Transient response of magneto-rheological fluids in high shear rate regime

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Contents

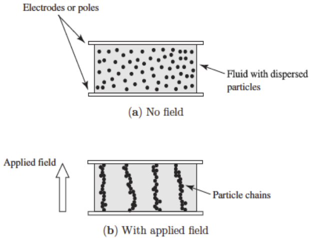
Introduction | smart fluids

Electro-rheological fluids (ERFs)

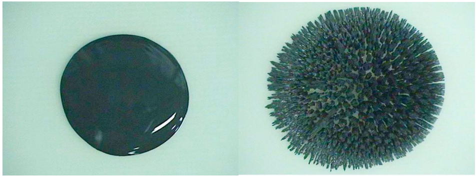
- non-conducting but electrically active particles (1-10 µm)
- suspended in a low viscosity base fluid
- electric field increases yield stress

Magneto-rheological fluids (MRFs)

- magnetically soft micron-sized particles
- suspended within the carrier fluid
- magnetic field induces yield stress (20x higher than in ERFs)



Working principle of field-responsive smart fluids [1].



MRF sample.

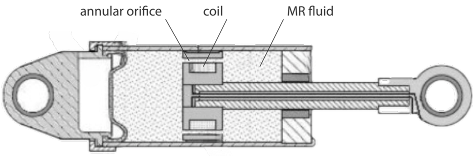
Motivation | magnetorheological fluids

Engineering context

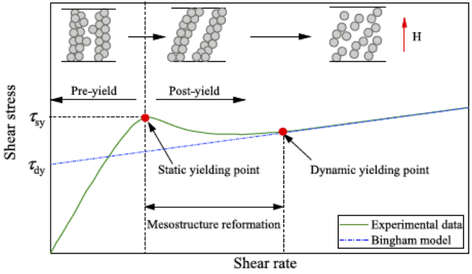
- adaptive shock absorbers for military applications
- operated at very high shear rates

Challenges (high shear rates)

- predict hydrodynamic response time as function of Bingham number
- determine adequate constitutive model (beyond Bingham fluid)
- identify transferability of phenomena to application length/time scales



Schematics of MR damper.



Schematic of the flow curve.

Model | field equations

Governing equations

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \mathbf{v} \cdot \nabla \mathbf{v} - \nabla \cdot \mathbf{T} = \mathbf{f} + \mathbf{f}_e$$

$$\nabla \cdot \mathbf{v} = 0$$

$$\frac{\partial \mathbf{b}}{\partial t} + \nabla \times \mathbf{e} = \mathbf{0} \qquad -\frac{\partial \mathbf{d}}{\partial t} + \nabla \times \mathbf{h} = \mathbf{j}_\mathrm{f}$$

$$\nabla \cdot \mathbf{d} = \rho_\mathrm{f} \qquad \nabla \cdot \mathbf{b} = 0$$

Constitutive relations (homogeneous, isotropic, non-Newtonian MRF [2])

$$\mathbf{T} = \alpha_1 \mathbf{I} + \alpha_2 \mathbf{D} + \alpha_3 \mathbf{B} + \alpha_4 (\mathbf{DB} + \mathbf{BD}) + \alpha_5 \mathbf{D}^2 + \alpha_6 \left(\mathbf{D}^2\mathbf{B} + \mathbf{BD}^2\right)$$

with $\mathbf{D} = \frac{1}{2}\left(\nabla \mathbf{v} + (\nabla \mathbf{v})^\mathsf{T}\right)$, $\mathbf{B} = \mathbf{b} \otimes \mathbf{b}$

$$\mathbf{d} = \epsilon_r \epsilon_0 \mathbf{e} \qquad \mathbf{b} = \mu_r \mu_0 \mathbf{h}$$

Field densities

$$\mathbf{f} = \rho \mathbf{g} \qquad \mathbf{f}_e = \mathbf{j} \times \mathbf{b} \qquad \rho_\mathrm{f} = 0 \qquad \mathbf{j}_\mathrm{f} = \sigma \mathbf{e}$$

Model | field equations, simplified for virtual lab tests

Governing equations

$$\rho\frac{\partial \mathbf{v}}{\partial t} + \rho\mathbf{v}\cdot\nabla\mathbf{v} - \nabla\cdot\mathbf{T} = \mathbf{f} + \mathbf{f}_e \qquad \frac{\partial \mathbf{b}}{\partial t} + \nabla\times\mathbf{e} = \mathbf{0} \qquad -\frac{\partial \mathbf{d}}{\partial t} + \nabla\times\mathbf{h} = \mathbf{j}_\mathrm{f}$$

$$\nabla\cdot\mathbf{v} = 0 \qquad \nabla\cdot\mathbf{d} = \rho_\mathrm{f} \qquad \nabla\cdot\mathbf{b} = 0$$

Constitutive relations (homogeneous, isotropic, Bingham-type MRF)

$$\mathbf{T} = -p\mathbf{I} + 2\eta\mathbf{D} \quad \text{with} \quad \eta = \eta_0 + \dot{\gamma}^{-1}\tau_0,\ \dot{\gamma}^2 = 2\mathbf{D}:\mathbf{D},\ \tau_0 \propto \operatorname{tr}\mathbf{B}$$

