Theoretical and experimental analysis of MR valve

Z Leicht¹, H Urreta¹, A Sanchez¹, A Agirre¹, P Kuzhir² and G Magnac³

¹IDEKO, S. COOP. Arriaga Kalea 2, 20870 Elgoibar, Spain
²LPMC, University of Nice – Sophia Antipolis, 06108 Nice Cedex2, France
³Cedrat Technologies, 15 Chemin de Malacher - Inovallée - 38246 Meylan, France

E-mail: zleicht@ideko.es

Abstract. The properties of magnetorheological (MR) fluid can be rapidly varied by the application of a magnetic field. This behaviour allows the designer to construct a machine that’s quality can be changed in action, according to the variation of the surround and to the expectations. The commercial use of MR fluid is already not limited in dampers and breaks. Thanks to the advantageous quality - that requires low voltage - is on the increase. Using the MR fluid in a valve, the pressure drop can be adjusted by the intensity of the magnetic field, without moving parts. In this work a MR valve has been designed, that can supply a hydrostatic bearing lubricated with magnetic fluid. Its behaviour has been simulated with three models. The analytical model based on the Bingham law of the magnetic fluid flow, the Buckingham model (Bingham modified) and the dimensional model suggested by Lord Corporation, the manufacturer of used MR fluid, MRF 122 2EG. The results of the simulations are compared with the experimental data.

1. Introduction

In this work a novel MR valve has been designed and manufactured to adjust the flow rate and the pressure drop of the MR fluid feeding any magnetic device, such as a magneto-hydrostatic bearing, end application of the project. The experimental results have been compared to a model based on the Non-Newtonian viscous theory, since the MR fluid behavior differs from the Newtonian viscous equation. According to the model, the MR fluid possesses a yield stress below that the fluid behaves like a semi-solid, or even a solid. Just after the shear stress exceeds this value is allowed of flow. The MR fluid used during the experiment is a product from Lord Corporation (MRF 122 2EG). The results of the simulations are compared with the experimental data.

2. Model for non-Newtonian behaviour

The MR fluids in general case behave corresponding to the Newtonian constitutive equations. Applying a magnetic field the characterization of the fluid alters into a non-Newtonian fluid. There are many different theories presented in the works of Carlson and Jolly [1,2], Wereley [3] and Goncalves [4] prescribing the material with distinct behavior from Newtonian fluids. The Bingham model ensures a base to analyze the MRF-122-2EG from Lord Corporation. This fluid possesses a yield stress below that the fluid behaves like a semi-solid, or even a solid. Just after the shear stress exceeds this value is allowed of flow. The MR fluid used during the experiment is a product from Lord Corporation (MRF 122 2EG).

\[ \tau = (\tau_0 \cdot H + K \cdot \dot{\gamma}) \cdot \text{sgn}(\dot{\gamma}). \] (1)
Where H is the field intensity, K is the viscosity with no magnetic field applied and $\dot{\gamma}$ is the shear rate.

3. Magnetorheological valve

In a MR valve, the MR fluid flows through the duct between inflow core ($B_1$) and the outflow core ($B_2$) as it is depicted in figure 1.a. When the power of coil (C) is turned on and magnetic field is exerted on MR fluid, the flow through the relief valve will change its state into semi-liquid or extremely into solid. Only when the supply pressure gets high enough to offset the yield stress, the fluid can flow through the valve again. Thus, this type of relief valve can regulate the pressure of a MR fluid system under a certain flow rate.

The test bench configuration is depicted in figure 1.

![Figure 1. The profile of the MR valve (a) and construction of the test bench (b).](image)

The cylinder (marked with A in the figure 1.b) contains the MR fluid. Its moving supports the constant flow rate to the valve (B). With the electromagnet (C) the pressure drop of the valve can be changed. The inflow and outflow pressures are measured by the sensors (D). The fluid after crossing the valve is collected in the tank (E). After the measurement switching the flap (F) the fluid returns to the cylinder, and the measurement can be repeated.

The pressure drop generated by the gap treads between the inflow core ($B_1$) and the outflow core ($B_2$). The piece G of the figure 1a determines the geometry of the gap. Different flow conditions can be examined by replacing this part, and thanks to the test bench design, it can be changed rapidly.

In the figure 2.a a typical velocity distribution of MR fluid is depicted.

