Simulation of A Rotary Magnetorheological Fluid Damper

D. Harder*[1], L. Fromme[1], and R. Naumann[2]
[1]Department of Engineering and Mathematics, University of Applied Sciences Bielefeld, Bielefeld, NRW, Germany
[2]ISyM – Institute of System Dynamics and Mechatronics, University of Applied Sciences Bielefeld, Bielefeld, NRW, Germany
*dimitri.harder@fh-bielefeld.de

Abstract: This paper presents a simulation model of a rotary damper filled with a magnetorheological fluid (MRF). The most important characteristic of the MRF is the variable viscosity, which can be controlled by an external magnetic field. In the simulation model, the fluid is described as a Bingham fluid model which is coupled to an electromagnetic field simulation to analyze the damping characteristic in dependence on the coil current. For the calculation of the shear rate the angular velocity of the disk is needed, which can be computed by solving an additional ordinary differential equation. The numerical results show the expected behavior of the damper, i.e. a hysteresis in the damping characteristic.

Keywords: magnetorheological fluid, Bingham model, Jiles-Atherton model, hysteresis, rotary damper

1. Introduction

The aim of the University of Applied Sciences Bielefeld is to design a speed-proportional rotary damper. For this purpose, we want to use a magnetorheological fluid inside the damper. Magnetorheological fluids (MRF) are composed of small iron particles and a carrier liquid. MRF respond to an applied magnetic field with a change in their rheological behavior, i.e. the iron particles chain together along the magnetic field lines [1], see figure 1. The magnetic field can be generated by a coil, therefore a control of the viscosity of the MRF can be realized. The usage of this effect can be found in numerous applications, such as clutches, brakes and shock absorbers [2, 3]. Unfortunately, all these applications show strongly nonlinear behavior.

The temporal change of the coil current, i.e. the magnetic field, causes a hysteresis behavior of the magnetization in the ferromagnetic material of the disk and casing in the rotary damper. This behavior is taken into account with the Jiles-Atherton model [4].

2. Fundamentals of MRF

The carrier liquid and the magnetized particles are the main constituents of the magnetorheological fluid. The common carrier liquids are hydrocarbon oil, silicon oil and water. The particles are made of carbonyl iron powder which is produced by thermal decomposition of iron pentacarbonyl ($Fe(CO)_5$). The iron content of the particles in the powder is between 97.0 and 99.5%.

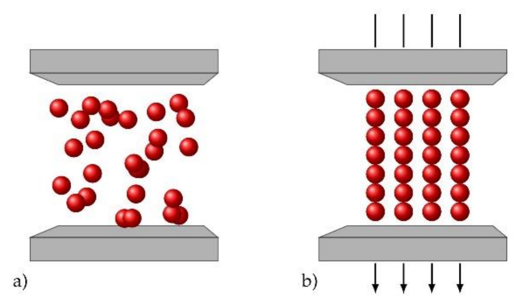

Figure 1. a) Particles in the MRF without an external magnetic field. b) Chain-like structure of the particles in the MRF with an external magnetic field.

The most important characteristic of MRF is the yield strength dependence on the magnetic field. The maximum of the yield strength also depends on the volume ratio of the particles in the MRF and is in the range of 25 – 100 kPa. The volume ratio of the particles in the fluid is usually in the range of 20 – 45%. J. David Carlson [1] has described two useful empirical equations for the properties of the most commonly used MRF. The first equation describes the dependence of the yield strength τ_H on the magnetic field and is shown in figure 2:

$$\tau_H = C \times 271700 \times \Phi^{1.5239} \times \tanh(6.33 \times 10^{-6} H) \quad (1)$$

The relationship between the magnetic flux density B and the magnetic field strength H in the MRF is given by the second equation, see also figure 3:

$$B = 1.91 \times \Phi^{1.133}\left[1 - \exp(-10.97\mu_0 H)\right] + \mu_0 H \qquad (2)$$

In both equations, Φ is the particle volume fraction. The constant C describes the carrier liquid and is 0.95, 1 or 1.16 for silicone oil, hydrocarbon oil or water [1].

