Shear Mode Damper Testing Using Flake Shape Based Magnetorheological Fluids

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Abstract: Use of anisotropic iron particles in the magnetorheological (MR) fluid having a high yield stress is a challenge as it increases the viscosity of the fluid in off-state. In this clause, a novel flake shaped iron powder based MR fluid with high yield stress is synthesized and used in shear mode MR damper (SMMD). MR damper design is optimized using fluid properties and Bingham model. Damping performance of newly synthesized MR fluid damper is at par with the available friction based damper used in front loaded washing machine. The unique feature of this design is minimal volume of the fluid (1.5 ml) required to achieve damping force of 50N. Effect of different volume percentage of particles in MR fluid is evaluated in terms of damping force. Effect of testing parameters like displacement and frequency of excitation on damping force was evaluated. Effect of settling of particle on damper performance is discussed in this work. It shows that the flakes shaped-based MR fluid show better stability against gravity. The smaller quantity of present flake shaped-based MR fluid will reduce the cost of shear mode damper.

1. Introduction

By using passive damper between structure and delicate equipment, it is possible to take in either shock (high damping) or vibration (low damping) during normal operation. Therefore, research was concentrated on developing active dampers for vibration isolation [1]. Semi-active damper utilizing Magnetorheological (MR) fluids also can be used for this requirement. The MR fluids are combinations of carrier oil, iron particles (micron-Sized). It’s rheological properties are tune due to magnetic particles in presence of magnetic field [2,3]. MR effects (rheological properties) in the MR fluid has found numerous applications like MR shock absorbers [4], MR mounts [5], clutches, brakes [5,6], recoil system [7-9] etc.

In all these applications, the maximum effect is limited by the saturation magnetization of the dispersed magnetic particles. The performance of MR fluid in applications is judged by three parameters called figure of merits [10]. These are: (i) \( F_1 = \frac{\tau^2}{\eta} \), where \( \tau \) is yield stress and \( \eta \) is the viscosity of MR fluid at zero magnetic field, maximizing this figure of merit, helps in minimizing the device size and electrical power consumption. (ii) \( F_2 = \frac{\tau^2}{\rho \eta} \), here \( \rho \) is the density of MR fluid. This is an important term, when one deals with weight-sensitive applications and (iii) \( F_3 = \tau BH \), here \( B \) and \( H \) are magnetic flux density and intensity of the fluid. Minimization of this figure of merit will help to reduce current requirement, and it is usually required for high bandwidth applications. Then all these virtues are to be optimized for the MR fluid properties. While the suitability of an MR fluid for a particular use depends on factors such as stability, durability and temperature range, therefore, it becomes very significant to design new MR fluids, which can enhance the MR effect.
In earlier research, much attention has been focused on the use of spherical carbonyl iron particles as a dispersion material because of its high saturation magnetization value. More frequently than not, good MR fluids should be stable against settling and should have high magnetic strength. The major focus on MR fluid research has been to enhance the MR effect, to improve stability against sedimentation and re-dispensability of MR fluids [10-19]. In summation, many efforts have been reported by adding nanoparticles and viscoelastic media to improve stability and re-dispersion. According to recent research, MR fluid based on micro- and nano-fibres have shown better sedimentation stability and higher yield stress comparable to spherical particles for a given volume fraction and magnetic field intensity [20-23].

Furthermore, our recent works, reported the suitability of flake shaped particles for MR fluid synthesis and it’s an application in device [22-23]. The study proposes that the MRF exhibit an improvement in τ at low field with <0.1% per day sedimentation rate. In addition, flake shaped iron particles required low magnetic field to reach the saturation, compared spherical iron particle-based MRF. Having a high value of saturation magnetization of spherical iron-carbonyl powder, in all the MR based applications, the MR fluids are synthesized using these powders. Use of non-spherical shape iron powders in developing MR based applications are very uncommon. The major difficulty of using the anisotropic particles is to get a high value of the first figure of merit F1. This is imputable to the growth in the viscosity as well as a limitation of the higher volume fraction of particle loading. Few works, reports on applications of flakes-shaped (plate-like) iron particles dispersed MR fluid for damping applications [22-24]. At all this reported work, the damping force is depressed. As a result, the required volume in the damper becomes high to get the same damping force values, which can be obtained using spherical iron particles.

The primary focal point of current work is first to improve the damping performance using flake shaped particle-based MR fluid. To achieve the first aim, we have modified the synthesis conditions of flake-shaped MR fluid and studied its MR properties. In the present paper, we concentrate on shear mode MR damper (SMMD), which can be used as washing machine damper. In the present condition, in front-loaded washing machine friction damper is used and test result of this damper is as shown in figure 1. Friction damper is tested at 1Hz frequency with 5mm of stroke length this damper can generate 40N of force which is not tuneable with the different operating speed of the washing machine. Therefore, in the present work design of SMMD based on the above result is carried out and tested. Present work is also identifying the influence of volume % of particles on MR damper to enhance the performance of damper as well as effect of different test parameters on performance of damper is discussed in details. In next section theory related to SMMD is discussed and MR fluid properties followed by result and discussion.

