Fluid-Structure Interaction Analysis of a Peristaltic Pump

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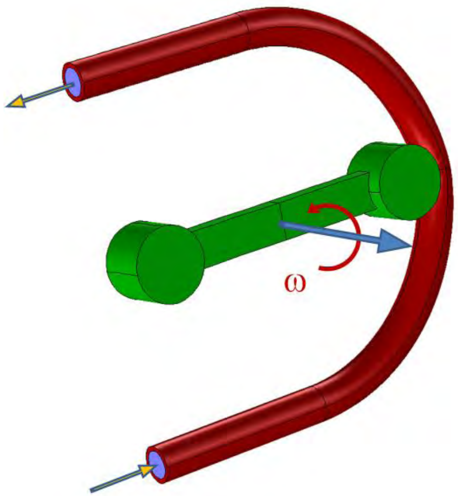

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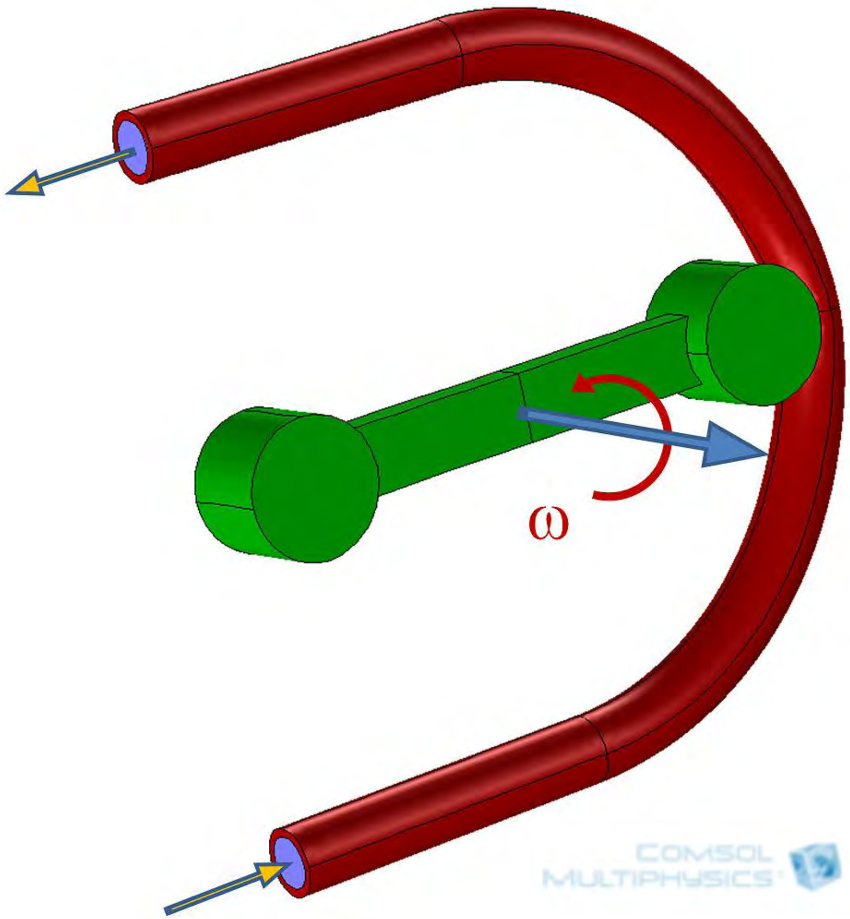
Peristaltic Pumps

- Valuable for pumping abrasive fluids, corrosive fluids and delicate fluids
- Rugged pump design requiring minimal maintenance
- Used in pharmaceutical, petrochemical, biomedical and food processing industries

Pump Modeling

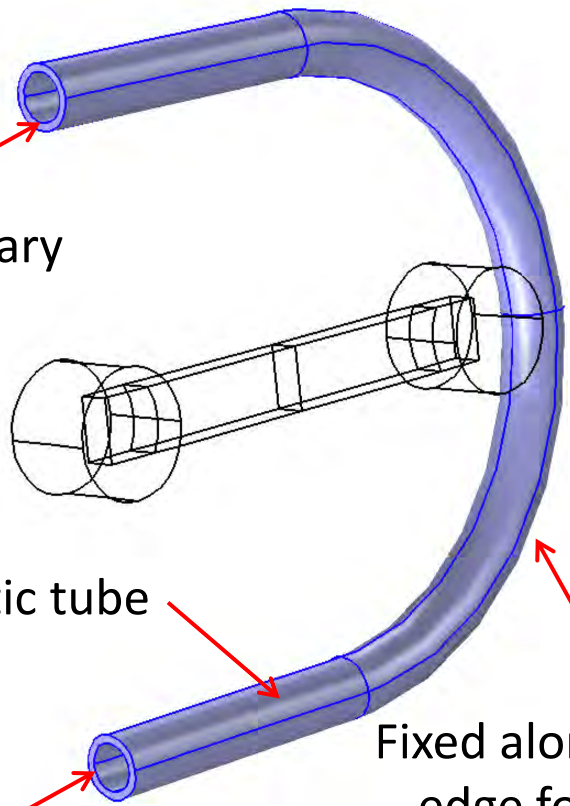
- Nonlinear, coupled fluid-structure interaction
- Structural nonlinearities include:
  - Tube material behavior
  - Contact
  - Large deformations
- Important to know tube stresses and strains for lifetime prediction
- Optimal design depends on fluid properties and flow rate

