Geometry Optimization of Magneto-Rheological Damper Based on Magnetic Saturation

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1 Introduction

Magneto-rheological fluids are materials that exhibit a change in rheological properties with the application of a magnetic field. The MR effect can be applied to a hydraulic damper for better control of vibration [1, 2]. In technical and laboratory context, the most common configuration used with magneto-rheological fluids is based on a modification of the typical hydraulic actuator structure (Fig. 1). An outer cylinder is filled up with MR fluid, and an inner piston moves inside. Between the two main components, a constant annular gap is ensured, in which MR fluid is free to flow during the piston displacements in the device chamber. The piston, which is one of the two paramagnetic elements, has a central groove along its lateral surface, where one or more electric coils of copper are housed. The cylinder corresponds to the second pole of the field. When current is supplied to the coil, some areas of the fluid in the gap piston–cylinder are "activated" (i.e., material is polarized), and the formation of particle chains starts. Increasing the intensity of the magnetic field, the number and strength of the chains of particles between the two poles of the circuit increase. The flow resistance can be adjusted, starting from the total absence of magnetic field to the state of magnetic saturation of the fluid, where a complete alignment of ferromagnetic particles takes place and a further increase in current does not produce, at constant speed, greater damping force. In this solution, an external oil reservoir must to be used in order to collect the fluid volume moved by the entrance of the piston rod in the cylinder chamber [3].

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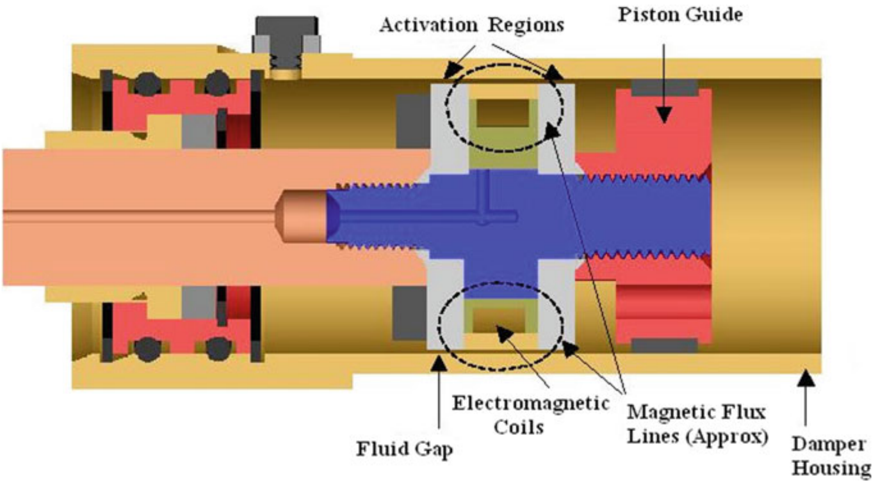


Fig. 1 MR damper: main components [3]

2 MR Damper Design

2.1 Input Data with Design Conditions

The specifications are used for input data, and the limiting conditions are used for design solutions.

The specifications are as follows:

a. controllable level of mechanical power: $W_m = 80$ W
b. maximum velocity of MR damper: $v_0 = 0.03$ m/s.

The design conditions are as follows:

a. internal diameter of damper cylinder: $d_{\text{in}} = 0.04$ m
b. piston rod diameter: $d_{\text{rod}} = 0.02$ m
c. length of the piston: $l = 0.036$ m.

2.2 Selection Criterion of MR Fluid

To choose the most effective MR fluid, the normal characteristics of different MR fluid must be studied. The normal characteristics of MR fluid indicate by the figure of merit. The MR fluid provides the maximum force when it generates the maximum yield stress [4]. This condition is achieved when the MR fluid is magnetically saturated. In this study, the Lord Corporation 132 DG MR fluid is chosen. For shear strain rate, $\gamma = 140\ \text{s}^{-1}$ and magnetic field, $H = 250$ kA/m, the following values can be obtained:

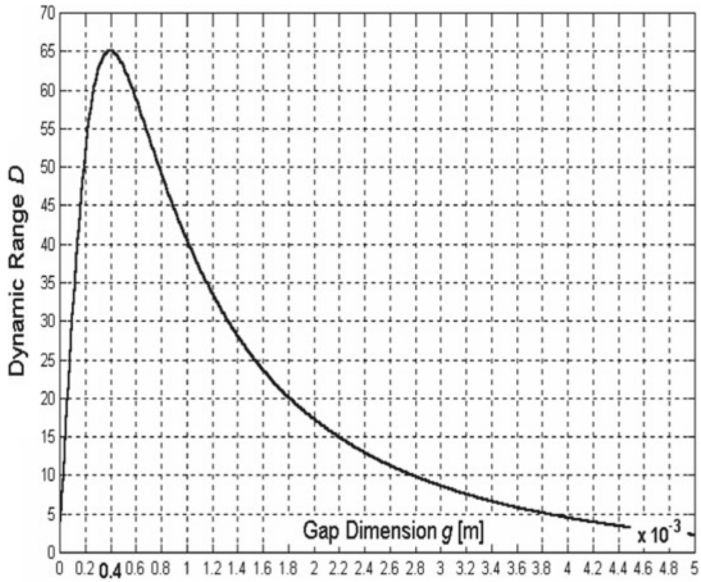


Fig. 2 Variation of dynamic range (D) with gap dimension (g) [5]

- The magnetic flux $B = 0.83$ T.
- The yield stress $\tau_y = 44.1$ kPa.
- The off state plastic viscosity $\eta = 0.25$ Pa s.

2.3 Hydraulic Design

The MR damper will be more effective when the controllable range of force should be as high as possible. The controllable force will increase when the gap is small but for small gap the viscous force increases and dynamic range decreases. For large gap size, both the viscous force and controllable force decrease [5]. Hence, there exists an optimal gap size which maximizes the dynamic range D. From Fig. 2, $g = 0.4 \times 10^{-3}$ m for $D_{\max} = 65$. Now the hydraulic circuit parameters are calculated on the basis of above gap size.

2.4 Magnetic Circuit Design

Parallel to the working mode of MR fluid, the realization of a suitable magnetic circuit in the device is fundamental, because the final load damping performances depend on fluid-activated shear stress τ_y that depends on magnetic field produced B.

The main objective of circuit design, once chosen the maximum current intensity i for the working condition of the device, was to calculate the necessary number of coils N that allowed to generate the desired magnetic field, according to the limits on the geometry and on safety [6, 7]. Following steps are used to size the magnetic circuit:

(1) Operating point of MR fluid: magnetic field, $H = 250$ kA/m, the magnetic flux density, $B = 0.83$ T.
(2) The steel used for piston and cylinder should have high magnetic permeability (C% < 0.15).
(3) Two equal poles are considered with pole length; $l_p = 6 \times 10^{-3}$ m.
(4) Magnetic flux density is calculated for the steel core from the continuity of magnetic flux (ϕ), ϕ in the MR gap = ϕ in the steel = constant.
(5) The effective area of the pole is found to be $A'_f = 7.38 \times 10^{-4}$ m^2 and $B_{steel} = \phi/A_0 = B_f A'_f/A_0 = 1.5$ T.
(6) $H_{steel} = 1000$ A/m (on the basis of B versus H magnetic curves).
(7) Magnetic coil contains the ampere turns (Kirchoff's law): $NI = \Sigma H_i L_i = 300$ A-turns.
(8) Taking $I = 2$A yields $N = 150$.
(9) Calculated inner coil diameter for a coil: $d_c = 2.28 \times 10^{-2}$ m.
(10) Calculated coil length: $l_c = 2.4 \times 10^{-2}$ m.

Iterative calculation is used to design the hydraulic circuit and magnetic circuit.

3 Finite Element Analysis of MR Damper

Through hydraulic and magnetic design, the main design parameters for MR damper have been selected. Now the piston head geometry is analyzed in detail because the design parameters directly affect the behavior magnetic saturation. For better vibration control, it is always desired that all of the components are below their saturation fields [8]. The main design parameters have been analyzed through a series of numerical magnetic analysis using the finite element method "ANSYS" (Fig. 3).

4 Results and Discussions

4.1 *Effect of Core Diameter (DC) (d_c)*

The flux density should reach its maximum value across the fluid gap for optimized damper during its operation. The core diameter is a critical design parameter to affect the limiting magnetic flux density. In Fig. 4, the magnetic flux density is plotted in

