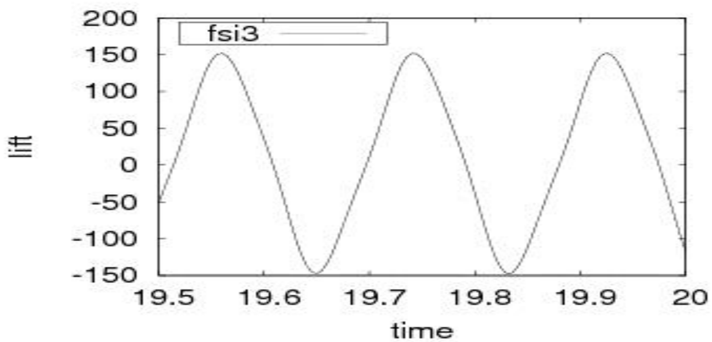


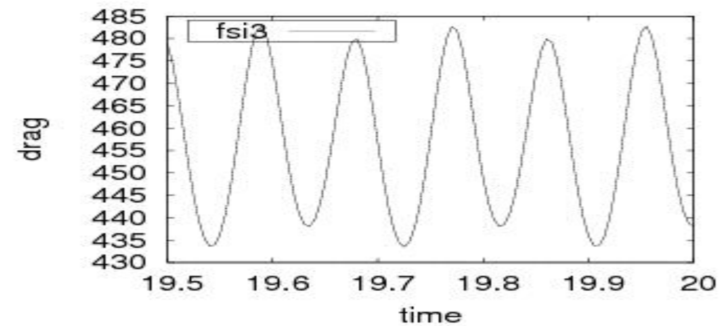
Test	ux of A $[\times 10^{-3}\mathrm{m}]$	uy of A $[\times 10^{-3}\mathrm{m}]$	drag	lift
FSI2	$-14.58 \pm 12.44[3.8]$	$1.23 \pm 80.6[2.0]$	$208.83 \pm 73.75[3.8]$	$0.88 \pm 234.2[2.0]$

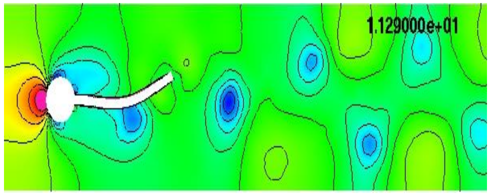
- **FSI3: large deformations, complex oscillations**

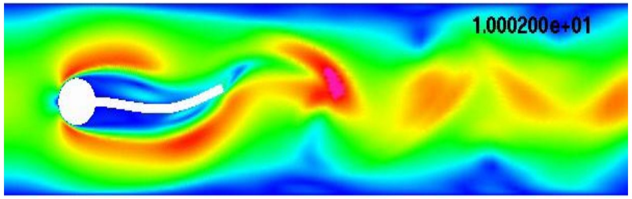


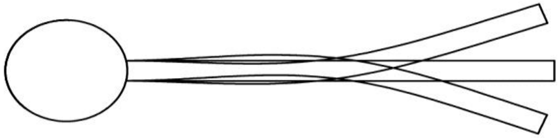






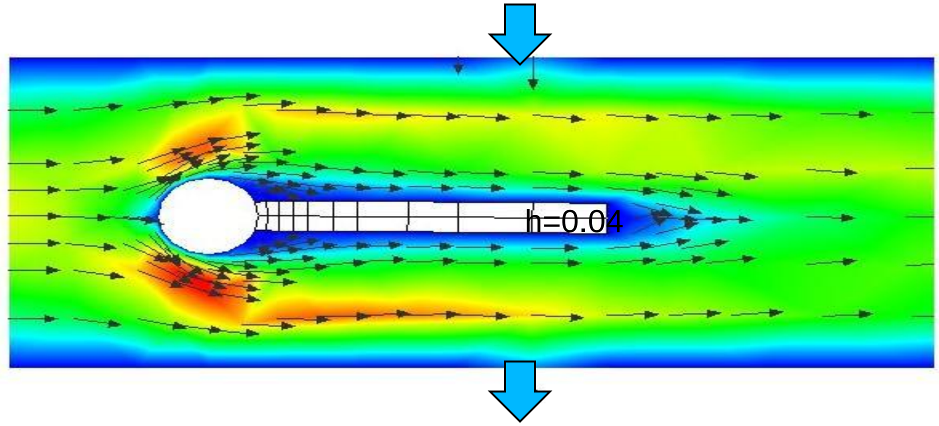






Test	ux of A $[\times 10^{-3} m]$	ux of A $[\times 10^{-3} m]$	drag	lift
FSI3	$-2.69 \pm 2.53[10.9]$	$1.48 \pm 34.38[5.3]$	$457.3 \pm 22.66[10.9]$	$2.22 \pm 149.78[5.3]$

- uncontrolled flow



	ux of A $[\times 10^{-3} \mathrm{m}]$	uy of A $[\times 10^{-3} \mathrm{m}]$	drag	lift
FSI1	0.0227	0.8209	14.295	0.7638

lift $\longrightarrow 0$

- Aim:

$$\text{minimize}\left(lift^2 + \alpha V^2\right)$$

w.r.t V1, V2.