Rotary Peristaltic Pump Model



- Two metallic rollers and an elastomeric tube pumping a viscous Newtonian fluid at a speed of 60 Hz
- Model setup parametrically using native COMSOL geometry

Tube Modeling

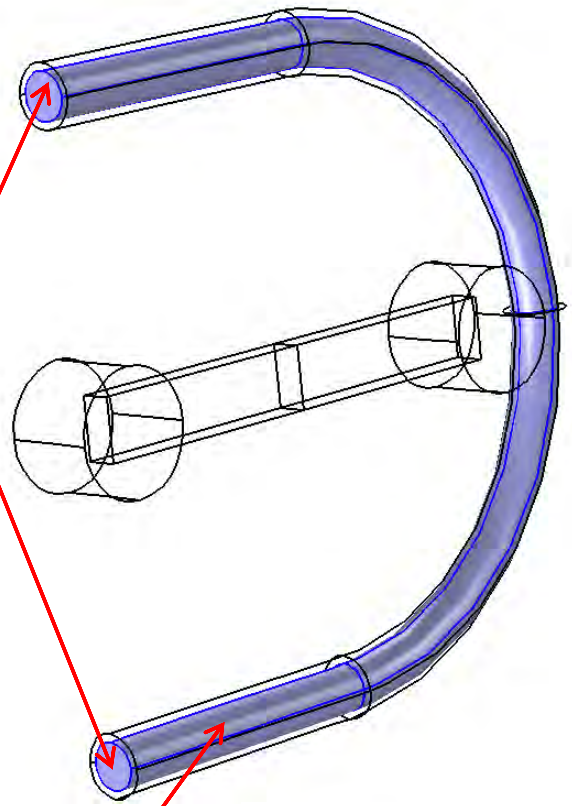


- Tube material one of main limiting factors affecting pump performance
- Typically made of elastomers like silicone or thermoplastic elastomers such as Norprene® or Tygon®

Available Material Models

- Linear elastic
- Nonlinear models
  - Hyperelastic
    - Neo-Hookean, Mooney-Rivlin, Murnaghan, User-defined
  - Viscoelastic
  - Geotechnical
- User-defined hyperelastic model most suitable for matching material model to experimental stress-strain behavior

Fluid Modeling



Open fluid boundaries

- Incompressible Newtonian fluid
- Laminar Navier-Stokes equations
- Peristaltic pumps commonly used for non-Newtonian fluids
- Moving fluid-mesh follows solid deformation
- FSI interface automatically handled by COMSOL

