Experimental Studies of In-House Developed Magnetorheological Fluid in a Damper

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Abstract: Applications of magnetorheological fluids which have wide applications in automotive and structural engineering in dampers, clutches etc., have been widely studied. The cost of commercially available MR fluids is restricting its extensive use. In this paper, a stable MR fluid is developed using in-house technology at a fraction of cost at which the fluid is available commercially. The developed fluid is tested for on-state as well as off-state rheological properties in a fabricated MR damper prototype. The off and on-state characteristic of the fluid in terms of viscosity and damping force respectively is evaluated and compared with the commercially available MR fluid. This study has revealed that the developed MR fluid is following the same pattern for damping force as that of commercially available MR fluid and can be used in various commercial applications at highly reduced cost.

Keywords: Magnetorheological fluid, dampers, magnetizable particles, carrier fluid, additive

1. Introduction

Magnetorheological (MR) fluids have attracted attention and interest due to its quick response, reversible changes in its rheological behavior when subjected to a magnetic field. The external magnetic field forces the ferromagnetic particles to form a chain-like structure which restrict the free fluid motion. The MR fluid exhibits rapid transition from a free-flowing liquid to a semi-solid state on an application of external magnetic field. Simplicity and more intelligence in its functionality are key features of the MR Fluid (MRF) technology. Excellent feature of this technology e.g., fast response, simple interface between electrical power input and mechanical power output and precise controllability makes the MRF technology more attractive for various applications. The discovery of the MR fluids is credited to Rabinow [1] at the US National Bureau of Standard in 1948. Since then the properties of magnetorheological fluids (MR) have been investigated for understanding MR fluids and devices based on it.

There are basically three components of a MR Fluid: base fluid, metal particles and stabilizing additives. The base fluid acts as a carrier for the metal particles and naturally combines its lubrication and damping features. To have high saturation point for a MR fluid, its viscosity should be small and be almost independent of temperature. In this way, the MR effect will be the dominant effect when compared with its base fluid viscosity. The effect is also found to vary with temperature and shear stress. In the off-state condition, the MR Fluids behave like base fluids in accordance to its compositions.

Rankin et al. [2] investigated the effect of the continuous phase yield stress on the MR response. Seval Genc [3] has investigated on-state rheological properties of the MR Fluids. The dependency of yield stress on the average particle size and magnetic properties of the particles is also established. Phulé [4] has discussed the effect on
sedimentation by using large particle size, the viscosity of fluid at zero magnetic field and change in yield stresses when fluid is induced to the magnetic field. Carlson [5] answered the question “What makes a good MR fluid?” and on what “It depends”. It mainly depends on the type of device in which the MR fluid is being used, the conditions to which the fluid is exposed and the duration of that exposure. Jolly et al. [6] presented the rheological and magnetic properties of several commercial magnetorheological (MR) fluids. They also showed that the various material properties may be balanced to provide optimal performance. Wereley et al. [7] used a mixture of conventional micron sized particles and nanometer-sized particles for the preparation of MR fluids. The settling rate of the bi-disperse fluids using nanometer-sized particles is reduced as the nano-particles filling the pores created between the larger particles, thereby reducing fluid transport during creeping flow. This reduction in the settling rate comes at a cost of a reduction in the maximum yield shear stress that can be manifested by such an MR fluid at its saturation magnetization. Shah et al. [8] have presented a new kind of low sedimentation magnetorheological fluid (MRF) which has been evaluated in terms of yield stress and flow behavior using MR damper. The proposed MRF is shown to be very effective in reducing adverse effects due to particle sedimentation. Farjoud and Bagherpour [9] presented a comprehensive process for electromagnet design for magnetorheological devices. Both steady-state and transient design are presented in a very systematic manner.

Figure 1: Activation of the MR Fluid: (a) No Magnetic Field and (b) Magnetic Field applied

Figure 1 illustrates the activation of a MR fluid. The MR fluids consist of magnetically permeable micron-sized particles dispersed throughout the carrier medium either a polar or a non-polar fluid, which influence the viscosity of the fluids under no external magnetic field. The Figure 1(a) shows the particles in the fluid which are randomly dispersed in the medium when there is no magnetic field applied. In the presence of a magnetic field, the particles start to move and align themselves along the lines of magnetic flux and show the formation of chains of the particles Fig. 1 (b). It thus creates more yield strength for the MR fluid. As this change in its rheology occurs instantly and is reversible in nature, the MR fluids become the most attractive smart fluid for real-time control applications of various applications and particularly in the field of vibration control of automotive industry. The commercialization of the MR technology begins in year 1995 with the use of rotary brakes in aerobic exercise equipments. Afterwards, the application of magneto-rheological material technology in real-world systems has grown steadily. During the past few years, a number of commercially available products (or near commercialization) have been developed [10] e.g.,:
a) Linear MR dampers for real-time active vibrational control systems in heavy duty trucks.
b) Linear and rotary brakes for low-cost, accurate, positional and velocity control of pneumatic actuator systems.
c) Rotary brakes to provide tactile force-feedback in steer-by-wire systems.
d) Linear dampers for real-time gait control in advanced prosthetic devices.
e) Adjustable real-time controlled shock absorbers for automobiles.
f) MR sponge dampers for washing machines.
g) Magneto-rheological fluid polishing tools.
h) Very large MR fluid dampers for seismic damage mitigation in civil engineering structures.
i) Large MR fluid dampers to control wind-induced vibrations in cable-stayed bridges.