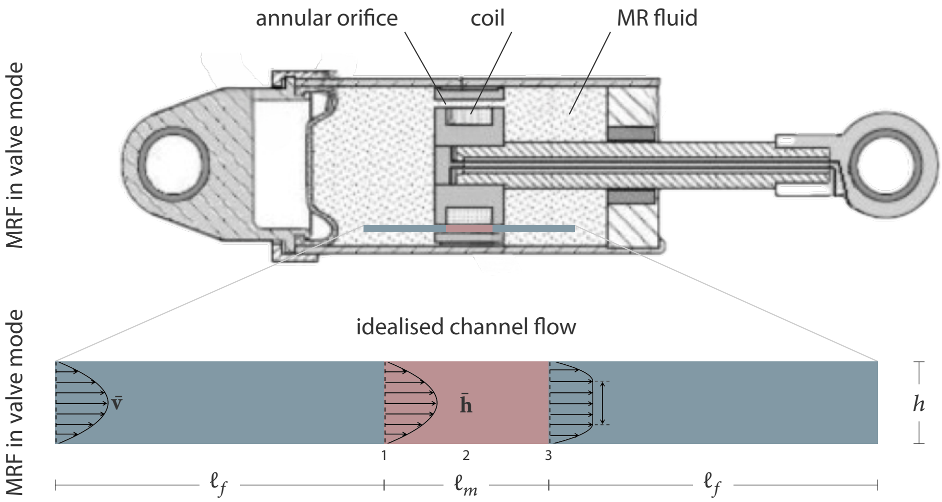
$$\text{with} \quad \mathbf{D} = \frac{1}{2}\left(\nabla\mathbf{v} + (\nabla\mathbf{v})^\top\right), \quad \mathbf{B} = \mathbf{b}\otimes\mathbf{b}$$

$$\mathbf{d} = \epsilon_r\epsilon_0\mathbf{e} \qquad \mathbf{b} = \mu_r\mu_0\bar{\mathbf{h}}$$

Field densities

$$\mathbf{f} = \rho\mathbf{0} \qquad \mathbf{f}_e = \mathbf{j}\times\mathbf{b} \qquad \rho_\mathrm{f} = 0 \qquad \mathbf{j}_\mathrm{f} = \sigma\mathbf{e}$$

Virtual Test Stand | setup



Virtual Test Stand | predictions

Formulation

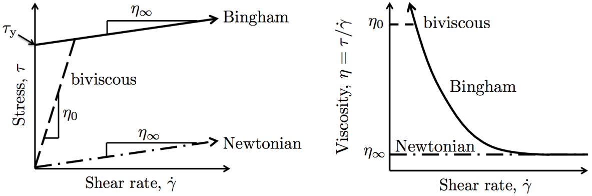
- velocity-pressure
- material: bi-viscous/regularised Bingham
- optional: non-dimensional form

Discretisation

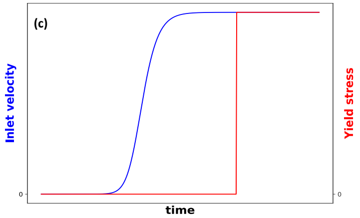
- in space: finite elements, Taylor-Hood
- in time: generalised-α method
- SUPG-type advection stabilisation

Solution methods

- Newton-Raphson with line search
- GMRES, delayed LU preconditioning
- implementation using FEniCS



Bingham model characteristics [3].



Temporal state evolution.

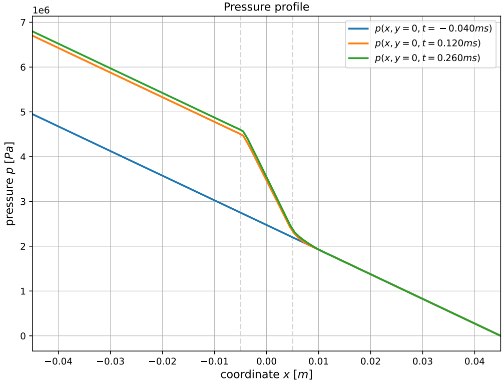
Results | transient response in valve mode

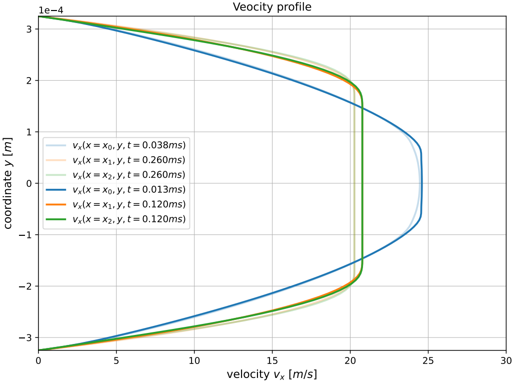
Scales

- ▶ $\ell_m = 10\,\text{mm}$, $h = 0.65\,\text{mm}$
- ▶ $t < 1\,\text{ms}$

Material parameters (commercial MRFs)