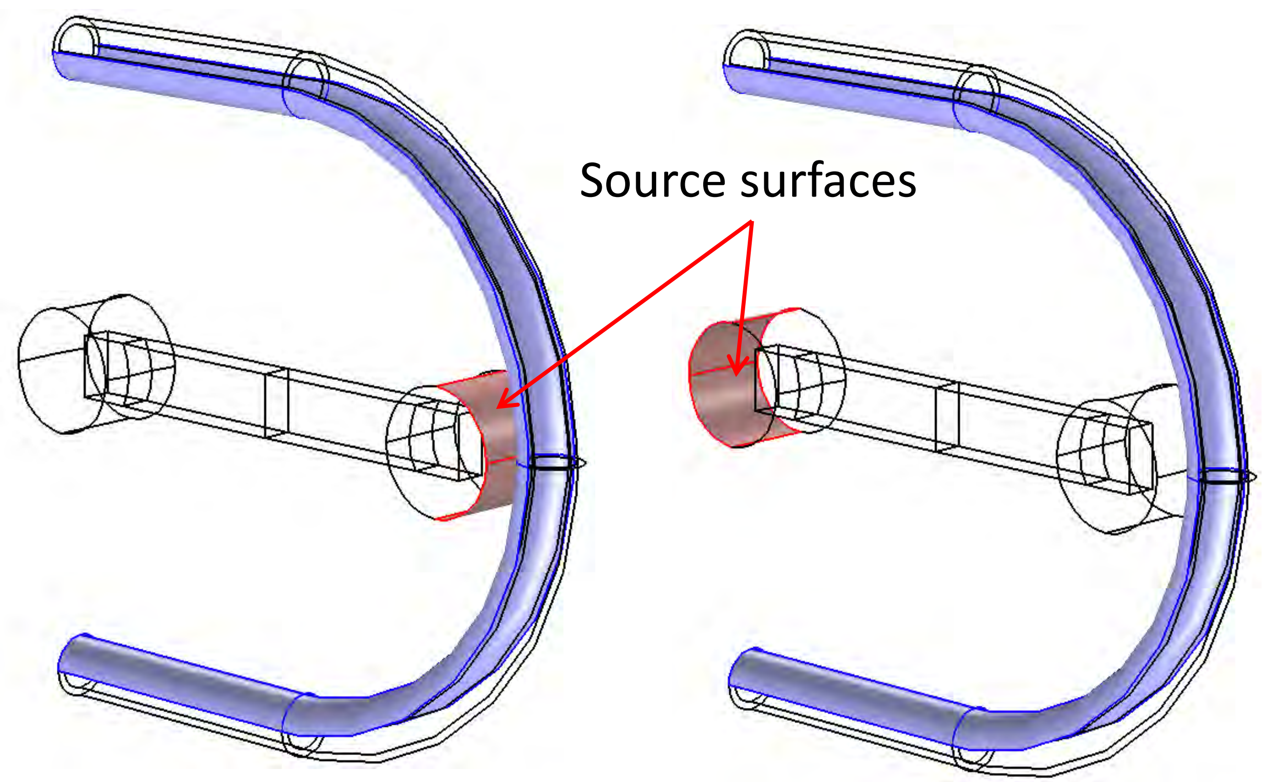
Fluid-structure interface:

$$\mathbf{u}_{\mathrm{fluid}} = \mathbf{u}_{\mathrm{w}}$$

$$\mathbf{u}_{\mathrm{w}} = \frac{\partial \mathbf{u}_{\mathrm{solid}}}{\partial t}, \quad \mathbf{u}_{\mathrm{w}} = \mathrm{fsi.vWall}$$

$$\sigma \cdot \mathbf{n} = \Gamma \cdot \mathbf{n}, \quad \Gamma = \left[-p\mathbf{I} + \mu\left(\nabla \mathbf{u}_{\mathrm{fluid}} + (\nabla \mathbf{u}_{\mathrm{fluid}})^T\right)\right]$$