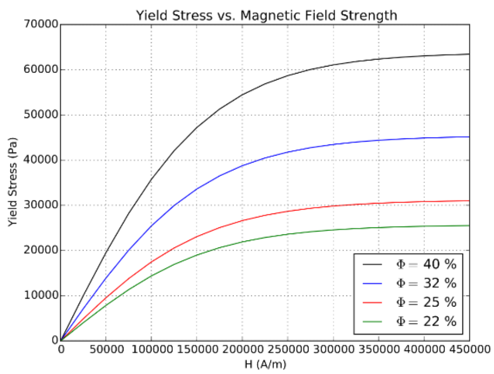

Figure 2. Yield strength vs. magnetic field strength for different particle volume fractions Φ and C = 0.95 for silicone oil, respectively.

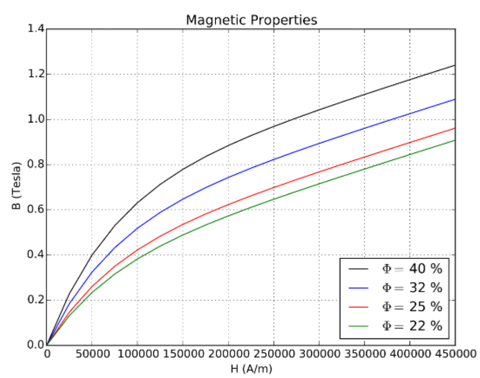

Figure 3. B-H curves for MRF with different particle volume fractions Φ.

The easiest way to describe the behavior of the MRF can be realized with the Bingham model [6], equation 3. The Bingham model describes the fluid, in absence of a magnetic field, as a Newton fluid. In presence of magnetic field, the fluid changes instantaneously the rheological behavior and the shear stress τ must be overcome the yield strength τ_H to show the Newton behavior again, see figure 4.

$$\tau = \begin{cases} \tau_H + \eta\dot{\gamma} & \text{for } \dot{\gamma} > 0, \\ -\tau_H + \eta\dot{\gamma} & \text{for } \dot{\gamma} < 0 \end{cases} \qquad (3)$$

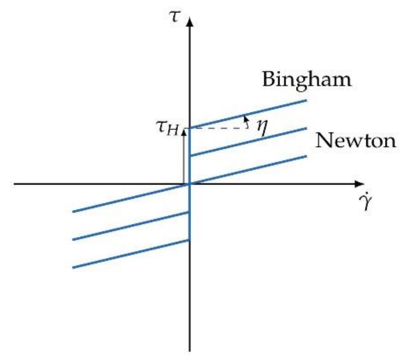

Figure 4. Bingham model: Shear stress vs. shear rate.

3. Model of the rotary damper

Figure 5 shows a simple 2D axisymmetric model of a rotary damper. The coil inside the damper generates the magnetic field.

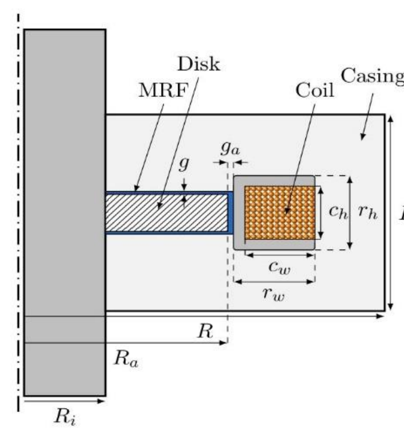

Figure 5. Simple 2D axissymmetric model of a rotary damper.