Nelder Mead

V1 velocity from top

V2 velocity from below

FSI Opt1

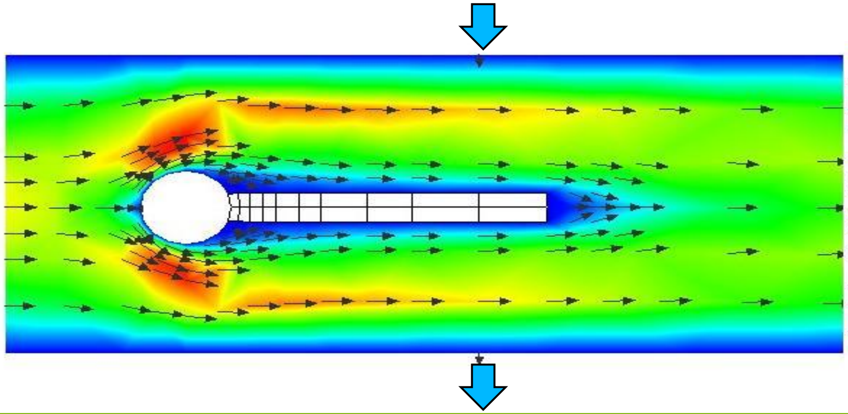
$$\text{minimize}\left(lift^2+\alpha V^2\right)$$

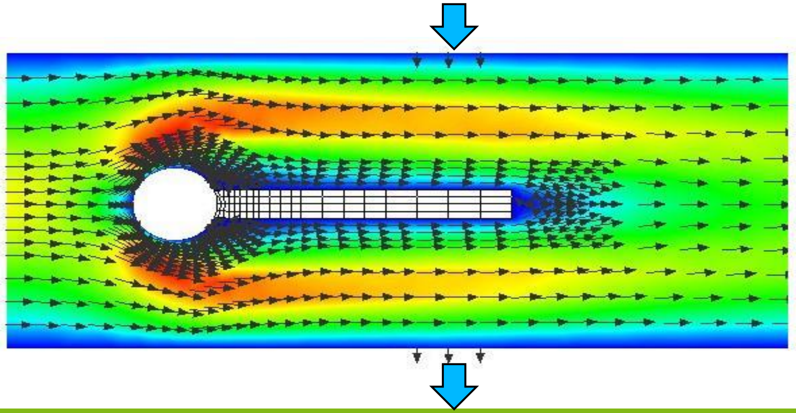
w.r.t V1, V2.

V1 velocity from top

V2 velocity from below

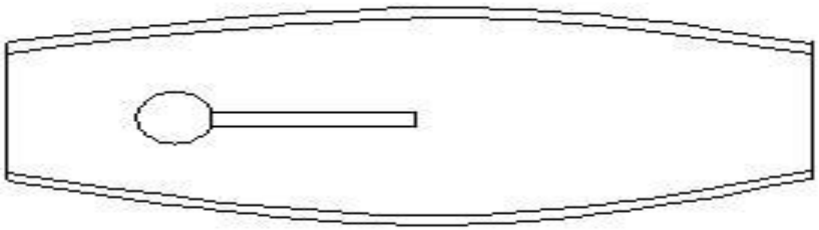
	Level 1				Level 2			
α	Iter steps	extreme point	drag	Lift	Iter steps	extreme point	drag	Lift
1e0	57	(3.74e-1,3.88e-1)	1.5471e+01	8.1904e-1	59	(3.66e-1,3.79e-1)	1.5550e+01	7.8497e-1
1e-2	60	(1.04e0,1.06e0)	1.5474e+01	2.2684e-2	59	(1.02e0,1.04e0)	1.5553e+01	2.1755e-2
1e-4	73	(1.06e0,1.08e0)	1.5474e+01	2.3092e-4	71	(1.04e0,1.05e0)	1.5553e+01	2.2147e-4
1e-6	81	(1.06e0,1.08e0)	1.5474e+01	2.3096e-6	86	(1.04e0,1.05e0)	1.5553e+01	2.2151e-6





- Future examples might be:

  - complete walls elastic
  - portion of elastic



1. $\text{minimize}\left(lift^2 + \alpha V^2\right)$ for deformed case
2. pressure loss minimize: $\text{minimize}\left(p_{in} - p_{out}\right)$

w.r.t elastic deformation of the wall

or

w.r.t geometrical and material properties of beam

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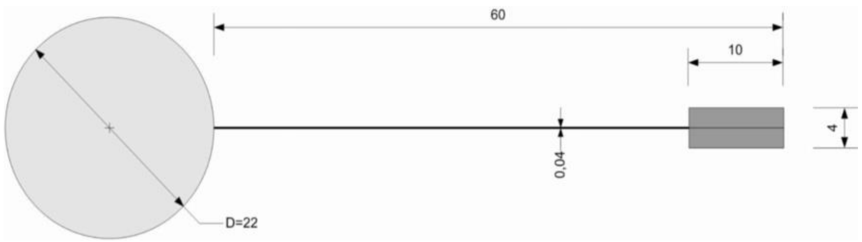
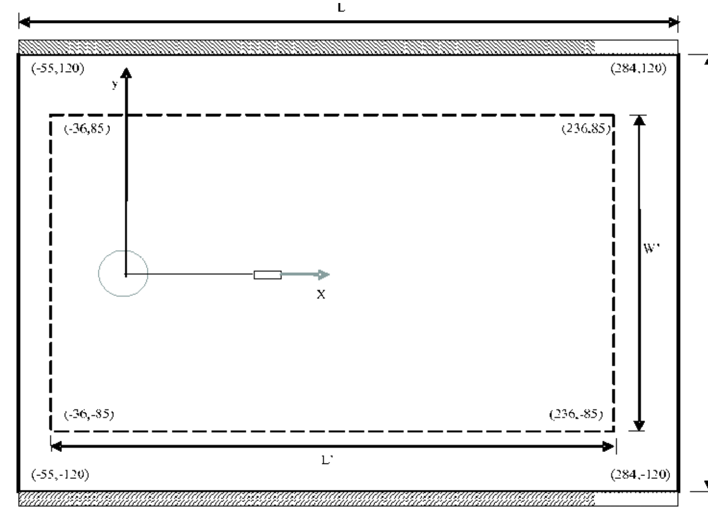
- **FSI4: benchmarking of experimental data**
  - Flustruc experiment, Erlangen, http://www.lstm.uni-erlangen.de/flustruc





fluid parameters	
density of the fluid kinematic viscosity	1.05e-6 [kg/mm^3] 164.0