Contact Modeling

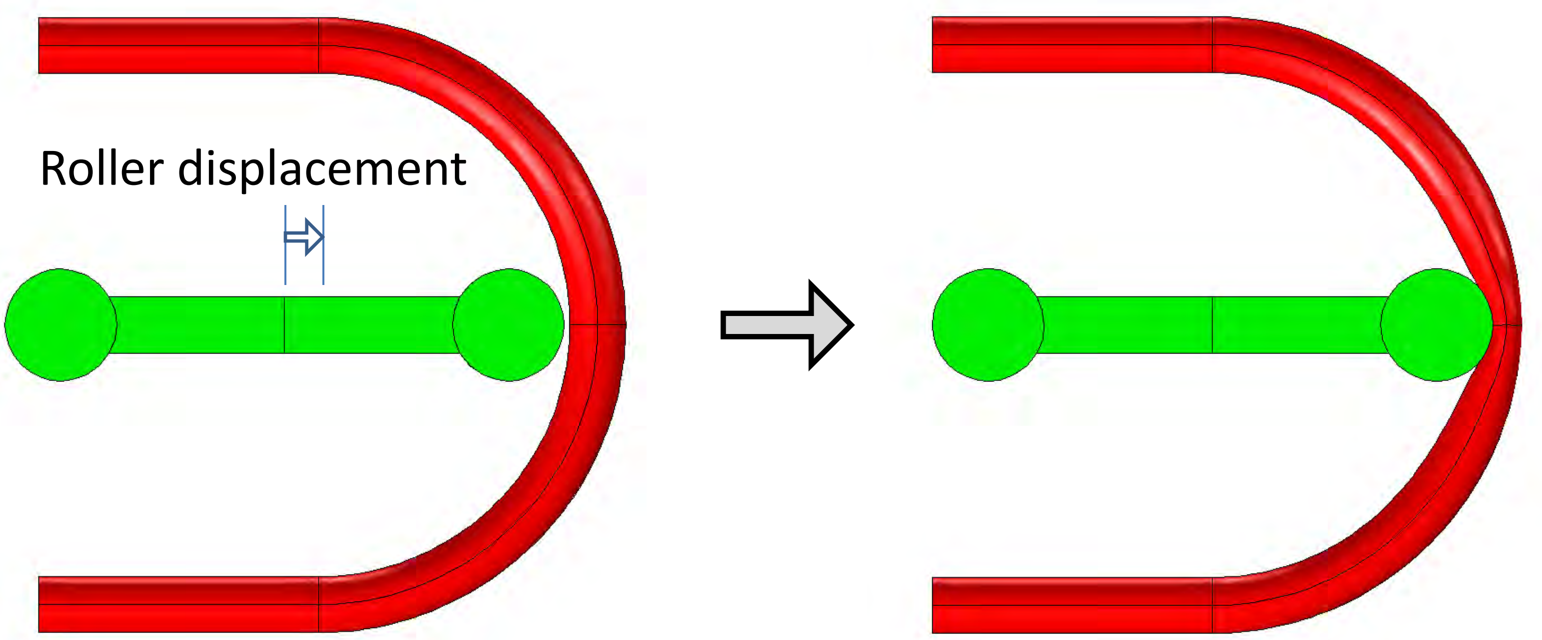


Contact Pair 1 Contact Pair 2

- Rollers are contact "source", tube is contact "destination" due to higher relative stiffness of rollers
- No friction, rollers not allowed to rotate
- Contact Lagrange multipliers solved for as "Lumped Step" in segregated solver

Step 1: Move Rollers in Place

- Damped transient analysis to get rollers in correct starting configuration

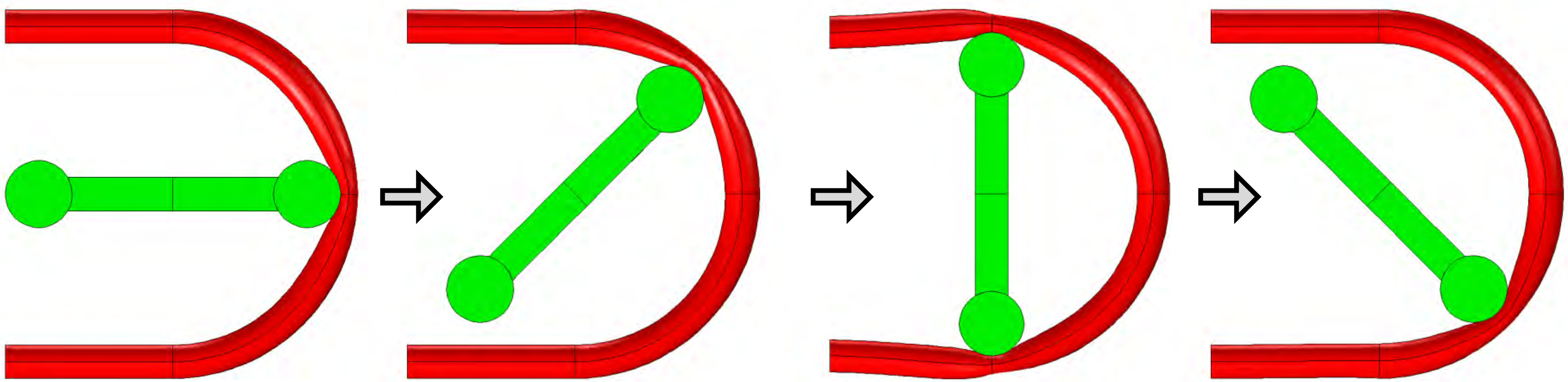


Initial model configuration

Initial pump configuration

Step 2: Rotate Rollers

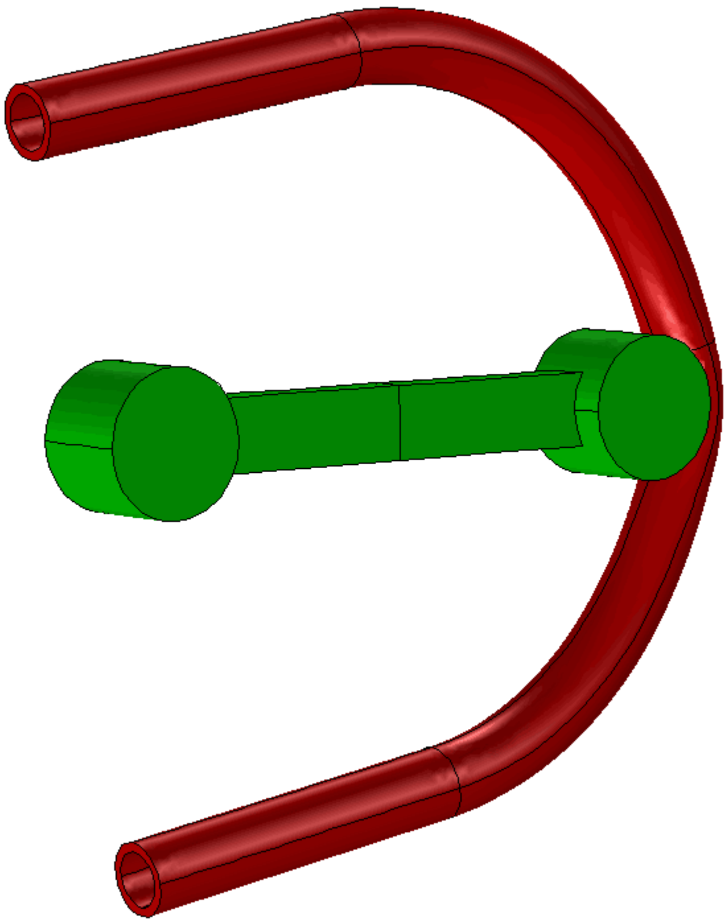
- Transient analysis with prescribed roller rotation
  - Wait until transient dies out