3.1 Selection of material parameters

The material properties of MRF do not exist in the library of COMSOL, therefore they must be defined manually. The characteristic values of the electrical conductivity and the relative permittivity are σ = 0 and ε_r = 5 and were taken from the literature [8]. For the magnetic behavior of the MRF, equation 2 has to be reversed to:

$$H = \frac{1}{\mu_0}\left(0.0911577 \times W\left(20.9527 \times e^{-10.97\left(B-1.91\times\Phi^{1.133}\right)} \times \Phi^{1.133}\right) + B - 1.91 \times \Phi^{1.133}\right) \quad (4)$$

This equation 4 (H-B curve for the MRF) is needed since COMSOL calculates the magnetic flux density B via the vector potential as dependent variable. The W in this equation is the Lambert W function.

To investigate the impact of hysteresis in the disk and casing material on the dynamic behavior of the damper two cases were analysed in the simulation model. In the first case "Stainless Steel 455 Annealed" was chosen for disk and casing.

In the second case the hysteresis behavior was taken into account using the Jiles-Atherton model [4]. The disk and casing material was defined as "steel AISI1035" with the Jiles-Atherton parameters from the literature [7]. Figure 6 shows the calculated B-H curve for the hysteresis behavior of the magnetization.

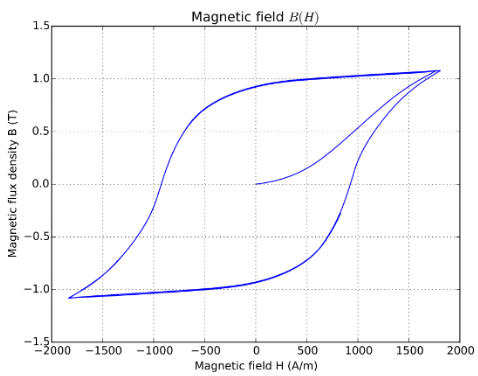

Figure 6. B-H curve for the disk and casing material "steel AISI1035".

3.2 Torque calculation

The braking torque can calculated with equation 3. The yield strength τ_H is given by equation 1 and η is the dynamic viscosity of the fluid in absence of the magnetic field. The braking torque can be defined as:

$$T = T_H \operatorname{sgn}(\dot{\gamma}) + T_\eta(\dot{\gamma}) \quad (5)$$

with

$$T_H = 2\pi N_{disk} \int_{R_i}^{R_a} r^2 \tau_H \, dr \quad (6)$$

and

$$T_\eta = 2\pi N_{disk} \int_{R_i}^{R_a} r^2 \eta \dot{\gamma} \, dr \quad (7)$$

where $N_{disk} = 2$ is the number of the disk surfaces which are in contact with the fluid, R_a is the outer and R_i the inner radius of the disk. The calculation of the shear rate $\dot{\gamma}$ is an approximation and can obtained by [3, 5]:

$$\dot{\gamma} = \frac{r\omega}{g} \quad (8)$$

Here g is the gap between the disk and the casing which is filled with the MRF, r is the radius coordinate and ω can be computed by

$$\omega = \int \frac{M_a - T(\dot{\gamma})}{J_s} dt \quad (9)$$

where M_a is the drive torque and J_s is the moment of inertia of the disk. The distribution of the magnetic field H and the shear rate $\dot{\gamma}$ in the MR-damper are functions of the radius r, therefore the equation 5 has to be calculated by numerical integration.

4. Simulation Results

In this section some simulation results are presented. Figure 7 shows the braking torque as a function of the coil current for the two cases without and with hysteresis. In the second case, due to the hysteresis of the magnetization of the ferromagnetic material of the rotary disk and the casing, the braking torque still has a value of about 2 Nm when the coil current is 0 Ampere. The braking torque can be reduced further by changing the direction of current to a minimum value of about 0.2 Nm.