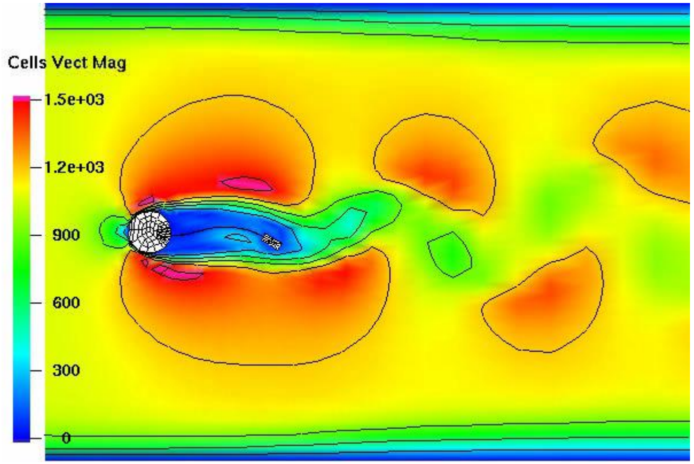
solid parameters	
density of the beam (steel) density of the rear mass shear modulus poisson ratio	7.85e-6[kg/mm^3] 7.8e-6 [kg/mm^3] 7.58e13 0.3

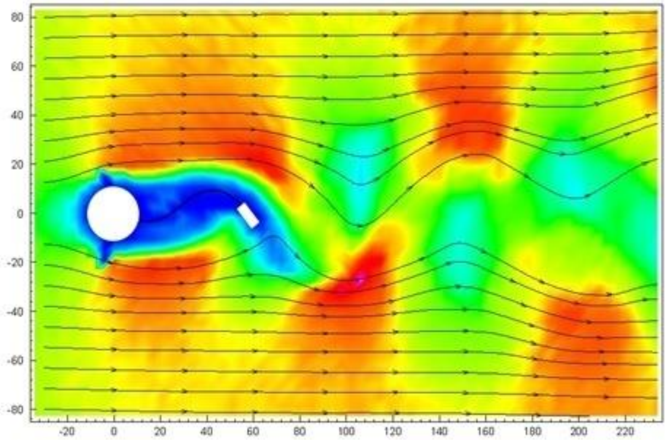
geometry parameter		value [mm]
channel length channel width cylinder center position cylinder radius elastic structure length elastic structure thickness rear mass length rear mass thickness reference point (at t=0) reference point	*L* *W* *C* *R* *l* *w* *w'* *h'* *A* *B*	338.0 240.0 (0.0, 0.0) 11.0 50 0.04 10.0 4.0 (71.0, 0.0) (11.0, 0.0)

FSI Benchmark

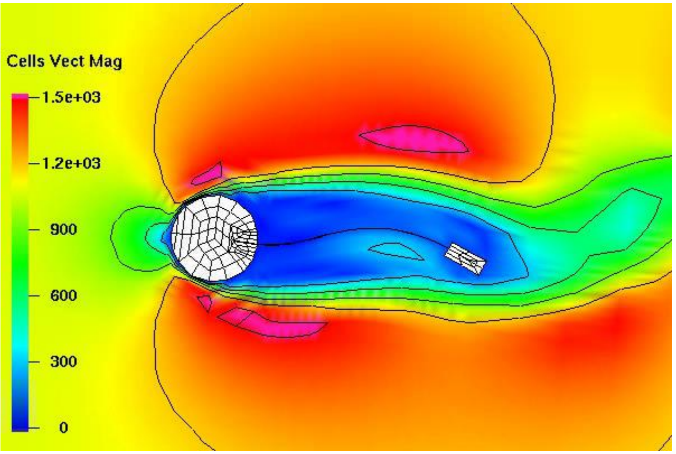
- **FSI4: benchmarking of experimental data**

  - + Laminar Flow (glycerine)
  - + “2D“ flow and deformation
  - - Rotational degree of freedom
  - - Large aspect ratio (thin structure)
  - - Corners





