EXPERIMENTAL ANALYSIS OF MAGNETO-RHEOLOGICAL FLUID (MRF) DAMPERS UNDER TRIANGULAR EXCITATION

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ABSTRACT

Magnetorheological dampers, or as they are more commonly called, MR dampers, are being developed for a wide variety of applications where controllable damping is desired. These applications include dampers for automobiles, heavy trucks, bicycles, prosthetic limbs, gun recoil systems, and possibly others. This paper first introduces MR technology through a discussion of MR fluids and then by giving a broad overview of MR dampers those are being developed. Next section includes a discussion of MR damper types, mathematical fundamentals, and an approach to magnetic circuit design. Later, MR dampers are tested for dynamic behavior under triangular excitation.

Key words: MR Fluid, MR Damper, Hydraulic circuit, Magnetic circuit, Triangular excitation.

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1. INTRODUCTION

Magnetorheological (MR) fluids are materials that respond to an applied magnetic field with a dramatic change in rheological behavior. An MR fluid will be in a free-flowing liquid state in the absence of magnetic field, but under a strong magnetic field its viscosity can be increased by more than two orders of magnitude in a very short time (milliseconds) and it exhibits solid-like characteristics. The strength of an MR fluid can be described by shear yield stress. Moreover, the change in viscosity is continuous and reversible, i.e. after removing the magnetic field the MR fluid can revert to a free-flowing liquid. Using these characteristics of MR fluids, MR fluid devices have the ability to provide simple, quiet, rapid-response interfaces between electronic controls and mechanical systems. Hence scholars and industrialists have shown extensive interest in MR fluids and their applications. The devices based on MR fluids, including dampers, clutches, polishing devices and hydraulic valves, etc., have a very promising potential future; some of them have been used commercially in engineering applications such as automobiles, polishing machines, exercise equipment, etc.

Field responsive fluids include magnetorheological (MR) fluids, ferrofluids and electrorheological fluids. A common property of these materials is that, in most cases, they are all dispersions of particles in a carrier liquid and some aspect of their rheology is controlled by an external electric or magnetic field [1-3]. Typical magnetorheological fluids are the suspensions of micron sized, magnetizable particles (iron, iron oxide, iron nitride, iron carbide, reduced carbonyl iron, unreduced carbonyl iron, chromium dioxide, low-carbon steel, silicon steel, nickel, cobalt, and combinations thereof [4]) suspended in an appropriate carrier liquid such as mineral oil, synthetic oil, water or ethylene glycol. The carrier fluid serves as a dispersed medium and ensures the homogeneity of particles in the fluid [5]. Typically, the diameter of the magnetizable particles range from 3 to 5 microns [6,7].

The design and applications of MR devices has been an area of recent interest due to the controllable characteristics of MR material. Work has been done to improve some of the key characteristics of MR fluids, such as increasing its yield stress and thereby allowing for a wider variety of applications [7]. Significant work has been done on modeling the dynamic characteristics of MR devices, through a variety of approaches [8,9,10,11]. New approaches to developing MR devices are being explored and new designs are being tested [12,13,14,15,16,17]. In addition, some work has been done on MR device design methods [18] and device optimization [19]. There are several important patents on MR devices [20,21,22].

2. MR FLUIDS

For the current study, two MR fluids were prepared using two different concentrations (by volume) of magnetic particles. The MR fluids synthesized have different concentrations of iron particles. Depending upon the apparatus available to measure the concentration of iron particles, 100 ml of particles were measured while synthesizing both fluids and appropriate concentration of carrier fluid was added, to both, in order to balance the ratio of 40-60 for the first MR fluid and 36-64 for the second MR fluid. The first concentration of MR fluid incorporates 40% by volume of magnetic particles. These are carbon based iron particles and are called as carbonyl iron particles. They were mixed with the carrier fluid (i.e. Hydro-Carbon) only and kept undisturbed for a period of five days to observe the gravitational settling. It was observed that the particles settled approximately 120 ml in a period of 5 days from the total height of the fluid column. Later, additives were added to the mixture of iron particles and carrier fluid. The gravitational settling in this case was observed to be less than the settling of particles without the additives. Figure 1(right side container) shows the synthesized MR fluid for 40% by volume concentration of iron particles inclusive of additives (MRF-1).
The second concentration of MR fluid incorporates 36% by volume of iron particles. As the gravitational settling was observed in the synthesis of the first fluid, the second MR fluid was synthesized by directly mixing the carrier fluid and additives with the iron particles. Figure 1 (left side container) shows the synthesized MR fluid pertaining to 36% by volume iron particles (MRF-2).

3. MODELING & DESIGN OF MR DAMPERS

The design of MR fluid dampers assumes two main stages: 1) Hydraulic circuit design, and 2) Magnetic circuit design. Both stages presume an iterative calculus.