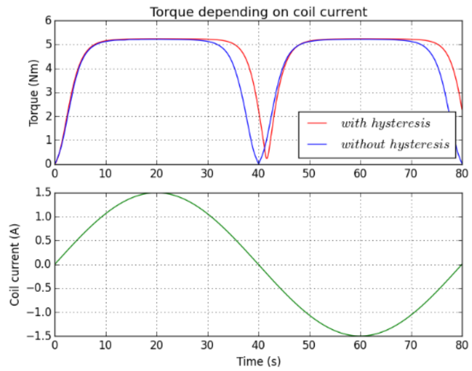

Figure 7. Torque dependent on coil current with and without hysteresis.

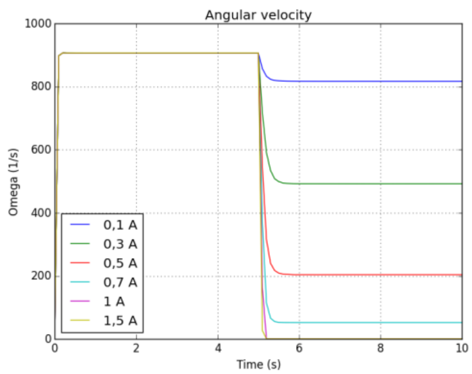

Figure 8. Angular velocity dependent on different coil currents at 5 seconds.

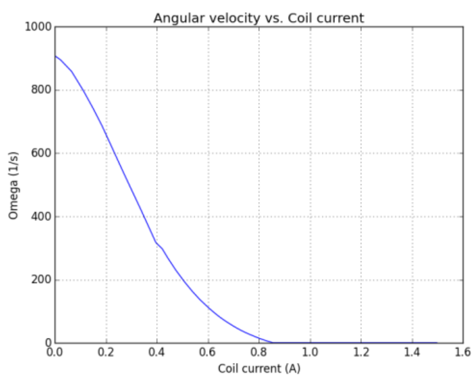

Figure 9. Angular velocity vs. coil current.

Figure 8 shows the results of another transient study of the damper. A constant drive torque M_a = 5 Nm speeds up the disk in the damper so that finally an angular velocity of about 900 1/s is reached. After 5 seconds the coil current is turned on and slows down the disk to a constant rotational speed depending on the strength of the magnetic field or in other words the coil current. Figure 9 demonstrates the dependence of the angular velocity on the coil current.

5. Conclusions and Outlook

In this paper a simulation model of a rotary damper filled with a magnetorheological fluid was analyzed. In addition, the impact of hysteresis in the ferromagnetic materials on the behavior of the damper has been considered. In future projects this simulation model can be used to study different scenarios in more detail. For instance, different MRFs can quickly be implemented by changing only two variables, the particle volume fraction Φ and the carrier liquid constant *C*. Also the transient response of the system on varying drive torques can be analyzed.

6. References

1. J.D. Carlson, M. Schwartz (edited by), "Magnetorheological Fluids", *Smart Materials*, pp. 17.1–17.8, CRC Press, 2009.
2. J. Goldasz and B. Sapinski, "*Insight into Magnetorheological Shock Absorbers"*, Springer, 2015.
3. K. Karakoc, E. J. Park and A. Suleman, "Design considerations for an automotive magnetorheological brake", *Mechatronics*, vol. 18 no.8, pp. 434–447, 2008.
4. Comsol, "Modeling Hysteresis Effects", *Comsol Multiphysics*, 2008.
5. Y. T. Choi, J. U. Cho, S. B. Choi and N. M. Wereley, "Constitutive models of electrorheological and magnetorheological fluids using viscometers", *Smart Materials and Structures*, vol. 14, pp. 1025–1036, 2005.
6. H. Giesekus, „*Phänomenologische Rheologie"*, pp. 213 – 214, Springer, 1994.
7. R. Demersseman, A. Benabou, S. Clénet and B. Lemaire-Semail, "Finite Element Modeling of the Hysteresis Effect in a Magnetorheological Brake", *Computer Field Models of Electromagnetic Devices*, pp.756-762, IOS Press, 2010.
8. M. T. Avraam, "MR-fluid brake design and its application to a portable muscular", *Univerité Libre de Bruxelles*, Dissertation, 2009.