Design and Optimisation of a Magnetic-inductive flow sensor with elliptical cross-section

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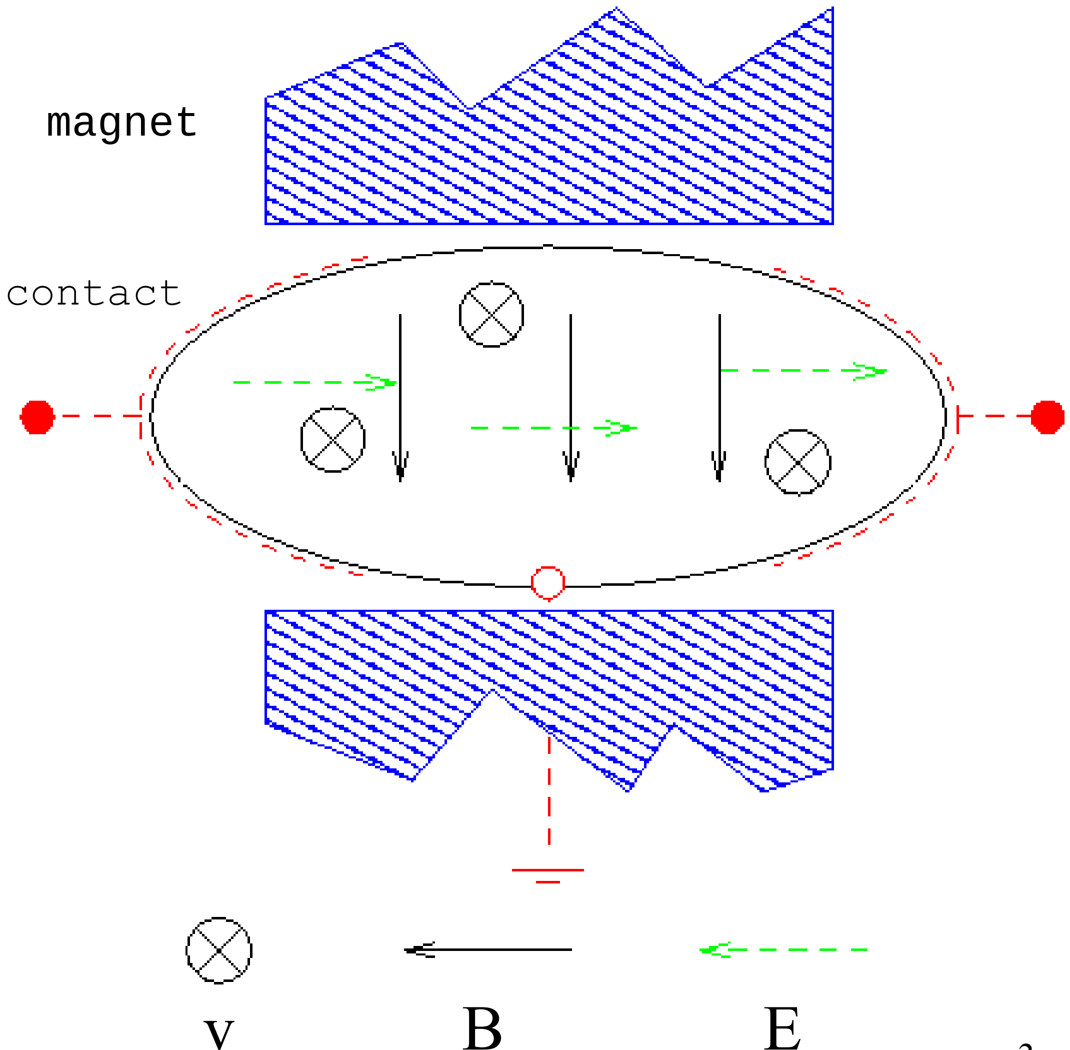
Outline

- Introduction to magnetic inductive flow sensor.
- Equations describing MI-effect
- FE-Modelling in CMP.
- Design optimisation - methodology.
- Model sensor.
- Result.
- Conclusion.

