MR-fluid brake design and its application to a portable muscular rehabilitation device

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PhD public defense
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Active Structures Laboratory
Muscular rehabilitation: market overview

CAT1: multi-function devices

CAT2: devices with limited functions

CAT3: unique function devices

Identified market segment
Major components of the device

Motivations for MR-brake selection:
- High compactness
- Low off-state torque
- No reducer required
- Smooth operation
- Safe (no active torque)
Magneto-rheological (MR-) fluid

3 components:
- iron particles (~1/1000 mm)
- carrier liquid (oil)
- additives (avoid particle settling and packing)

Rabinow, National Bureau of Standards, 1950

© BASF
Magneto-rheological fluid: model

Bingham model:

\[ \tau = \tau_y(H) + \eta \dot{\gamma} \]

- \(\tau\): shear stress
- \(\tau_y\): yield stress
- \(\eta\): viscosity
- \(\dot{\gamma}\): shear rate

Diagram shows the relationship between shear stress \(\tau\) and shear rate \(\dot{\gamma}\) for different magnetic field strengths \(H\). The graph illustrates how the yield stress \(\tau_y\) increases with increasing magnetic field, while the viscosity \(\eta\) remains constant. The diagram also indicates the force and speed applied to the MR-fluid.
MR-fluid properties

© BASF
Other « SMART » fluids

**Electro-rheological (ER) fluids:**

<table>
<thead>
<tr>
<th></th>
<th>MR-fluids</th>
<th>ER-fluids</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Max. yield stress</strong></td>
<td>50-100 kPa</td>
<td>2-5 kPa</td>
</tr>
<tr>
<td><strong>Max. field</strong></td>
<td>~250 G×A/m</td>
<td>~4 kV/mm</td>
</tr>
<tr>
<td>(<strong>limited by saturation</strong>)</td>
<td>(limited by breakdown)</td>
<td></td>
</tr>
<tr>
<td><strong>Viscosity</strong></td>
<td>0.1-1.0 Pas</td>
<td>0.1-0.9 Pas</td>
</tr>
<tr>
<td><strong>Operable temperature range</strong></td>
<td>-40 to +150°C</td>
<td>-25 to +125°C</td>
</tr>
<tr>
<td>(<strong>limited by carrier fluid</strong>)</td>
<td>(limited by polarization mechanisms)</td>
<td></td>
</tr>
<tr>
<td><strong>Stability</strong></td>
<td>unaffected by most impurities</td>
<td>cannot tolerate impurities</td>
</tr>
<tr>
<td><strong>Response time</strong></td>
<td>&lt;millisecond</td>
<td>&lt;millisecond</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>3-4 g/cm³</td>
<td>1-2 g/cm³</td>
</tr>
<tr>
<td><strong>Power supply (typical)</strong></td>
<td>2-25 V at 1-2 A</td>
<td>2-5 kV at 1-10 mA</td>
</tr>
<tr>
<td></td>
<td>(250 W Watts)</td>
<td>(250 W Watts)</td>
</tr>
</tbody>
</table>

- larger devices
- more difficult to use « out of the lab »
- safety issues

**Ferro-fluids:**
- particle size: 1/1 000 000 mm !!!

- fluid can be oriented via magnetic field but *no yield stress* → cannot be used to generate forces
- used inside « friction-less » seals (hard-disks...)

© Kodama / Takeno
MR-fluid working modes

- **Valve mode**
  - Pressure
  - Flow
  - Magnetic field

- **Shear mode**
  - Force
  - Speed
  - Magnetic field

- **Squeeze mode**
  - Force
  - Displacement
  - Magnetic field

- **Pinch mode**
  - Pressure
  - Flow
  - Magnetic field
Application: semi-active vibration isolation

DAMPERS:
- Valve mode
- Pressure
- MR-fluid
- Applied magnetic field

CAR ENGINE MOUNTS:
- Rubber
- MR-fluid
- Gap
- Coil
- Bottom compliance

Graph:
- $X_{engine}$
- $X_{base}$
- Frequency
- Low stiffness (MR-valve open)
- High stiffness (MR-valve closed)
- Best isolation = combination of both curves
Applications of MR-fluid dampers

- civil engineering:
- automotive:
  - © AUDI
  - Der neue Audi TT
  - © AUDI

- rehabilitation:
  - © LORD corp.
  - MR-fluid
  - control
  - position
  - force

© LORD corp.
Application: MR-fluid rotational brakes/clutches

- T-shaped rotor
- Drum
- Inverted Drum
- Multiple Disks
- Disk

Legend:
- active MR-fluid area
- output axis
- magnetic circuit (rotor)
- magnetic circuit (stator)
- coil
- magnetic flux line
Applications of MR-brakes/clutches

Automotive:
- GM radiator fan drive clutch
- MAGNA coupling clutch between front and rear axle (4x4)
- brake for steer-by-wire

Force-feedback:
- haptic knobs
- force feedback devices for rehabilitation after stroke

Muscular exercise/rehabilitation:

© OSSUR Rheoknee
## Selected designs for prototyping

<table>
<thead>
<tr>
<th></th>
<th>Drum</th>
<th>Disk</th>
<th>Inverted drum</th>
<th>T-shaped</th>
<th>Multiple-disks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rotor radius</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td><strong>Torque/volume</strong></td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td><strong>Dynamic range</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Mechanical simplicity</strong></td>
<td>++</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### 1st prototype (1Nm)
- easy to build
- radial compactness

### 2nd prototype (2Nm)
- more difficult to build
- higher compactness
Performance tests: test-bench
Performances tests: some results

![Graph showing output torque vs. input current for different prototypes using different fluids.](image)
Performances tests: some results
Performances tests: some results
Performances tests: some results
Rehabilitation device: components

Embedded Electronics

User interfaces

Control signals → Position data → Force data

MR-fluid brake

Position sensor

Force sensor

Wireless communication

Patient display

Physiotherapist laptop

Mechanical hardware
Rehabilitation device: components

- Encoder
- Optical encoder (HP - HEDL55)
- MR brake
- Tension/compression load cell (ELPF-T3M-2.5kN)
- Bearings
- Load cell
- Support
Rehabilitation device: MR-brake design

T-shaped design selected because good compromise between mechanical simplicity and compactness

- Inner gap: 45mm
- Outer gap: 45mm
- Length: 120mm

Density Plot: [B] [Tesla]

- Experiment
- Simulation

Output Torque [Nm]

Off-state torque due to remanent magnetic field

2Nm
Rehabilitation device: exercise modes

CONCENTRIC

ECCENTRIC

Torque [Nm]

Joint angle [°]
**Rehabilitation device: exercise modes**

<table>
<thead>
<tr>
<th>MODE</th>
<th>ISOMETRIC</th>
<th>ISOTONIC</th>
<th>ISOKINETIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>constant position</td>
<td>constant force</td>
<td>constant speed</td>
</tr>
<tr>
<td></td>
<td>static</td>
<td>dynamic</td>
<td>dynamic</td>
</tr>
<tr>
<td>Resistance</td>
<td>applied resistance = max. muscle force but at discrete positions</td>
<td>applied resistance limited to weakest point in ROM</td>
<td>applied resistance = max. muscle force all over the ROM</td>
</tr>
</tbody>
</table>

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**Graphs:**

**Graph a:** External Resistance [Nm] vs Joint Angle [°]

- **isokinetic**
- **isometric**
- **isotonic**

**Graph b:** % of maximum muscular force being exercised vs Joint Angle [°]

- **isokinetic**
- **isometric**
- **isotonic**
Rehabilitation device: control scheme
Rehabilitation device: torque controller

Experiment on test-bench
Exercise controller: isometric mode

Control law

\[ T_{\text{ref}} = k(\theta_{\text{measured}} - \theta_{\text{ref}}) \]

contact stiffness

Experiment on rehabilitation device

Experiment on test-bench

<table>
<thead>
<tr>
<th>Direction of motion</th>
<th>TORQUE [Nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta_{\text{ref}} = 180^\circ )</td>
<td>1.5</td>
</tr>
<tr>
<td>( \theta_{\text{ref}} = 270^\circ )</td>
<td>2.0</td>
</tr>
<tr>
<td>( \theta_{\text{ref}} = 360^\circ )</td>
<td>1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference position:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0^\circ )</td>
</tr>
<tr>
<td>( 30^\circ )</td>
</tr>
<tr>
<td>( 60^\circ )</td>
</tr>
<tr>
<td>( 90^\circ )</td>
</tr>
</tbody>
</table>

PRONATION

SUPINATION
Exercise controller: isotonic mode

Experiment on test-bench

Experiment on rehabilitation device
Exercise controller: isokinetic mode

Control law

\[ \theta_{\text{measured}} \rightarrow \text{PID} \rightarrow \text{saturation} \rightarrow T_0 \rightarrow T_{\text{ref}} \]

\[ T_0 = \text{torque threshold} \]

Experiment on rehabilitation device

![Graphs showing angular speed and torque over position for pronation and supination at different speeds (50 %/s, 100 %/s, 150 %/s).]
Benchmarking with CYBEX

- Clinical tests conducted on 8 healthy subjects (for the 3 DOF of the wrist) for the isokinetic exercise (peak torque measurements)

- High level of repeatability between measurements

**Joint angles:**
- pronation/supination
- flexion/extension
- abduction/adduction
Statistic tools

Scatter plot

Box and Wiskers plot
Comparison of test/re-test repeatability level

Similar repeatability level between on both machines (same median difference and IR between two successive tests)
Agreement of measurements on both devices

**Disagreement (mainly in anti-clockwise direction)** possibly due to drift in gravity compensation on CYBEX
Conclusion & future work

Achieved results:

- A quantitative comparison of MR-brake architectures has been performed based on various figures of merit.

- Various MR-brake prototypes (drum and T-shaped designs) have been built and tested with 2 different MR-fluids.

- A portable rehabilitation device based on a MR-brake has been designed and manufactured.

- The performances of the prototype have been compared with a commercial device (CYBEX) based on a sample of subjects.

Future work:

- Adapt the design to accommodate larger body joints (knee...).

- Large scale clinical study to confirm the therapeutic efficiency of the device.

- Investigate technology transfer opportunities.
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AND NOW...
LET’S HAVE A DRINK!