3.1. MR Damper Geometry

The MR fluid damper devices operate in pressure driven flow mode (PDF). During motion of the MR damper piston, fluids flow in the annular gap between the piston and the cylinder housing. For quasi-static analysis of MR fluid dampers, assume that: 1) MR dampers move at a constant velocity; 2) MR fluid flow is fully developed; 3) a simple Bingham plasticity model may be employed to describe the MR fluid behavior.

Conform the Bingham plasticity model the flow is governed by (Bingham’s equations):

\[
\begin{align*}
\tau &= G \cdot \gamma, \quad \tau < \tau_s \\
\tau &= \tau_s (H) + \eta \cdot \gamma', \quad \tau > \tau_s.
\end{align*}
\]

(in the absence of magnetic field \( \tau = \eta \cdot \gamma' \)).

In (1), H is the magnetic field, \( \gamma' \) is the fluid shear rate, \( \eta \) is the plastic viscosity (i.e. viscosity at \( H=0 \)), and \( G \) is the complex material modulus.

In an analogous fashion to (1), the pressure drop developed in a device based on pressure driven flow mode is commonly assumed to result from the sum of a viscous component \( \Delta P_\eta \) and a field dependent induced yield stress component \( \Delta P_\tau \). This pressure may be approximated by:
\[ \Delta P = \Delta P_\eta + \Delta P_\tau = \frac{12 \cdot \eta \cdot Q \cdot L}{g^3 \cdot w} + \frac{c \cdot \tau_y \cdot L}{g} \]  

(2)

where \( L, g \) and \( w \) are the length, gap and width of the flow channel between the fixed poles, \( Q \) is the volumetric flow rate, \( \eta \) is the fluid viscosity with no applied field and \( \tau_y \) is the yield stress developed in response to an applied field. The parametric \( c \) has a value ranging from a minimum value of 2 (for \( \lambda < 1 \)) to a maximum value of 3 (for \( \lambda > 100 \)). Where \( \lambda \) is control ratio or dynamic range (\( \lambda = \Delta P_\tau / \Delta P_\eta \)).

The calculus relations for parameters are:

\[ A_p = \pi \left[ \left( \frac{d_{cy} - 2g}{2} \right)^2 - \frac{d_{ck}^2}{4} \right] \]

(3)

\[ w = \pi (d_{cy} - g) \]

(4)

\[ c = 2.07 + \frac{12 \cdot Q \cdot \eta}{12 \cdot Q \cdot \eta + 0.4 \cdot w \cdot g^2 \cdot \tau_y} \]

(5)

\[ Q = A_p \cdot v_p \]

(6)

### 3.2. MR Damper Magnetic Circuit

![Figure 2](image)

**Figure 2** Basic magnetic circuit design procedure (Engineering Note 1999b)
For completeness, the description of the magnetic circuit design described in the Lord Corporation Engineering Note (1999b) is summarized in this section. The MR damper magnetic circuit typically uses low carbon steel, which has a high magnetic permeability and saturation, as a magnetic flux conduit to guide and focus magnetic flux into the fluid gap. Tasks in the design of a magnetic circuit are to determine necessary amp-turns (NI) for the magnetic circuit.

The typical design process for a magnetic circuit is as follows:

(1) Determine the magnetic induction $B_1$ in the MR fluid to give desired yield stress $\tau_y$ (Fig.2 (a)).

For $\tau_y = 46.5$ kPa, $B_1 = 0.85$ T.

(2) Determine the magnetic field intensity $H_1$ in the MR fluid (Fig.2 (b)).

For $B_1 = 0.85$ T, $H_1 = 250$ kA/m.

(3) The total magnetic induction flux is given by $\Phi = B_1 A_f$, where $A_f$ is effective pole area including the fringe of magnetic flux. Because of the continuity of magnetic induction flux, the magnetic induction $B_s$ in the steel is given by

$$B_s = \frac{\Phi}{A_s} = \frac{B_1 \cdot A_f}{A_s}$$

where $A_f = 1.4702 \times 10^{-3}$ m$^2$, $A_s = 1.432 \times 10^{-3}$ m$^2$ and $B_s = 0.872$ T.

(4) Determine the magnetic field intensity $H_s$ in the steel using Fig.2 (c).

For $B_s = 0.872$ T, $H_s = 0.45$ kA/m.

(5) By using Kirchoff’s Law of magnetic circuits, the necessary number of amp-turns (NI) is

$$NI = \sum H_i L_i = H_t g + H_s L$$

Where $L$ = length of steel path.

NI is calculated as 283 amp-turns. Taking I=2A, yields N=141.