Introduction

- Conducting fluid.
- Outer magnetic field.
- Displacement of ions (like Hall-effect).
- Measure electric field.
- Optimise design with FEA.

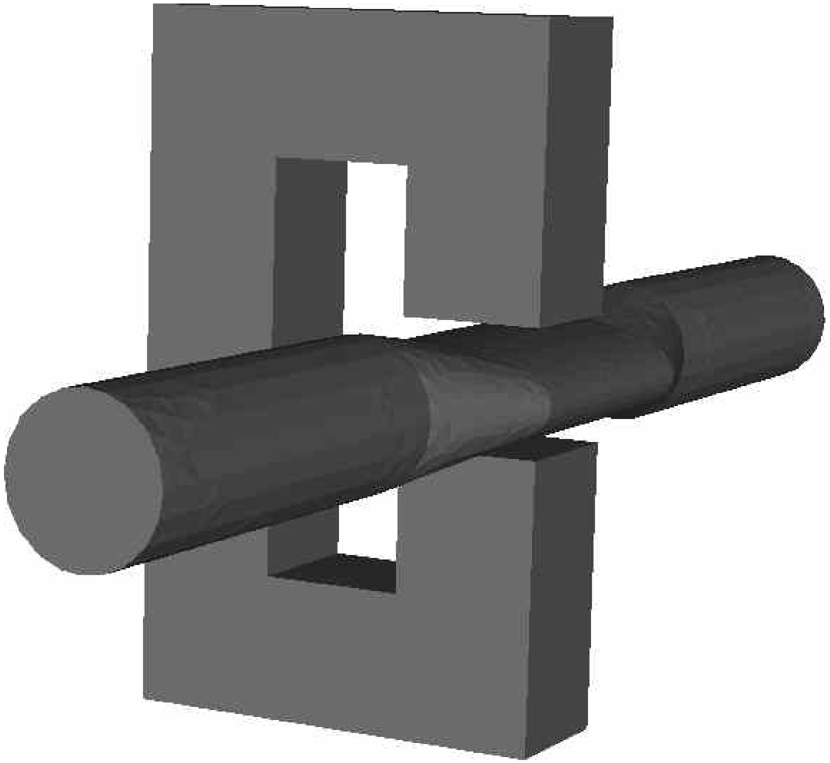


Introduction (cont.)

- Established measuring device.
- Usually AC-magnetic field.
- New: permanent magnet, smaller devices, but sophisticated electronics.
- Here: improve by adapting tube cross section.
- But findings also valid for standard device.

3-D Geometry

- Tube
- Magnet
- Return yoke



MI-equations

- Drift current for each ion species $$j_i = \mu_i q_i n_i (\mathbf{E} + \mathbf{u} \times \mathbf{B})$$
- Continuity in stationary case $$\nabla \cdot j_i = 0$$
- Poisson's equation to solve $$-\Delta\phi = \nabla \cdot \mathbf{E} = -\mathbf{B} \cdot (\nabla \times \mathbf{u})$$
- Induced charge density $$\rho = \epsilon_{H20} \mathbf{B} \cdot (\nabla \times \mathbf{u})$$
- Neumann Boundary condition.

Equations

- Navier-Stokes (NS), incompressible fluid (for water flow).
- Magnetostatics (MS), permanent magnet and return yoke.
- Electrostatics (ES) for MI-charge density.
- Coupling: ES depends on NS and MS (i.e. can be solved sequentially).

Equations (NS)

- Boundary conditions
  - no-slip: hard walls
  - slip: symmetry planes
  - inlet: parabolic profile
  - outlet: normal flow, pressure zero.
- Use *Fluid dynamics/incompressible flow* from CMP.