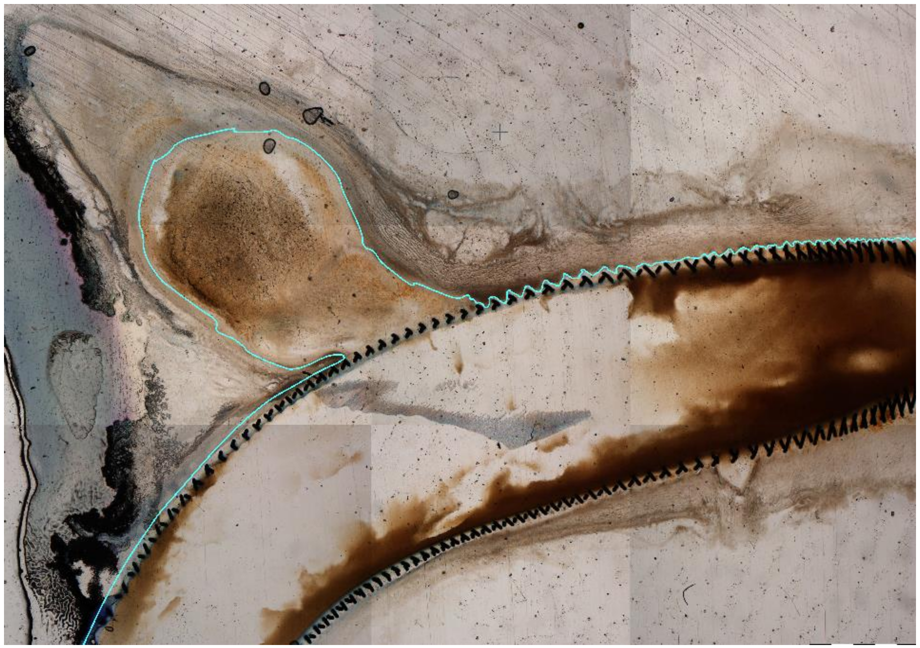
Flustruc experiment, Erlangen



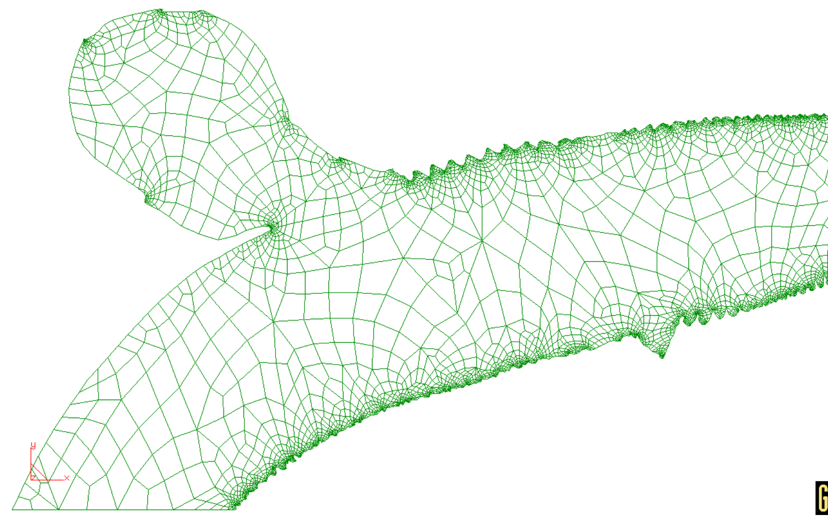
Computation

Brain Aneurysms and stent implants

- **Aim:** Numerical study of FSI due to stent geometries **and** elastic wall behaviour



Cerebral aneurysm



Mesh for numerical Simulation

Steady state results, vector magnitude

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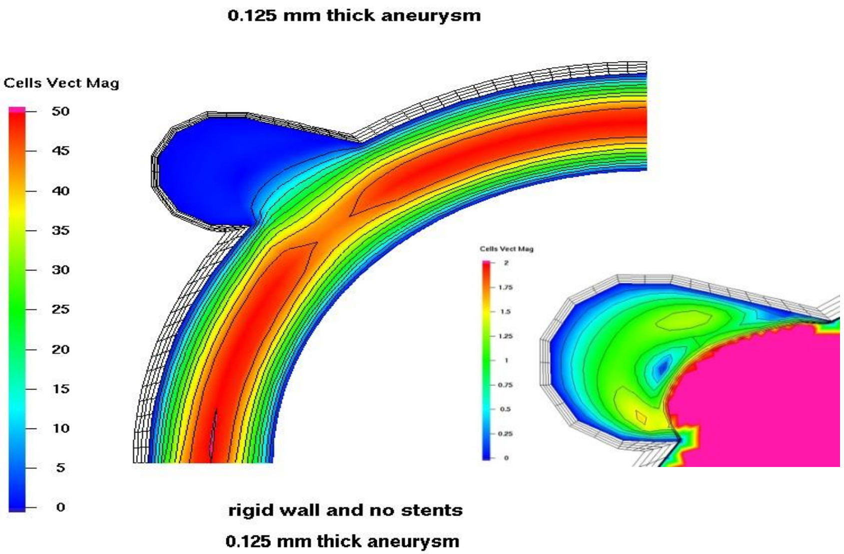