![Figure 1: Force- displacement curve of friction damper at 1 Hz frequency and 5 mm displacement.](image)

2. Theory

Bingham model and parallel plate concept (Figure 2) are used to represent damping force [23-25],

\[ F = (\tau_s (B) \times L \times b) + (L \times b \times \mu \frac{v}{l}) \]  

(1)
Where $\tau_y(B)$ is shear stress of MR fluid at a given $B$, $\mu$ is viscosity of MR fluid, $v$ is velocity of moving plate, $t$ is the gap between the plates, $L$=length of plate, $b$= breadth of plate.

By using equation 1 design of SMMD is carried out. The design consists of electromagnetic coil and piston with outer casing (figure 3). In between piston and electromagnetic coil MR fluid is placed. Gap between these two components is MR fluid gap ($g$), which kept 1mm. In this configuration comparing with parallel plate thus, piston is acts as moving plate and velocity is represent as $v_p$ and electromagnetic coil acts at stationary plate. By substitute the width ($b$) with $2\pi D_p$ and length ($L$) with ‘$L_e$’. By considering this equation, 1 can be re-written as, so damping force.

$$F = (\tau_y(B) \times L_e \times \pi D_p) + (L_e \times \pi D_p \times \mu \frac{v_p}{g})$$

(2)

Where, $D_p$ is diameter of piston; First portion of the equation 2 shows the force is the depends on ‘$\tau_y$’ and it depends on ‘$B$’ (magnetic field). Second portion of equation 2 shows force is not a function of ‘$B$’. It is also known as $F_{\text{off-state}}$. Equation 2 also known as $F_{\text{on-state}}$.

From the above mention, equation 2 design of MR damper is carried out and optimized as per need of damping force 40N which is generated in presently available washing machine damper. The finalized dimensions are presented in Table 1.

| Parameter                  | Symbol | Dimension in mm |
|----------------------------|--------|-----------------|
| Outer diameter of cylinder | $D$    | 50              |
| Inner diameter of cylinder | $D_i$  | 40              |
| Effective length of piston |        | 36              |
| Diameter of piston         | $D_p$  | 5               |
| Outer pole length          | $W$    | 5               |

Figure 2: Parallel plate configuration.

Figure 3: Cross section view of SMMD.
For any kind of MR damper magnetic flux produce due to external current in MR fluid gap is very important. Therefore, Using ‘COMSOL Multiphysics’ software magnetic field simulation is carried out. For the simulation, the material used for the electromagnetic coil is having high magnetic permeability. The distribution of magnetic field (MF) is as shown in figure 4. Magnetic flux dissemination in MR fluid gap is represent with line graph at different current is as shown in figure 5. Figure 5 shows the distribution of MF along the MRF gap is nearly constant. Maximum flux is at piston and at outer cylinder, which is nearly 0.6T. The value of flux at MR fluid is 0.21T.

MR fluid properties use in this simulation is as shown in Figure 6. In this paper two different volume percentage, based MR fluid is used for the testing so behaviour of shear stress (yield stress) with different MF is as shown in Figure 6. Table 2 shows the different properties of MRF18 and MRF26. Based on the dimensions in table -1 SMMD is manufacture. All the parts and assembly of SMMD are as shown in Figure 7.

| Properties                          | Values     |
|-------------------------------------|------------|
| Maximum yield stress (kPa)          | 18±01      |
| viscosity (mPa.s) @ 40°C            | 68±01      |
| Volume percentage (%)               | 15         |
| Magnetic permeability, relative @low Field | 3.5     | 4     |
3. Results and Discussions

3.1 Testing of Damper

Testing of SMMD is performed using damper testing machine (AGMPL-15027) (figure 8). Sinusoidal excitation of fixed frequency and amplitude (stroke length of damper or displacement) is generated using the hydraulic drive. Load cell is measured the force. Linear displacement is sensed using LVDT. DC power supply is used for energizing the electromagnetic coil to produce the MF.

For testing MR fluid filled in damper is 1.5 ml. After that, the damper was set along the test rig and initially, three cycles were recorded. The average of the three cycles has been counted for final plot of force versus displacement curve.

3.2 Effect of Applied Current

First, MR damper tested at 0A current. In figure 9, black scatter point shows maximum force is 12N in rebound, and minimum is -11N in at $B=0$ (No current is supplied to the coil). This condition is considered as off-state condition where $B=0$ ($F_{\text{off-state}}$). This is only due to the friction between the piston and rubber oil seal. As the current increases MF in the MR fluid gap increases, which result in to rise in yield stress thus force rises. In the presence of MF, particles are magnetize and orient in the direction of MF. Which help to formulate the chain of particles, which generates the column like structure. In the presence of column like structure, fluid becomes semi-solid and provide resistance to motion of the piston. The strength of the columnar structure depends upon the MF strength. As current increases, the MF strength increases so the strength of columnar structure increases, which results in higher damping force. Damping force is 42N and -43N at 1A current for MRF18. For this test frequency of excitation is kept 1Hz.
Figure 10 shows the comparison between experimental data with theoretical model from equation 2 for 0A to 1A current. Good similarity observed between both data. It validates the theory. As current increases due to MR effect, force increases.