Equations (MS)

- No electric and displacement current.
- Permanent magnet: constant magnetisation.
- Return yoke (ferromagnetic): high permeability.
- Constitutive equations:

$$\mathbf{B} = \begin{cases} \mu_0(\mathbf{H} + \mathbf{M}) \\ \mu_0 \mu_r \mathbf{H} \end{cases}$$

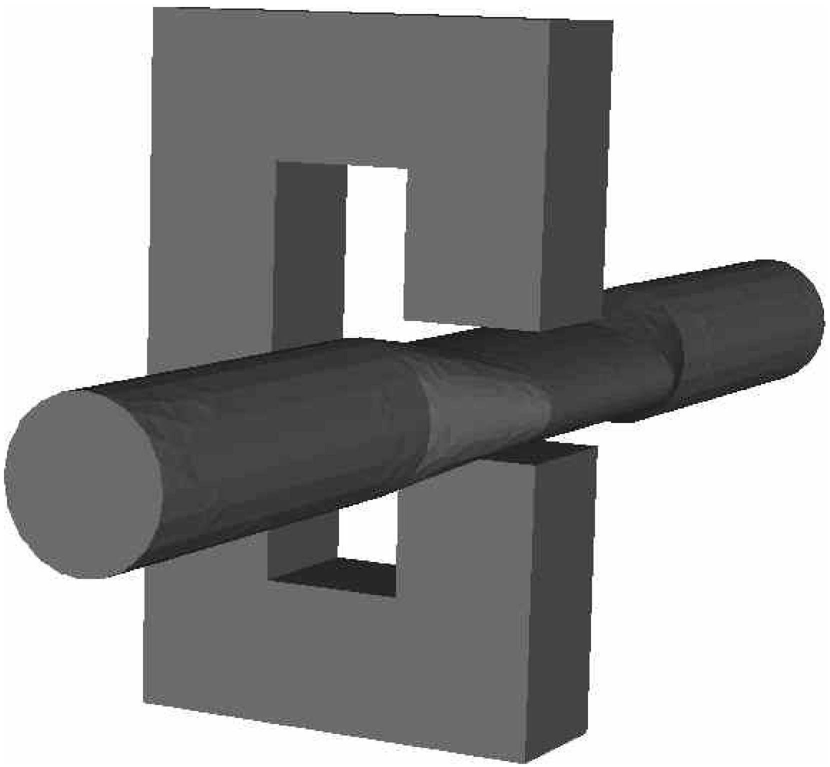
Equations (MS, cont.)

- Solve using weak mode (*Weak Form, Subdomain*) of CMP.
- Solve for a scalar potential, because **H** is curl-free: $$\mathbf{H} = \nabla \psi$$
- Dirichlet ($\mathbf{H}_t$, sym. plane), Neumann ($\mathbf{B}_n$, outer).