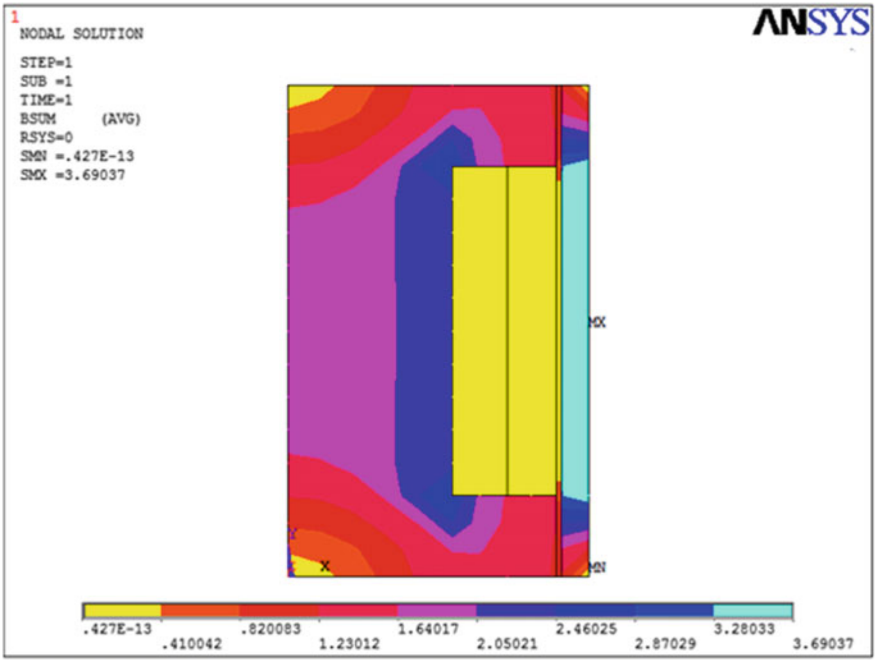
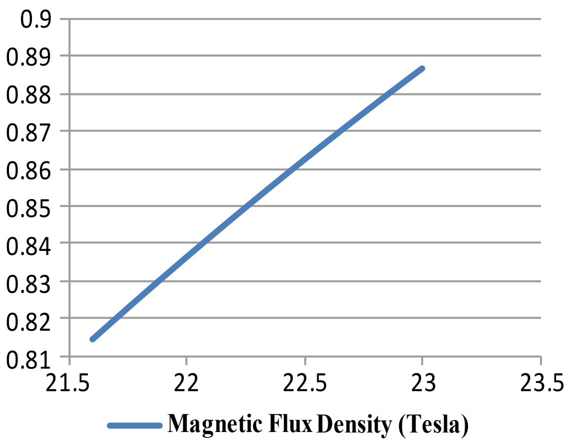


Fig. 3 Two-dimensional magnetic flux density (B_{SUM})

Fig. 4 Variation of magnetic flux density with core diameter



the gap versus the core diameter.

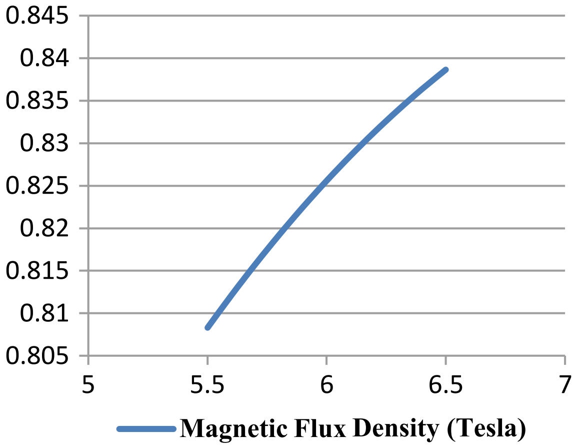


Fig. 5 Variation of magnetic flux density with magnetic pole length

4.2 *Effect of the Magnetic Pole Length (LP) (l_p)*

Figure 5 shows the variation of the magnetic flux density versus gap as a function of magnetic pole length.

The result of the MR damper model indicated that at the input design variables ($d_c = 22.8$ mm, $l_p = 6$ mm), the magnetic flux density is 0.877 Tesla which is more than the saturated value of 0.83 Tesla. At the optimum values ($d_c = 21.8$ mm, $l_p = 6.1$ mm) through magnetic analysis, the magnetic flux density is 0.828 T, which is close and less than saturated value.

5 Conclusions

The maximum magnetic flux density in the fluid gap is generated below the saturated value by optimizing the dimensions and also verified by simulation. In this study, the effects of the design variables (DV's), core diameter (d_c) and magnetic pole length (l_p) on the magnetic flux density in the fluid gap were investigated. The result of the MR damper model indicated that at the input design variables ($d_c = 22.8$ mm, $l_p = 6$ mm) the magnetic flux density is 0.877 Tesla which is more than the saturated value of 0.83 Tesla. At the optimum values ($d_c = 21.8$ mm, $l_p = 6.1$ mm) through magnetic analysis, the magnetic flux density is 0.828 T, which is close and less than the saturated value. So this study will help to design the MR damper for better control of vibrations.

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