![Figure 2. Velocity and shear stress distribution across the gap in the case of (a), Bingham model, and (b), Buckingham model.](image)

The plug thickness $\delta$ according to the Bingham model equations is

$$\delta = -\frac{2\tau_0}{d \ p/d \ x}. \quad (2)$$

The pressure drop, supposing a duct length $L$ and a linear pressure gradient:

$$\Delta p = \frac{2\tau_0 L}{\delta}. \quad (3)$$
To achieve a more accurate model, the Buckingham theory is applied [5]. It supposes a non-linear magnetic flux distribution across the gap. In the case of relatively large gap, the value of the flux density increases at the walls. With this, the equation (3) is modified in the value of \( \tau_0 = f(h) \), being \( h \) across distance in the gap. Through this larger yield stress, the plug thickness also became larger, as it is depicted in figure 2.b.

4. Comparison the results of different models

The test material MRF-122-2EG (Lord Corporation), is a hydrocarbon-based fluid with high yield stress and fast response time. The geometry of the valve is: length, \( L=30\text{mm} \) and width, \( W=28\text{mm} \). Three different gaps has been examined, namely 1, 2 and 3 mm in the thickness. An iron core and a coil, inducing the magnetic field by the applied current intensity, have generated the magnetic field intensity into the MR fluid.

Three different models have been compared in this work: The solution advised by Lord Corporation (a dimensional solution), Bingham model and the modified Bingham model, named Buckingham model. Bingham solution doesn’t fit to experimental data in any of analyzed conditions, this way, yield stress variation proposed by Buckingham model is mandatory to get right results in this kind of MR valves, see figures 3, 4 and 5.

Figure 3. Pressure drop as a function of the flow rate \( h=3 \text{ mm} \)

Figure 4. Pressure drop as a function of the flow rate \( h=2 \text{ mm} \)

Comparing Buckingham model and dimensional one (suggested by Lord), the approximation given by fluid’s manufacturer agree with experimental results at relative large gaps 2 and 3 mm (figures 3
and 4), meanwhile at small gap (1mm, figure 5) the pressure drop is oversized. That is because the Lord solution supposes a non-linear flux distribution independently to the thickness, and on the other hand, Buckingham theory considers the dependence to the gap’s size in the effect of flux density. This way, when the gap thickness is relatively small (1mm in this case) the differences between both models appear, and the solution of Buckingham model agrees with experimental data due to it takes account flux inequality across the valve’s gap, providing more accurate solutions.

Figure 5. Pressure drop as a function of the flow rate $h=1$ mm

5. Conclusion
The MR valve designed and manufactured in this work has two favorable features: In one hand, the wide working range in the pressure drop and flow rate, and since the pressure drop is adjusted by the magnetic field intensity, the valve works without moving parts, thus diminishes the chance of failure. And on the other hand, the simple design of magnetic poles provides a quick and low cost geometry modification to try different design’s solutions in the test bench. Modeling the valve, i.e. describing the flow-rate in function of pressure drop, three cases have been analyzed. With large gap, the simple and dimensional model proposed by Lord provides enough right results. However with small gap, the dimensional model it’s not enough accurate and analytical solutions (based in Bingham theory) are required. Bingham model doesn’t fit to this kind of valves due to non-linear magnetic flux distribution. This way, Buckingham model’s proposed modification to Bingham theory is applied, and its results fit accurately to experimental data.

References
[1] Jolly, M. R., Bender, J. W., and Carlson, J. D., “Properties and applications of commercial magnetorheological fluids,” Journal of Intelligent Material Systems and Structures, Vol. 10, No. 1, p. 5, 1999.
[2] Jolly, M. R., Carlson, J. D., Munoz, B. C., “A Model of the Behavior of Magnetorheological Materials,” Smart Materials and Structures, Vol. 5, p. 607-614, 1996.
[3] Wereley, N. M., Pang, L., “Nondimensional Analysis of Semi-Active Electrorheological and Magnetorheological Dampers Using Approximate Parallel Plate Models,” Smart Materials and Structures, Vol. 7, p. 732-743, 1998.
[4] Goncalves, F. D., “Characterizing the Behavior of Magnetorheological Fluids at High Velocities and High Shear Rates”, Dissertation, Blacksburg, Virginia, p.20-25, (2004)
[5] Mikulowski G., Batterby C.D., “Flux Density Variation in Magnetorheological fluid devices” (Poland, Ecomas Thematical Conference on Smart Sstructures and Materials), http://smart.ippt.gov.pl/pdf/2007_ECCOMAS-gdansk_GM-DB.pdf, 2007.