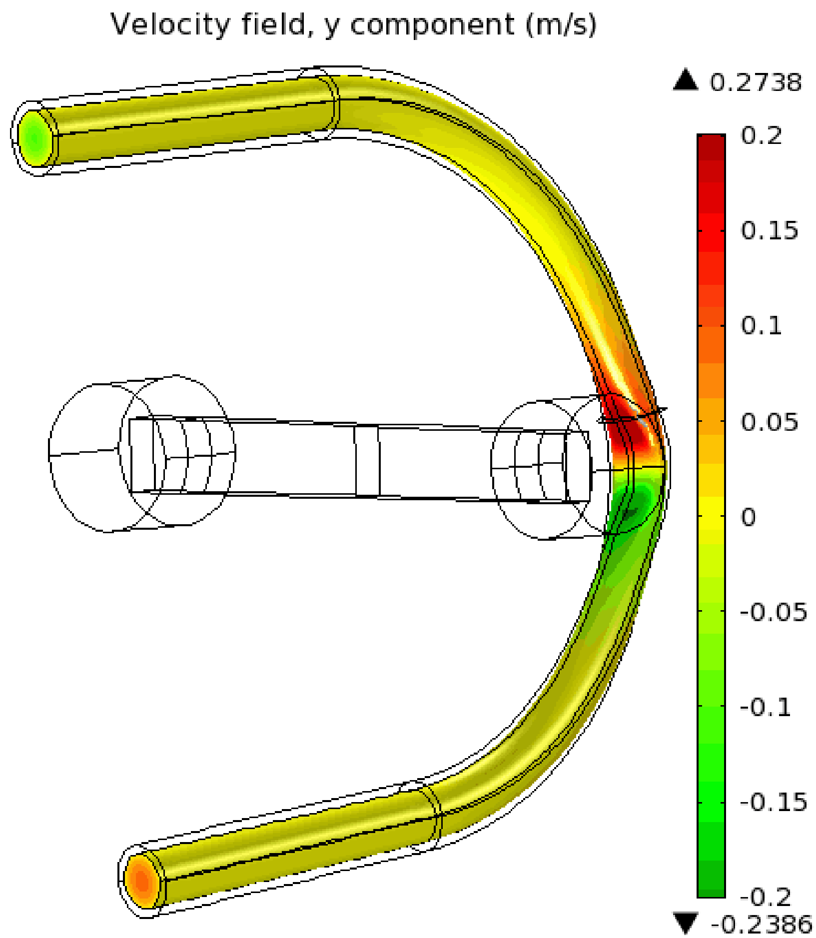
Solution Approaches for FSI Problem

- Solve both solid and fluid fields simultaneously
  - Two-way coupled solution
  - More accurate (for some pump configurations)
  - More computational resources (memory and time)
- Solve solid field followed by fluid field
  - Coupling only from solid to fluid
  - Less accurate
  - Less computational resources