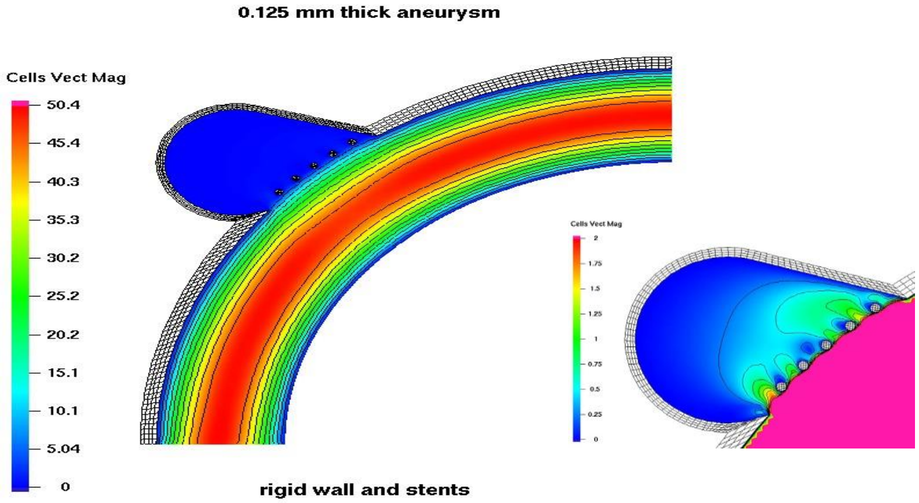

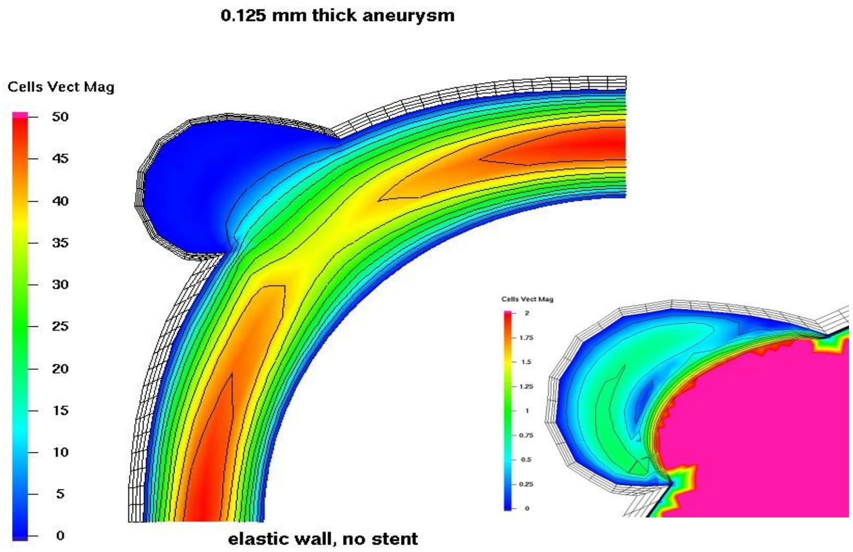

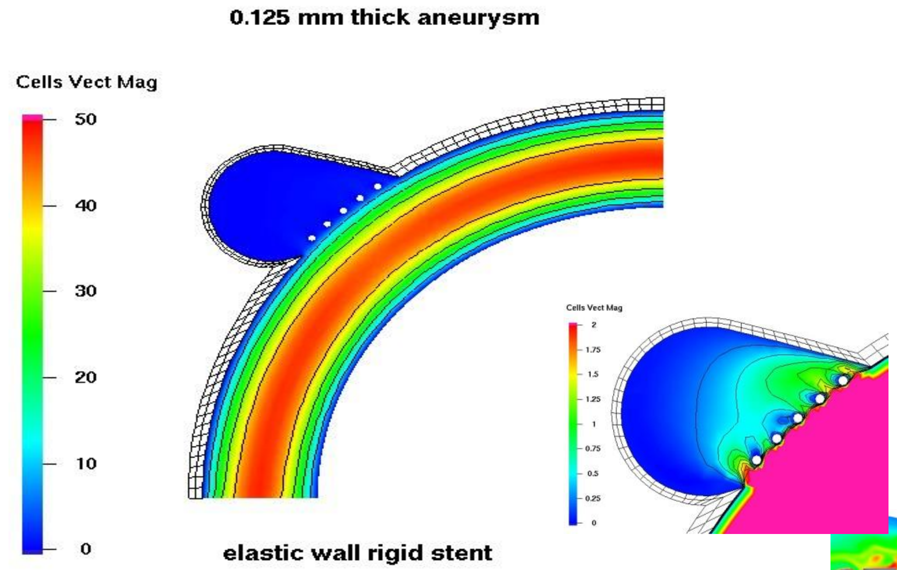

Tests: message
- Less flow through elastic
- Less flow through stents

Flow inside aneurysma, vector magnitude

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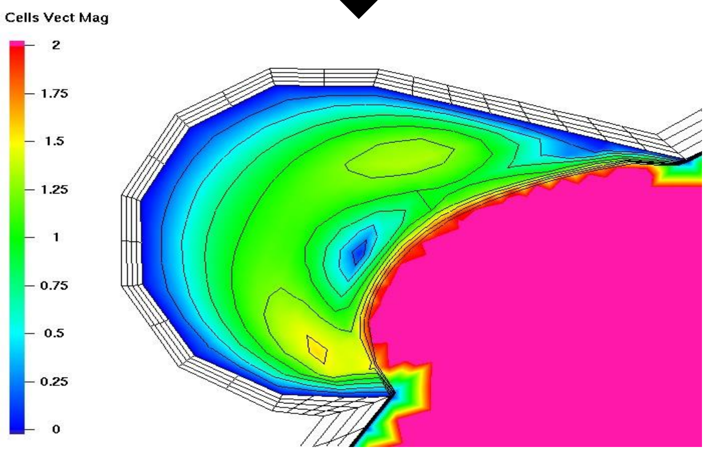
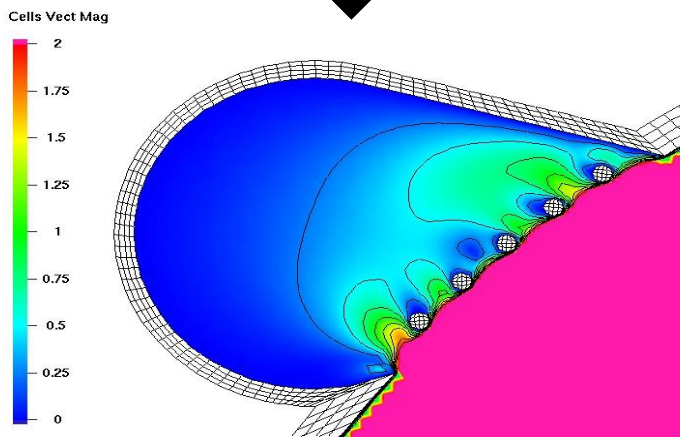
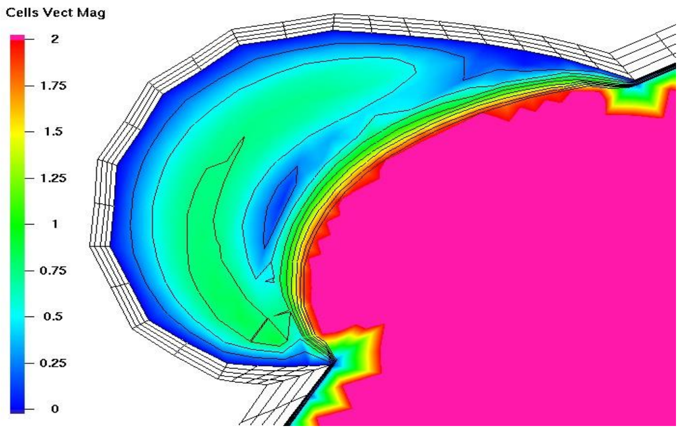
- Vector magnitude inside aneurysma
- Rigid wall without stents