![Figure 10: Damping force -current with theoretical comparison for MRF18.](image)

### 3.3 Effect of Volume Percentage of Particles

MR damper performance is depended upon many parameters one of the parameters is the volume percentage of iron particles added in the carrier fluid. As the volume percentage increases the yield stress is higher, due to strength of the columnar structure is more; thus, damping force increases. To investigate this MR fluid with 22% volume is synthesised and the properties of this fluid is discussed in table -2. Volume of MRF18 is 15%. With higher volume percentage, MRF26 generates the higher damping force compare to the MRF 1 at same current.

The test result of MRF26 with same testing parameters is as shown in figure 11 and 12. MRF26 force is 53N and -52N at 1A current (Figure. 11). For this frequency of oscillation kept 1Hz. For both the fluid, force at no current is same. Figure 13 shows the deviation in force with current for MRF18 and MRF26. Polynomial equation from the test results is represented with equation 3 for MRF26 and equation 4 for MRF18.

\[ F_d = 20.98 \times (I)^2 + 17.30 \times (I) + 12.72 \]  

\[ F_d = 18.30 \times (I)^2 + 12.54 \times (I) + 11.67 \]

Where, \( I \) is current.

### 3.4 Effect of Different testing parameters

To investigate the effect of different testing parameters like stroke length (displacement) and frequency of sinusoidal excitation. Figure 14 shows the force at a fixed frequency of 1Hz and 1A current for different displacement.

![Figure 14: Damping force vs. Displacement and Current for MRF18 and MRF26.](image)
Figure 11: Force-displacement for SMMD for MRF26.

Figure 12: Damping force-current with theoretical comparison for MRF26.

Figure 13: Damping force-current for MRF18 and MRF26.

Change in damping force with displacement is very low so one can say SMMD damping force does not depend upon the displacement. Deviation in damping force for displacement of 5mm to 16mm is nearly ±2N, which is within the range of error bar of instrument. At 5mm displacement damping force is 50N for MRF26 and 42N MRF18 and at 16mm damping force is 53N and 43N for MRF26 and MRF18 respectively. In figure 14 linear fitted equation shows the maximum deviation in damping force with per millimetre of displacement for MRF18 is 0.17 (slope of the line) and for MRF26 is 0.13.

Another important testing parameter is frequency of excitation. To investigate this kept the current and displacement is fixed (1A and 10mm). Figure 15 shows the change in force at various frequency is linear. Change in damping force with frequency is also lower but slightly higher compared to displacement. This deviation is range from 50N to 54N from the range of 0.2Hz to 1Hz for MRF26 and 38N to 42N for MRF18. Deviation in damping force with frequency is ±3.5 for MRF18 and 2.5 for MRF26.

3.5 Effect of time
Use of flake shaped particles also influence on sedimentation rate. To investigate this test is performance with the damper at different time interval. For this MR damper is tested at 0A current and 1A current at fixed frequency of 1Hz and 10mm displacement for different three-time interval. First damper is filled with MR fluid and tested, which mention as 0hr test. Than retain, the damper in stable condition and same test is performed after 24hr and collect the force displacement plot. Same test is performed after 48 hr and 72hr.
Figure 14: Damping force -displacement at frequency of 1Hz and 1A current for MRF18 and MRF26.

Figure 15: Damping -frequency at 1A current and 5 mm stroke length for MRF18 and MRF26.

Figure 16: Damping force-displacement curve after a different time interval.

Figure 17: Damping force at different waiting period time at 0A and 1A current.

Figure 16 shows the variation in damping force of SMMD at 0hr, 24hrs, 48hrs, and 72hrs for 0A and 1A current. All the test results are almost similar. It shows better stability of MRF26 in damper application. Figure 17 shows the deviation of damping force at different time interval and it is nearly straight horizontal line; thus with time, the effect of settling of the particles is very less. Damping force remains unchanged at 0A and 1A current after different time interval.

4. Conclusions

In this work design of SMMD is carried out based on the MR fluids which is synthesised using different volume percentage of flaked shaped iron particles. For design of SMMD friction damper of front-loaded washing machine is considered as reference. Based on the optimized design, the damper is manufactured and tested on damper testing machine. Test result shows that with increases in applied current damping force of SMMD increases. Variation of damping force also depends on the volume percentage of particles and applied current. From the results, it can be concluded that using MRF18 in SMMD, on-state force is three times higher compare to off-state condition. Similarly, for MRF26 ratio of on state to off-sate force is nearly four time higher, which conclude that with higher volume percentage gives higher damping force due to higher yield stress. Stroke length and frequency effect on force is very small. From that, one can say for constant damping force at different stroke and frequency SMMD provides best solution. Flake shaped based fluid also shows the better stability in terms of damping performance at different time interval. Last, we can conclude that, SMMD fluid volume required for the damping is nearly 1.5ml. Which can reduce the cost of damper and design SMMD can be used in washing machine application.
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