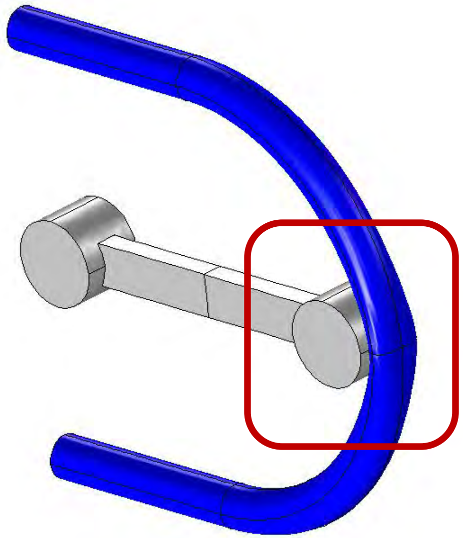
Pump Deformation

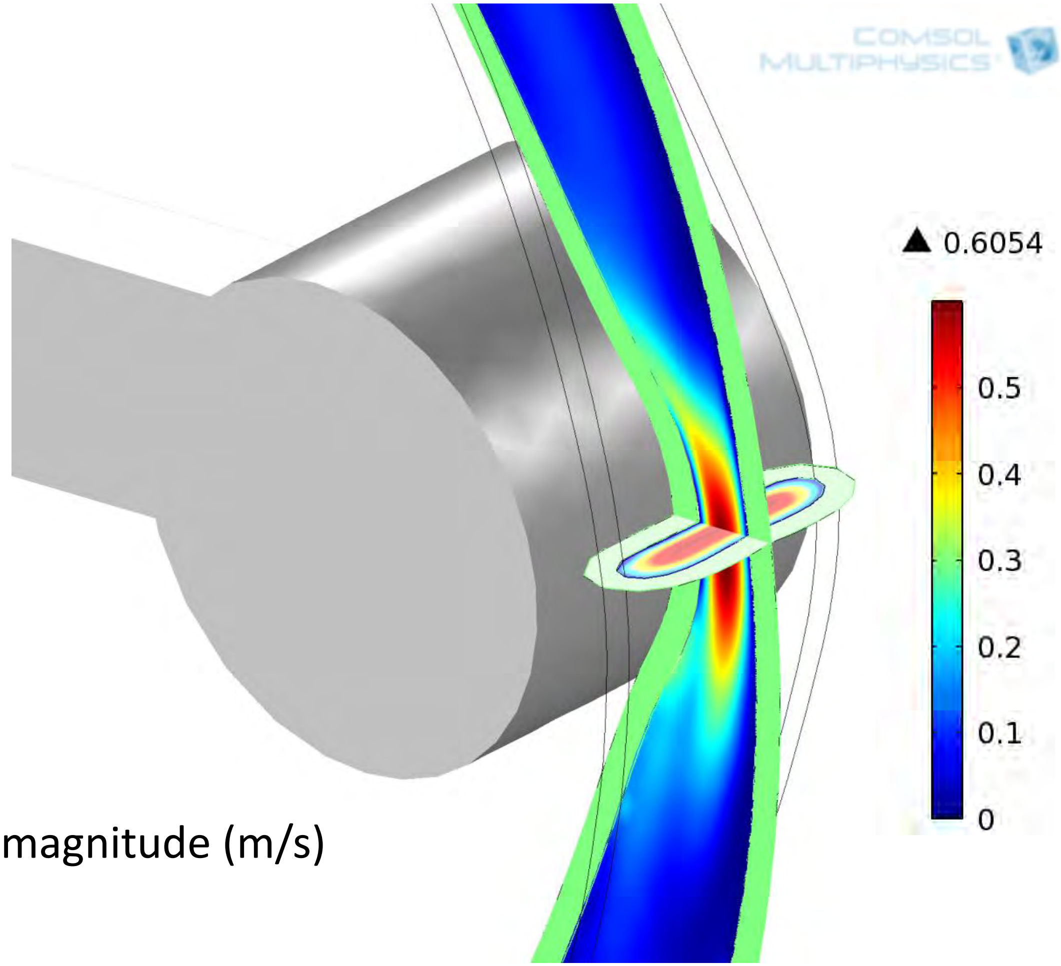


Fluid Velocity



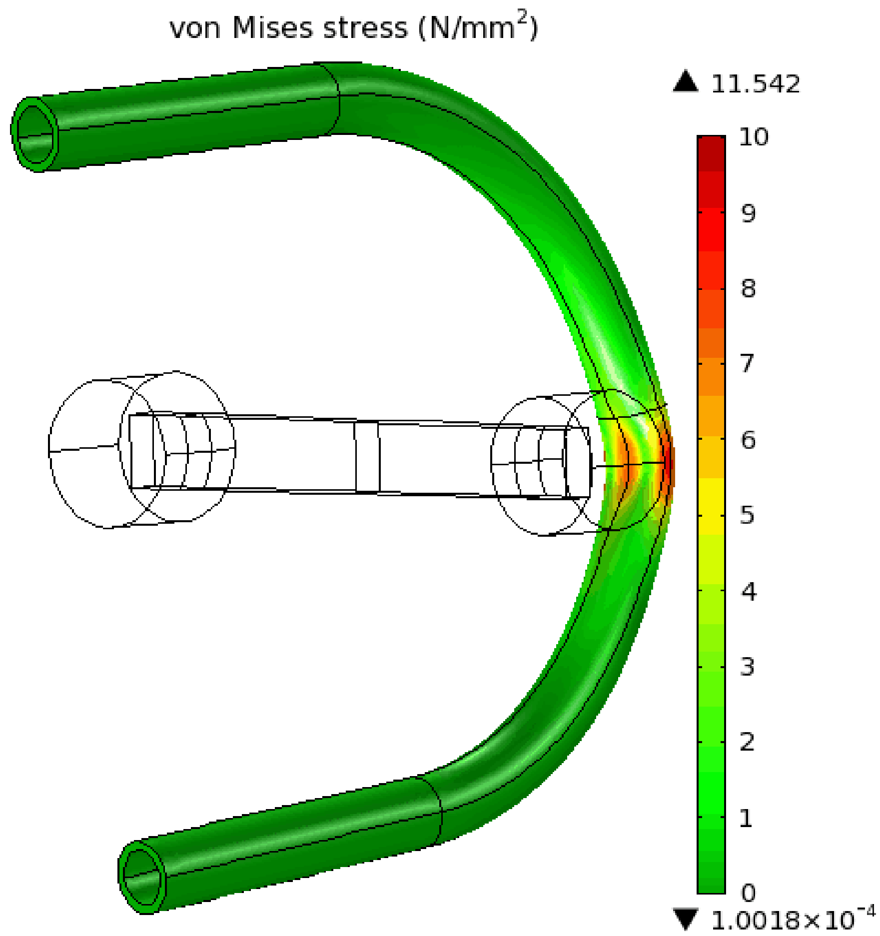