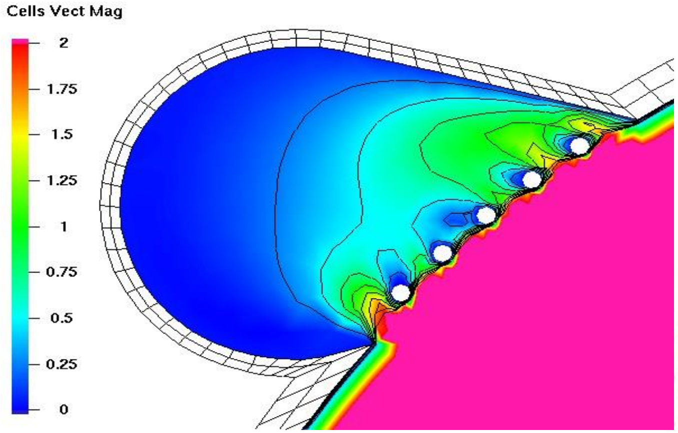
- Vector magnitude inside aneurysma
- Rigid wall and stents



- Vector magnitude inside aneurysma
- Elastic wall without stents

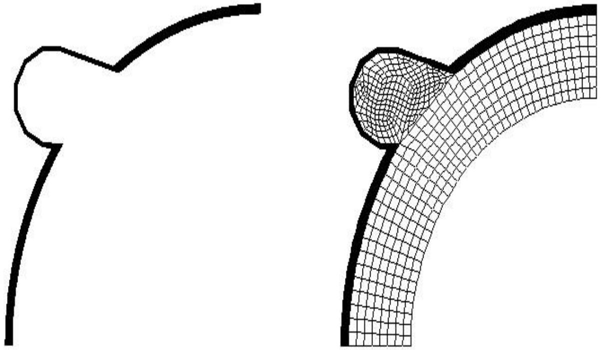


- Vector magnitude inside aneurysma
- Elastic wall stents

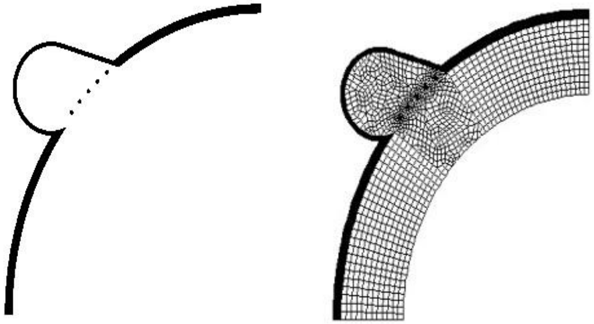


Structure

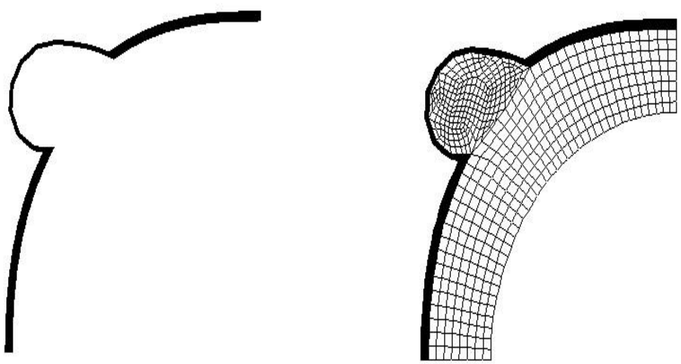
- Wall structure
- Rigid wall without stents



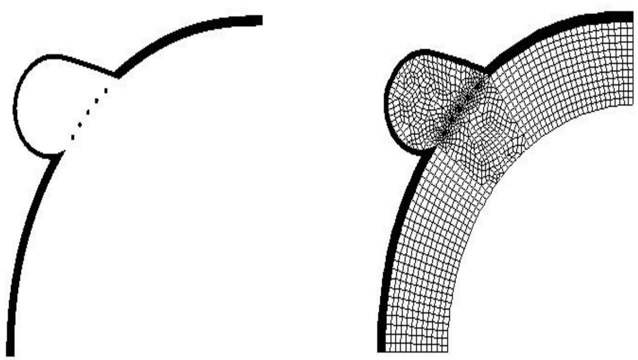
- Wall structure
- Rigid wall and stents



- Wall structure
- Elastic wall without stents

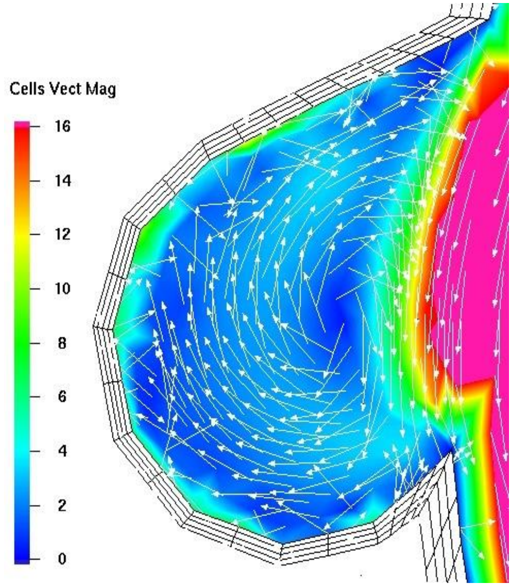


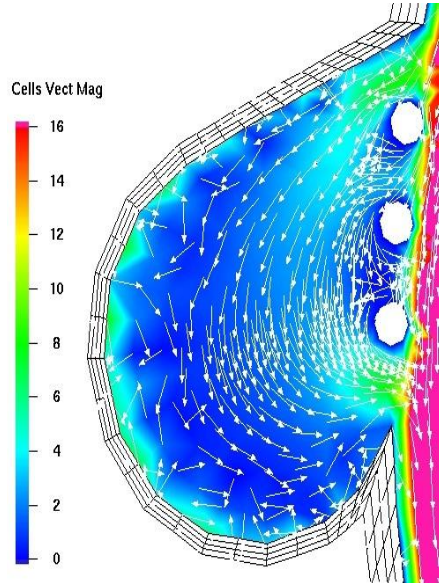
- Wall structure
- Elastic wall with stents