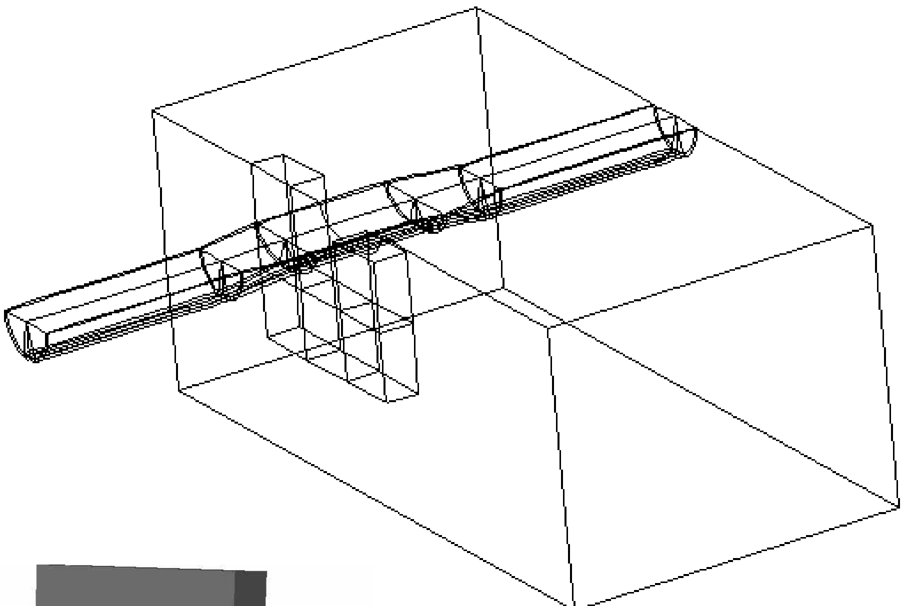
$$0 = \int_\Omega \hat{\mathbf{H}} \cdot \mathbf{B} \, dV = \int_{\mathrm{magnet}} \mu_0 \nabla \hat{\psi} \cdot (\mathbf{M} + \nabla \psi) \, dV$$
$$+ \int_{\mathrm{rest}} \mu_0 \mu_r \nabla \hat{\psi} \cdot \nabla \psi \, dV$$

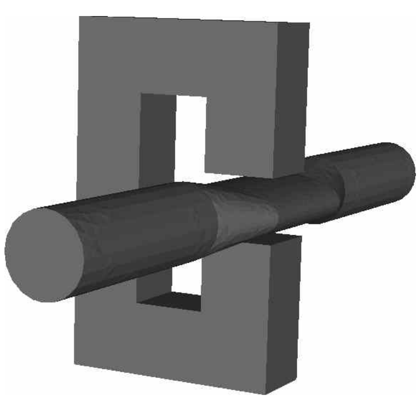
Model sensor

- Circular inlet/outlet (radius 1 cm)
- Elliptical cross-section
- Design goals:
  1. Small flow resistance (pressure drop same as in circular tube), for target range (1...5 m/s)
  2. Linearity of the MI-signal
  3. Maximise MI-signal.



Exploiting symmetry





- MS only one quarter.
- NS only one quarter (but a different one).
- ES one half.
- Use coupling variables for communication.

Design optimisation method

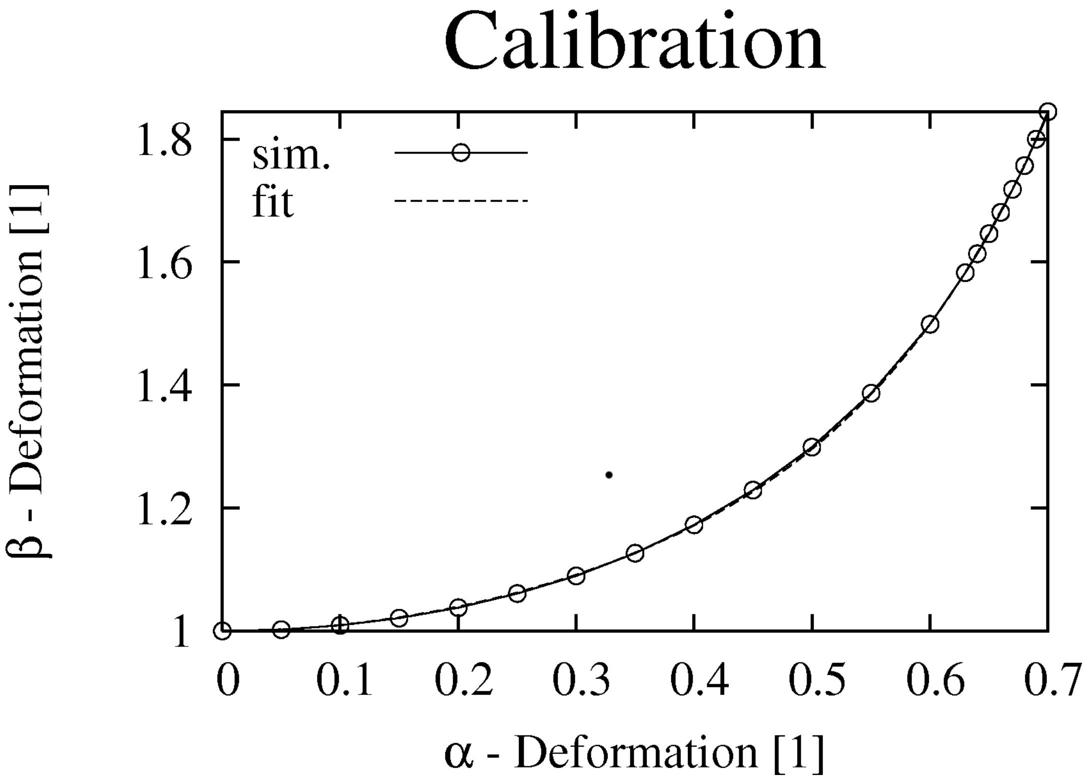
1. Parametrised CAD, deformation + scaling.
2. Calibration: solve NS, observe pressure drop, find scaling so that pressure drop is constant.
3. Solve MS for calibrated deformations.
4. Solve ES for MI charge, find potential at contacts.
5. Find deformation range where potential is linear.
6. Find optimal deformation.