Fluid Velocity



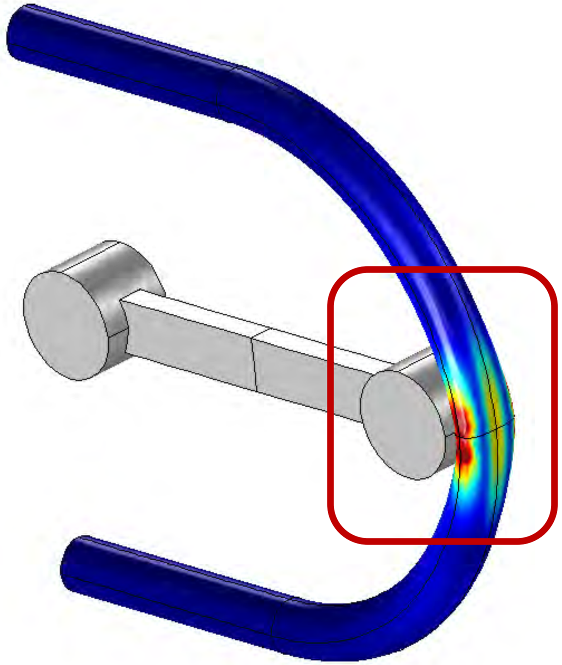


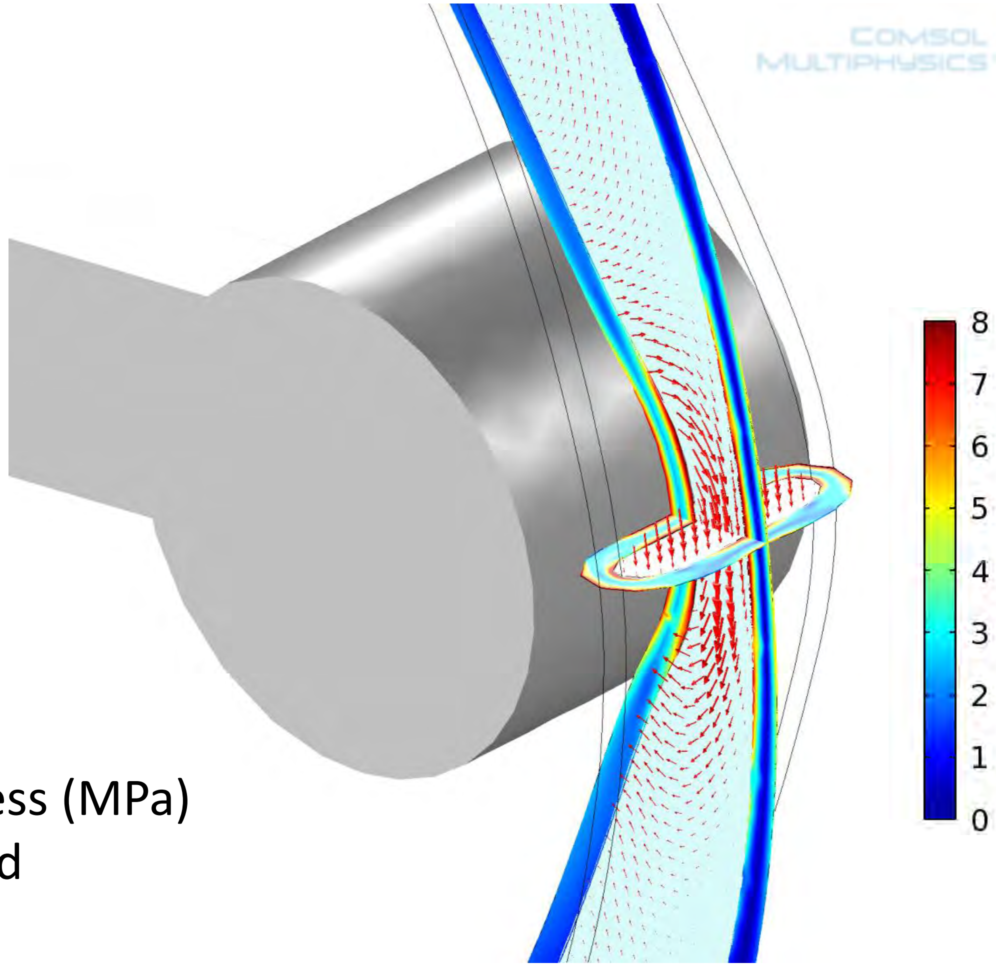
Fluid contours: Velocity magnitude (m/s)