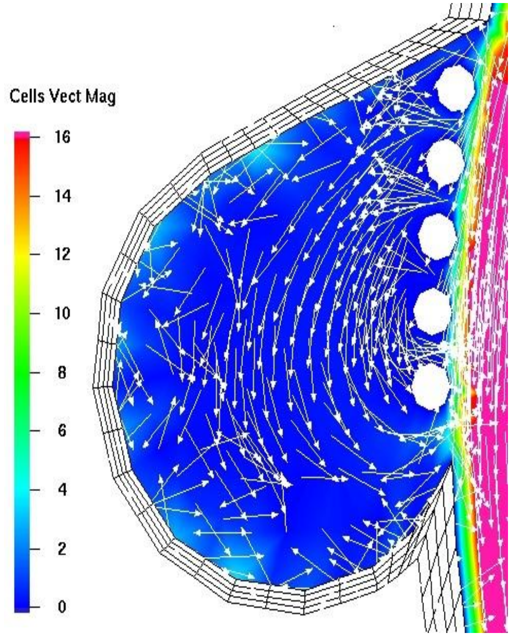


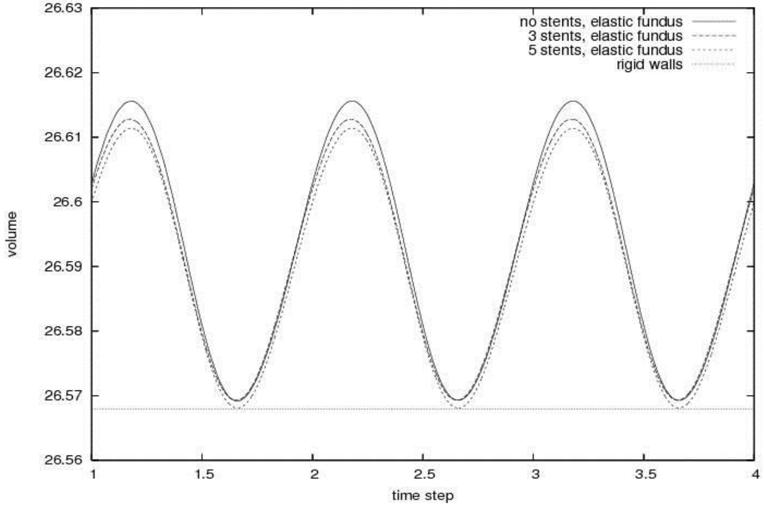
Aneurysm (pulsatile inflow)

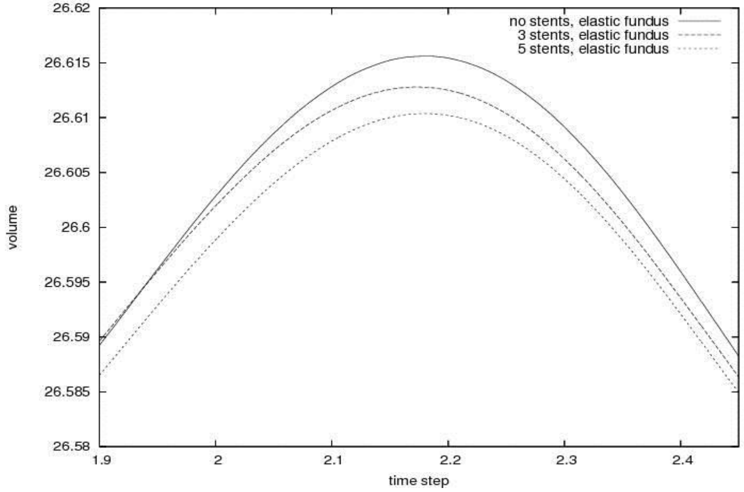
- Strong influence of stent geometry and elastic wall deformations









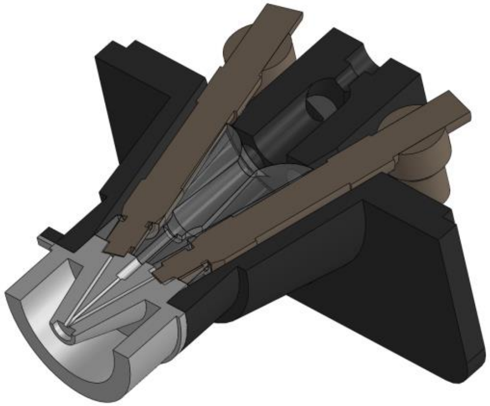
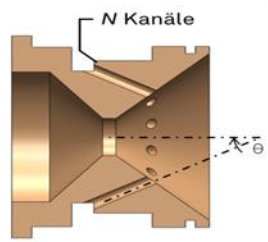


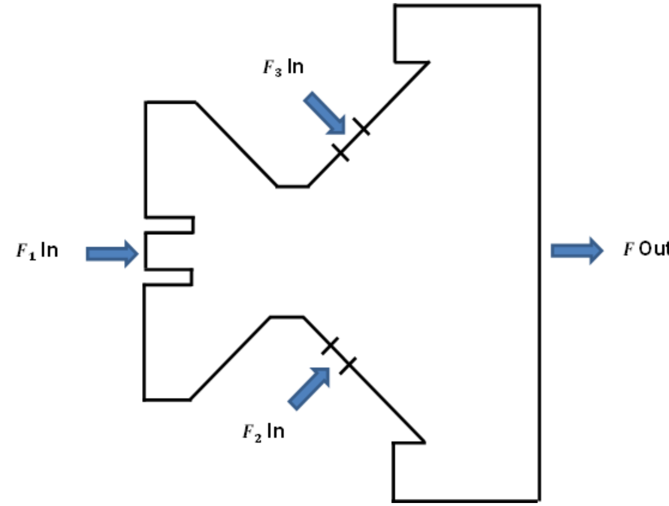
Next Steps

- Combine elastic behavior with stents
  ➡ Analyze different elastic properties and stent geometries

- More realistic material law for vessels
- Non linear flow model
  - Fluid with shear dependent velocities i.e, biological fluids such as blood flow
  - People who addressed these studies are:
    Cho, Kensey (89-91), Cokelet (72), Cross (65), Davies et al. (90), Nakamura, Sawada (88).