Parametrisation

- Ellipse with half-axis: $(\beta(1-\alpha)a, a/(1-\alpha))$.
- α deforms shape (quench).
- β adjusts area.
- Linear transition to circular inlet/outlet, adjust position of pole faces.
- Use extrusion script:

```
fem.geom=extrude(fem0.geom,...
  'distance',[0.03,0.04,0.06,0.07,0.1],...
  'scale', [1,k*k2,k*k2,1,1;1,1/k,1/k,1,1]);
```

Calibration

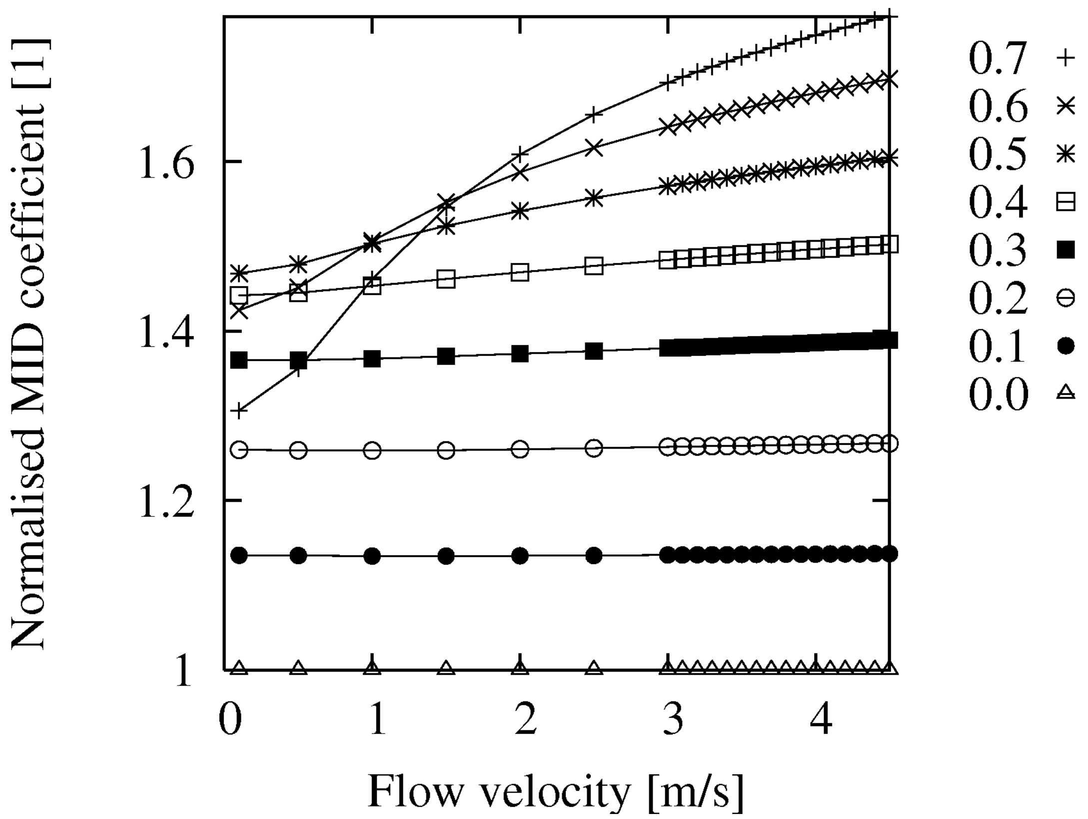


- For each α solve NS for range of β.
- Find β-value for which pressure drop is identical to circular tube.
- Fit polynomial.

$$\beta(\alpha) = 1 + 0.922\,\alpha^2 + 0.698\,\alpha^4 + 1.618\,\alpha^6$$

MI - simulation

Full simulation of quenched tube