In this paper, a stable magnetorheological fluid is developed using in-house technology at a fraction of cost available commercially. The various properties of the in-house developed fluid are determined experimentally under on and off state condition in a fabricated MR damper prototype. This study has revealed that the developed MR fluid is following the same pattern for damping force as that of commercially available MR fluid and can be used at a low cost in various commercial applications.

2. MR Fluids Preparation and Testing

A severe limitation of commercially available MR fluids, for its industrial and other applications, is its very high cost i.e., US $ 750 per liter. There is only one firm in the world i.e., LORD Corp. Inc. USA, that supplies the MR fluid for research and allied work. So, there is a dire need to prepare a MR fluid indigenously at minimal possible cost for its extensive research and also to promote its various low end applications.

2.1. Components of MR Fluid

The MR fluids are mainly built up by three main components i.e., dispersed phase (the magnetizable particles), continuous phase (the carrier liquid) and additives (stabilizers). From the literature survey, it has understood that materials particles in the fluid must be magnetically multi-domain so that they can exhibit low levels of magnetic coercivity and higher inter-particle force. This is achieved by choosing the particle material of higher saturation magnetization. After making the survey on internet as well as the local market, the pure iron particle of 300 mesh size is selected and is used for the preparation of the MR fluid samples in the laboratory. The primary function of the carrier liquid is to provide a low permeability and non-magnetic base liquid in which the magnetically active phase particles remain suspended. In order to keep the off-state viscosity low, silicone oil with viscosity 100 cSt (which corresponds to 0.96 Pa-s as its dynamic viscosity) is used for the preparation of the MR fluid samples. The additives form the third component of the MR Fluid. It is used in the MR fluids for many purposes, e.g., prevention and minimization of sedimentation, prevention and minimization of coagulating of the particles, maintain a coating on the particles in order to enhance re-dispersibility and to enhance anti-oxidation. White lithium grease is used as an additive for the MR fluid samples.

After critical literature review, the material composition for the MR fluid samples is first fixed and is listed in Table 1. Four samples of MR fluid are prepared by using different weights of MR fluid constituents. Two levels for each constituent are fixed and,
thus, the four combinations are selected to represent its inter effect on its properties. The levels fixed for making these four samples are listed in Table 1.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Fe Particle (gm)</th>
<th>Silicone oil (gm)</th>
<th>Grease (gm)</th>
<th>wt. % of materials w.r.t. whole fluid weight</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Fe Particle</td>
<td>Silicone oil</td>
<td>Grease</td>
<td></td>
</tr>
<tr>
<td>MRF1</td>
<td>200</td>
<td>112.5</td>
<td>8.75</td>
<td>62.26</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>35.02</td>
</tr>
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<td></td>
<td></td>
<td></td>
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<td>2.72</td>
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<td>MRF2</td>
<td>200</td>
<td>133</td>
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<td></td>
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<td>38.55</td>
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<td></td>
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<td></td>
<td>3.48</td>
</tr>
<tr>
<td>MRF3</td>
<td>220</td>
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<td>12</td>
<td>63.86</td>
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<td></td>
<td></td>
<td></td>
<td>32.66</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>3.48</td>
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<tr>
<td>MRF4</td>
<td>220</td>
<td>133</td>
<td>8.75</td>
<td>60.82</td>
</tr>
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<td></td>
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<td>36.76</td>
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<td></td>
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<td></td>
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<td>2.42</td>
</tr>
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</table>

2.2. Off-state Rheology Testing of In-house Developed Fluid

A rheometer is used to measure a material’s rheological properties. It is based on the principle of a viscometer. The testing of the prepared MR Fluid samples, for its off state properties, is done at Anton Paar office, Phase-5, Udhyog Vihar, Gurgaon.

Shear stress-shear strain and shear stress-dynamic viscosity data for all four MR Fluid samples are determined experimentally. The fluids before testing is stirred properly with a spatula and then filled into the measuring cylinder of the machine. To make the MR Fluid samples more homogenous further stirring is done on the rheometer itself for 60 seconds. The MR Fluid of 19 ml volume is used in testing of one sample. The behavior of the fluid samples is determined by obtaining 50 data points at a time interval of 2 second at a constant temperature of 25°C on the rheometer.