Massively parallel DFO

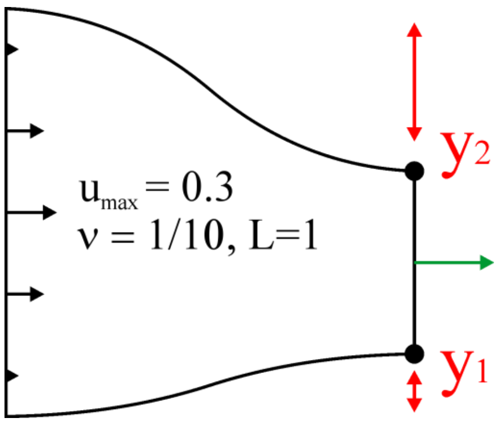
- LiBo Nozal simulation
-  



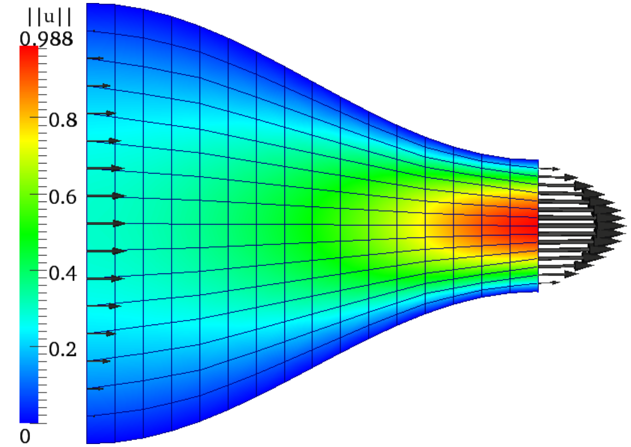
- Existing software packages ...
  - Most powerful package: **DAKOTA** (from Sandia Nat. Lab.)
    - parallel, derivative-free, open source
    - simple interface to simulation
    - collection of many state-of-the-art algorithms (nonlin. optimisation, constraints, uncertainty,...)

Current developments

- Proof of concept: DAKOTA with FeatFlow solver (Nav.–St.)



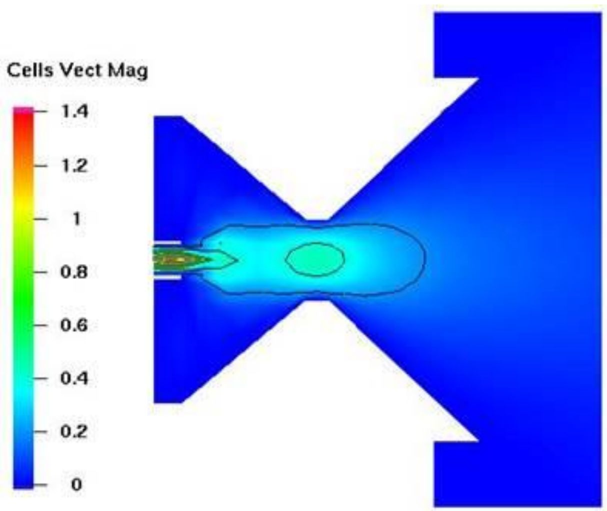
- Pattern search
- #it = 53
- $y = (-0.15, 0.14)$

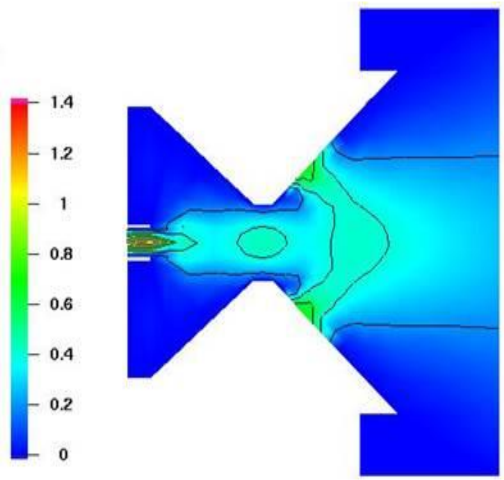


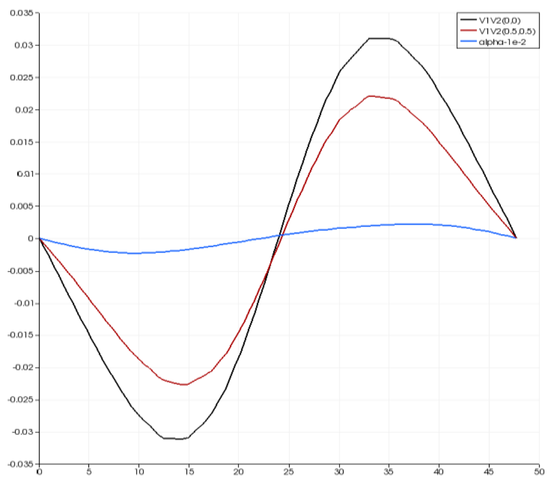
- Find $y = (y1, y2)$ such that central outflow = (1, 0).
- Status
  - **LiDo cluster:** Different strategies + long-term optimization
  - **LiBo nozzle:** Verification of analytic nozzle models

Nozzle

- ZFP "Optimization"
- coupling from Simulation software (FEATFLOW) with Optimization tool (DAKOTA)
- Parallel optimization prototypical 2D nozzles (here : incompressible, minimizing the speed in the vertical direction on the right side
- Speed profile without secondary inlet supply (left) and with optimized secondary inlet supply (right)







Summary

New Numerical and Algorithmic tools are availible using

- ✓ **Monolithic Finite Element Method**
- ✓ **Arbitrary Lagrangian-Eulerian Formulation**
- ✓ **Fast Multigrid Solver with local MPSC smoother**

For the simulation of FSI with application to hemodynamics aneurysma