![Figure 3 Proposed MR fluid damper](image)

4. TESTING OF MR DAMPERS

It consists of a damper, hydraulic system, sensors, data acquisition system and power supply. A brief description of each is presented in the subsequent paragraphs. The details of the experimental setup are shown in figure 5.
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**Dampers:**
Conf.1: Double step, Low-Carbon Steel, Gap-0.4 mm, Coil wire-26 ASW.
Conf.2: Double step, Medium-Carbon Steel, Gap-0.6 mm, Coil wire-32 ASW.
Conf.3: Single step, High-Carbon Steel, Gap-0.8 mm, Coil wire-27 ASW.
Conf.4: Single step, Ultra-High-Carbon Steel, Gap-1 mm, Coil wire-33 ASW.

![Figure 4 MR Dampers](image)

**Hydraulic System:**
The damper is driven by an actuator configured with two 10-gpm Moog servo valves with a bandwidth of 60 Hz. The actuator has a 50 mm diameter cylinder and a 40 mm stroke and is fitted with low-friction Teflon seals to reduce nonlinear effects and it was built by Denison Hydraulics India Limited, Hyderabad. The actuator is controlled by a servo-hydraulic controller in displacement feedback mode. The maximum speed under this configuration was 20 cm/sec.

**Sensors:**
A position sensor, manufactured by OPKON (Model LPT), was employed to measure the damper displacement. The position sensor has a full range of 1000 mm displacement, speed of 2 m/s and repeatability ≤0.05%. A load cell of tension and compression type, made by OIML and rated at 20 KN, was used to measure the damper resisting force. The input current going into the MR damper coils was measured by a Tektronix current probe with a sensitivity of 100 mV/A. The pressure difference on either side of the damper piston was measured by two pressure transmitters, made by SPY, have a maximum range of 200 bars. Additionally, a Fluke 80T-IIR infrared temperature probe with a sensitivity of 1 mV/°C was utilized to monitor the damper temperature during the experiment.
Data acquisition:
A data logger (Model: TC-800D) with 8 analogue inputs, manufactured by AMBETRONICS, was employed for data acquisition and analysis.

Power supply:
A regulated power supply (Model: BK-150200) was employed to provide DC power supply with a full capacity of 2 amps to input current to the MR damper coils for quasi-static damper testing.

5. RESULTS & DISCUSSIONS

The force-velocity and variable input current tests were conducted using the setup shown above to investigate the behavior of the synthesized MR fluids and the dampers. In the experiment, velocities of 0.00, 0.05, 0.1, 0.15 and 0.2 m/s were employed. The input current to the damper coil was constant at 0, 0.5, 1, 1.5 and 2 A respectively.

5.1. Force-Velocity Behavior

The measured force-velocity behavior of the synthesized MR fluids and four dampers at various constant input current levels are plotted and shown in figures 6-10. The following observations are made from the results:

- A larger damping force is seen at high velocity, this may be due to the plastic viscous force.
- All the plots are almost parallel to each other and have very less slope. This indicates that the resisting force (F) of the MR damper is less dependant upon velocity (Vp). Velocity dependence can further be reduced by designing proper control system to vary online current flowing into the damper.
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**Figure 6** Comparison of Four Configurations for Two MR fluids for Variation of Force wrt Velocity at a current of 0A.

**Figure 7** Comparison of Four Configurations for Two MR fluids for Variation of Force wrt Velocity at a current of 0.5A.

**Figure 8** Comparison of Four Configurations for Two MR fluids for Variation of Force wrt Velocity at a current of 1.0A.
5.2. Variable Input Current Behavior

Force-current test for the synthesized MR fluids and four dampers at different constant velocity levels were conducted and results plotted in figures 11-14. The following observations were made:

- All the plots are clustered and have more slope, i.e. the effect of piston velocity (Vp) on the damper resisting force (F)/pressure (P) is much less compared to the damper input current (I).
- There is not much increase in force value after a current value of 1.5 A for MRF-I. This is due to the saturation of magnetic particles in the fluid.

Figure 9 Comparison of Four Configurations for Two MR fluids for Variation of Force wrt Velocity at a current of 1.5A.

Figure 10 Comparison of Four Configurations for Two MR fluids for Variation of Force wrt Velocity at a current of 2.0A.
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Figure 11 Comparison of Four Configurations for Two MR fluids for Variation of Force wrt Current at a piston velocity of 0.05 m/s

Figure 12 Comparison of Four Configurations for Two MR fluids for Variation of Force wrt Current at a piston velocity of 0.10 m/s

Figure 13 Comparison of Four Configurations for Two MR fluids for Variation of Force wrt Current at a piston velocity of 0.15 m/s

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6. CONCLUSION

In this paper, a fundamental understanding of the behavior of small capacity magnetorheological (MR) dampers has been developed through the modeling, design and experimental verification of dampers. Four different configurations of dampers have been proposed. The dampers differ with each other in material, gap size, gauge of coil wire and stages (steps) in the coil. Two different MR fluids, MRF-I (40%) & MRF-II (36%) are also proposed and their synthesizing is also discussed. From results it can be concluded that the MRF-I is saturated at current value of 1.5A. It can also be concluded that the damper configuration 1 with fluid MRF-I is the better combination compared to others.

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