Figure 2 shows the experimental data for shear stress (Pa) at different shear rate (s⁻¹) for the four fluid samples. The Figure shows Non-Newtonian fluid behavior for the MR fluid samples in the absence of magnetic field. The shear stress is found to be increasing with increase in its shear rate. The Figure also shows that the MR Fluid samples are following Bingham plastic model. At lower shear rate, the MRF3 sample is showing the higher shear stress. It is because of the presence of highest percentage of iron particles in the least percentage of silicone oil among these four samples. At the higher shear rate, all the fluid samples shows almost same behavior of shear stress.

The Figure 3 shows the experimental data of dynamic viscosity (Pa.s) with respect to shear rate (s⁻¹) in the experimentation on log-log scale. It is observed in the Figure that dynamic viscosity of all the MR Fluid samples decreases with increase in its shear rate. At low shear rate, the viscosity of MRF3 sample is greater than other samples. It is because of the presence of highest percentage of iron particles in the least percentage of silicone...
oil among the four samples. With increase in shear rate the viscosity decreases and at high shear rate, the viscosity varies from 0.244 to 0.32 Pa-s for all four fluid samples. At higher shear rate, the viscosity of MRF1 sample is 0.32 Pa-s while viscosity of MRF2 sample is 0.244 Pa-s. A shear thinning behavior of the MR suspension is also observed. Shear thinning effect is minimal for the MRF1 sample over the wide range of the shear rate.

2.3. SEM and Optical Scanning of In-house Developed Fluid

Figure 4 shows the optical image of MR Fluid sample observed by Optical Scanning Microscope. The fluid sample is also observed through Scanning Electron Microscope (SEM) at NIPER, Mohali with different magnifications to determine the average size of iron particles in it (Figure 5).

![Figure 4: Optical Image of MR Fluid in Optical Scanning Microscope](image1)

![Figure 5: SEM images of MR Fluid Sample at 320 times Magnification](image2)

2.4. On State Testing of MR Fluid of In-house Developed Fluid

On the basis of off state rheological testing of the four samples, the MRF3 came out to be the best sample [11] and hence is used further to analyze the performance of the MR fluid in the fabricated prototype MR damper [12] under on state conditions. The prototype MR damper is filled with MRF3 and experiments is conducted for determination of damping force of the damper under on-state conditions in the vibration control laboratory (Figure 6). The total damping force of the MR damper using the MRF3 fluid is shown in Table 2 under different input current given to the electromagnetic coil of the MR damper.

In the next step, the same MR damper is filled with the commercially available MR fluid i.e., LORD-MRF-122EG fluid purchased from M/s Lord Corp. Inc. USA. The experiment for the determination of total damping force is repeated under the same testing conditions. The total damping force of the MR damper using the fluid is shown in Table 2 under different input current setting to the electromagnetic coil of the damper. These data is shown qualitatively in Figure 7.

During the above experimentation, the displacement data of the piston of the MR damper is also noted down along with corresponding total MR damping force for these two fluids. The damping force v/s displacement curves for these two fluids have been plotted and are shown in Figures 8 and 9.

From the Figures 7-9, it has been observed that the behavior of the in-house developed MR fluid in terms of damping force is very much identical with the commercially available MR fluid.
The development of MR fluid in the laboratory has been initiated as a pilot study and further studies/research is proposed to be carried out to prepare better and more stable MR fluid samples which shall be very close in terms of all its properties with the commercially available MR fluids.

Table 2 Comparison of Total Damping Force in Prototype MR Damper

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Total Experimental Damping Force (N) using In-house MRF3 Fluid</th>
<th>Total Experimental Damping Force (N) using LORD-MRF-122EG Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>189.46</td>
<td>224.4</td>
</tr>
<tr>
<td>0.2</td>
<td>252.91</td>
<td>327.66</td>
</tr>
<tr>
<td>0.3</td>
<td>295.24</td>
<td>394.36</td>
</tr>
<tr>
<td>0.4</td>
<td>323.97</td>
<td>436.77</td>
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<tr>
<td>0.5</td>
<td>341.07</td>
<td>463.14</td>
</tr>
<tr>
<td>0.6</td>
<td>355.13</td>
<td>481.73</td>
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<tr>
<td>0.7</td>
<td>367.50</td>
<td>504.65</td>
</tr>
</tbody>
</table>

3 Conclusions

In this paper, a stable MR Fluids has been developed using in-house technology, at a fraction of the cost available commercially. The MR fluid samples were prepared using different weight composition of its constituents. The two levels for each of the MR Fluid constituent were fixed and thus four samples were prepared. Based on the experimental results of these samples under off state conditions, the best prepared MR fluid sample is tested for its on-state properties in the fabricated MR damper prototype. The results of the on-state total damping force of the in-house developed MR fluid is compared with the commercially available MR fluid i.e., Lord-MRF-122EG fluid under the same
experimental conditions. It is concluded from the experimental studies that the behavior of the in-house developed MR fluid is identical with the commercially available MR fluid. The results is encouraging although being a pilot study and further study/research is proposed to be carried out in future to prepare the better and more stable MR fluid samples which will be closer to the commercially available MR fluids.

References


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