Stresses in Tube



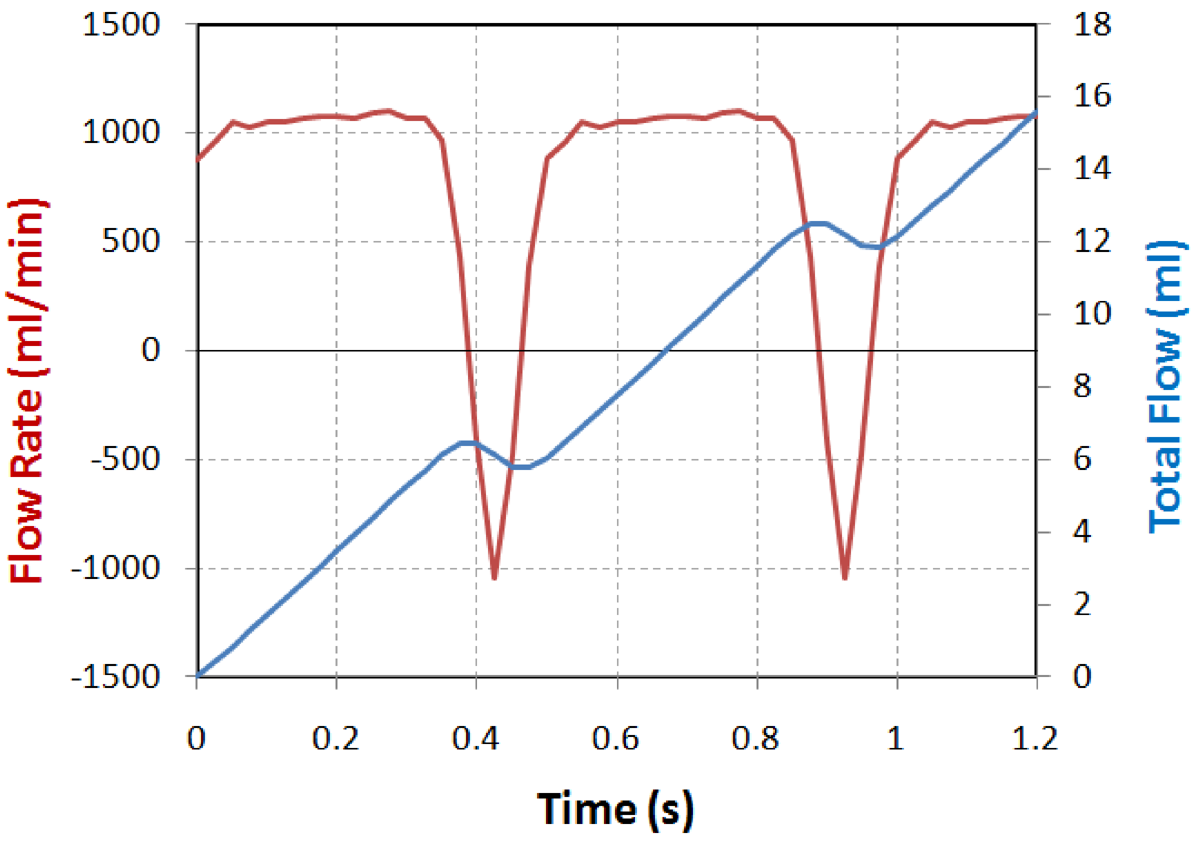
Stresses in Tube





Solid contours: Mises stress (MPa)
Fluid arrows: Velocity field

Flow Rate (and Fluctuations)



- Significant flow fluctuations including flow reversal at point of roller separation from tube (vertical roller position)
- In practice fluctuations reduced by roller design