- ▶ MRF132-DG: $\rho = 3106\,\text{kg/m}^3$, $\mu_0 = 0.112\,\text{Pas@}40\,°\text{C}$, $\tau_0 = 45\,\text{kPa@}230\,\text{kA/m}$
- ▶ MRF122-EG: $\rho = 2480\,\text{kg/m}^3$, $\mu_0 = 0.042\,\text{Pas@}40\,°\text{C}$, $\tau_0 = 30\,\text{kPa@}175\,\text{kA/m}$





Results | transient response in valve mode - steady-state

Magnetic field strength h

Pressure p

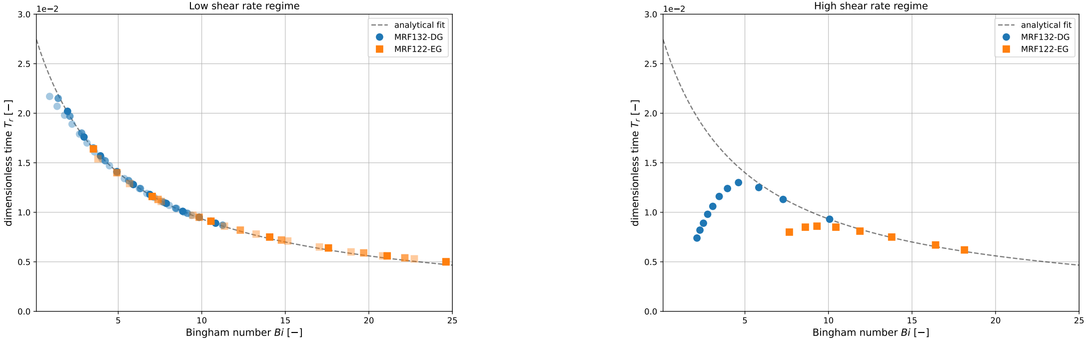
Velocity $\|\mathbf{v}\|$

Effective viscosity η_{eff} (yielded region)

Results | response times at low/high shear rates

Response time t_r

- Time needed by MRF to reach 90% of the steady-state velocity profile (pressure-driven).
- Time needed by MRF to reach 90% of the steady-state pressure drop (flow rate-driven, [4]).

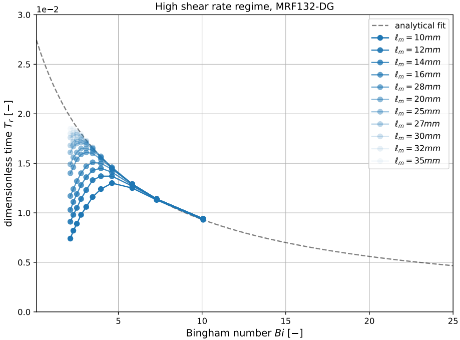


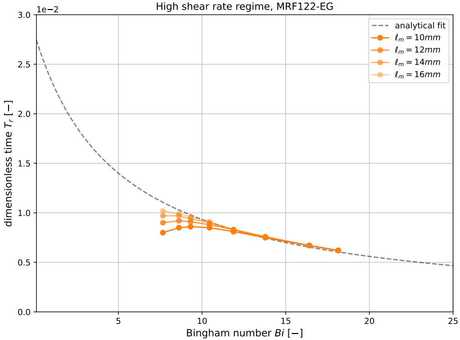
- Results at low shear rates consistent with established studies.
- Systematically deviating behaviour at high shear rates. → Bingham limitations, shorter dwell times

Results | dwell times at high shear rates

Dwell time t_d

- Average exposure time of MRF particles to magnetic field.
- Steady-state $t_d = \frac{v_m}{\ell_m}$ with mean (profile) velocity v_m.

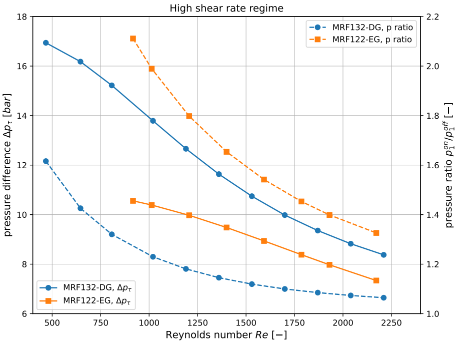




- The length ℓ_m is varied to study the effect of prolonged dwell time.
- For larger dwell times, the t_r trend aligns back to the low shear rate behaviour.

Pressure drop

- Pressure difference $\Delta p_\tau = p_1^{\text{on}} - p_1^{\text{off}}$ due to activated yield stress.
- Pressure ratio $p_1^{\text{on}} / p_1^{\text{off}}$ is a MRF efficacy measure.



- Pressure drop governed by ratio of yield stress and viscous stress, $\Delta p \propto \|\mathbf{T}_{\tau_0}\| / \|\mathbf{T}_{\mu_0}\|$.

Conclusions | summary and outlook

Summary

- study of MRF behaviour at high shear rates
- investigation of response time & pressure drop
- Bingham-type model insufficient to capture reduced dwell times

Outlook

- Enrich MRF constitutive model
- Study of the flow through orifice
- Scale to device operation (shock absorber)

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LINK COMMON

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