COMSOL Conference 2010, Paris
Energy Harvesting from Variation in Blood Pressure through Deformation of Arterial Wall using Electro-Magneto-Hydrodynamics

Alois Pfenniger\textsuperscript{1,2}, Volker Koch\textsuperscript{2}, Andreas Stahel\textsuperscript{2}, Rolf Vogel\textsuperscript{1}

\textsuperscript{1}ARTORG Cardiovascular Engineering, University of Bern, Switzerland
\textsuperscript{2}Engineering and Information Technology, Bern University of Applied Sciences, Switzerland
Outlook

- Introduction
- Simulation setup
- Simulation results
- Validation
- Conclusion
Introduction

- Arteries deform due to variation of blood pressure
  → Windkessel effect (elastic energy storage during systole)
- This cyclic deformation can be used to move an electric conductor in a magnetic field
  → an electric field is induced
- A load can be connected to the electric conductor’s terminals
  → energy is extracted

http://www.physiologie-online.com/ana_site/physio07.html
> **Proposed concept:** Use deformation of arterial wall through variation in blood pressure to drive a highly electrically conductive fluid in a compartment outside the artery.

\[ E_{\text{ind}} = -u_{\text{flow}} \times B \]
Geometry and Principle

> Artery dimensions: 20 mm length, 10 mm ID, 12 mm OD

17. November 2010
Simulation Setup

> 5 « application modes » used in COMSOL:
  — Incompressible Navier-Stokes
  — Solid, Stress-Strain
  — Moving Mesh
  — Magnetostatics, No Current
  — Conductive Media DC

> Mesh partly drawn manually:
  — avoid element inversion due to mesh deformation
  — ensure proper meshing at the boundaries between the different physics
  — reduce computational efforts

17. November 2010
Application Mode # 1

> Incompressible Navier-Stokes

\[ \nabla \cdot \vec{u} = 0 \]

\[ \rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = -\nabla p + \mu \nabla^2 \vec{u} + \vec{F} \]

- Body force, e.g. gravity
- Viscosity
- Pressure gradient
- Convective acceleration
- Unsteady acceleration

\[ \vec{F} = \vec{J} \times \vec{B} \quad \text{Lorentz-force against fluid motion} \]
Application Modes # 2, 3 & 4

> Solid, Stress-Strain (isotropic, linear elastic material)

\[ \sigma = D \cdot \varepsilon \]

> Moving Mesh (mesh nodes are perturbed to conform with the moving boundaries)

\[ x = x(X, Y, t) \]
\[ y = y(X, Y, t) \]

> Magnetostatics, No Current

\[ \nabla \cdot (-\mu_0 \mu_r \nabla V_m + \vec{B}_r) = 0 \]
Conductive Media DC

Lorentz and Coulomb forces
\[ \vec{F}_L = q \cdot (u \times \vec{B}) \]
\[ \vec{F}_C = q \cdot \vec{E} \]
\[ \vec{F}_C = -\vec{F}_L \Rightarrow \vec{E} = -u \times \vec{B} \]

Material law
\[ \vec{J} = \sigma \cdot \vec{E} \]
\[ \vec{J} = \sigma \cdot (\vec{E} + u \times \vec{B}) \]

Charge conservation
\[ \nabla \cdot \vec{J} = 0 \]
\[ \nabla \cdot (\sigma \cdot (\vec{E} + u \times \vec{B})) = 0 \]

Poisson’s equation
\[ \vec{E} = -\nabla \varphi - \frac{\partial \vec{A}}{\partial t} \]
\[ \nabla \cdot (-\sigma \cdot \nabla \varphi + \sigma \cdot u \times \vec{B}) = 0 \]

E-field bounded due to load R

17. November 2010
Summary

> **Equations**

\[ \nabla \cdot \vec{u} = 0 \]

\[ \rho \cdot \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = -\nabla p + \mu \nabla^2 \vec{u} + \vec{F} \]

\[ \sigma = D \cdot \varepsilon \]

\[ \nabla \cdot (-\mu_0 \mu_r \nabla V_m + \vec{B}_r) = 0 \]

\[ \nabla \cdot ( -\sigma \cdot \nabla \varphi + \sigma \cdot \vec{u} \times \vec{B} ) = 0 \]

\[ \vec{J} = \sigma \cdot (\vec{E} + \vec{u} \times \vec{B}) \]

> **Conservation of mass**

> **Conservation of momentum**

> **Stress-Strain, linear elastic**

> **Magnetic potential**

> **Electric potential**

> **Couplings:**

> — Fluid ↔ Structure: surface load, moving wall

> — Structure → Moving mesh

> — EMHD: \[ \vec{E} = -\vec{u} \times \vec{B} , \quad \vec{F} = \vec{J} \times \vec{B} \]

> **Constraints:**

> — Symmetry, fixed/free walls, magnetic/electric insulation…

> — Kirchhoff’s mesh rule for the generator and load resistor
Solver sequence

> Stationary:
  — Solve for internal resistance of tube
  — Solve for distribution of magnetic field

> Transient (segregated solver, two groups):
  — Group 1: Fluid-structure interaction (Incompressible Navier-Stokes + Solid, Stress-Strain + Moving Mesh)
  — Group 2: Electrical domain (Conductive Media DC + Kirchoff’s mesh rule)
Running the Simulation

Input: pressure pulse

Output: power

17. November 2010
Arterial Wall and Membrane Deformation
x- and z-Velocity
Magnetic flux density

17. November 2010
Electric Potential & Current Density

17. November 2010
Validation of the Simulation

- Qualitative: Influence of force counteracting the fluid’s motion
- Quantitative: Energy conservation

Energy production per cardiac cycle for 1/8 of the geometry:
\[ +26.4 \text{ nJ} \]

Difference in strain energy of arterial wall when energy is extracted:
\[ -29.4 \text{ nJ} \]

→ Error: 11%

17. November 2010
Conclusion

> Using the multiphysics capabilities of COMSOL, it was shown that the proposed concept can be simulated.

> The simulation was validated by considering energy conservation: the error between loss of elastic energy stored in arterial wall and generated energy amounts to 11%.

> A parameterised evaluation is necessary to find the optimal geometry in terms of generated power.