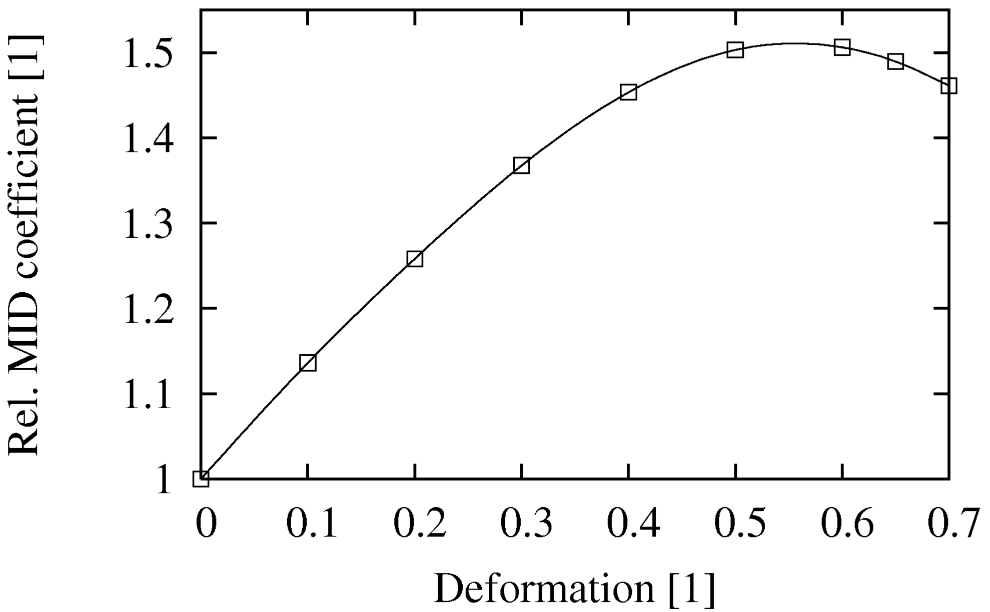


- NSE and ES for u_0-range.
- Plot V/u_0 versus u_0 for various values of deformation parameter α.
- For $\alpha>0.5$ the response is too non-linear.

Technological result

- Result (V/u_0) at target flow velocity (1 m/s) and deformation α.
- Maximum at α=0.55.
- Improvement of MI-signal of 50%!!!
- Smaller device or higher sensitivity.

Optimisation quenched tube



Modelling result/conclusion

- FE-simulation and design optimisation of magnetic-inductive flow sensor feasible.
- Easily verify design ideas.
- Flexibility of CMP allows to implement all equations.
- Flexibility in design due to scripting.