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Synthesis and Characterization of Antifriction Magnetorheological Fluids for Brake

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ABSTRACT

Magnetorheological (MR) fluids are smart materials with shear strength ranging between zero to 100 kPa under the influence of magnetic field. The present paper discusses the synthesis of MR fluid and its application in brake. In MR brake, gap between stator and rotor is filled with low (off-state) viscosity MR fluid. On the application of magnetic field, MR fluid changes its state from liquid to semi-solid by aligning magnetic particles in chains. Due to such chaining action, yield strength of fluid increases, friction between stator and rotor increases and fulfils the braking function. The strength of magnetic particle is a function of relative speed between stator and rotor, applied magnetic field, and volume percentage of magnetic particle. In this study antifriction (off-state) and strong chain (on-state) CI based MR fluid has been prepared by mixing oleic acid as antifriction additives and tetramethylammonium hydroxide as surfactant to reduce the agglomeration of the MR fluid. Yield strengths of the synthesized MR fluid in on-state and off-state have been compared with commercially available MRF 241ES fluid. A flywheel based MR brake experimental setup has been developed to analyze the performance of designed and developed MR brake. Results show that synthesized MR fluid is stronger and faster in response compared to MRF 241ES fluid.

Keywords: Magnetorheological fluids, braking torque, synthesis of fluid

1. INTRODUCTION

Magnetorheological (MR) fluid consists of micron sized magnetically permeable particles dispersed throughout the non-magnetic fluid carrier. Iron powder, having high saturation magnetization, is the most popular material to be used as magnetic particles. Under the presence of the magnetic field, magnetic dipole moment within particles induces, causing dipole interactions to form chains in the direction of flux paths. The formed particle-chains restrict fluid movement and increase yield strength of MR fluid. Rotational movement of disk (shear mode) and axial movement of pad (compression mode[1]) affect the particle chains, and therefore the braking torque of MR disk brake.

MR materials have been prepared and studied by many researchers. Fang[2], *et al*. prepared MR fluid by ball-milling the *guar* gum powder together with silicone oil and carbonyl iron (CI) powder. By forming a coating layer over the ground CI powder, the *guar* gum improves the sedimentation stability and thixotropy of the MR fluid effectively. Wu[3], *et al*. presented CI powders coated with *guar* gum as magnetic particles in the MR fluid. Their experimental results showed that inducing a *guar* gum coating not only greatly improved the sedimentation stability but also strengthened the yield stress of the MR fluid. However, one of the major limitations of *guar* gum is excessive absorption of moisture and so increase in humidity leading to microbiological degradation. The shelf life of *guar* gum has been reported as 1-2 years[4].

To improve dispersion stability of the MR fluid, Choi[5], *et al.* encapsulated CI particles with poly methyl methacrylate (PMMA) as core–shell structured particles. Fang[6], *et al*. introduced single-walled carbon nanotube (SWNT) in the CI based MR fluid to resolve its sedimentation problem. Cao[7], *et al.* prepared Fe_3O_4/PMMA composite particles based MRFs exhibited better MR effect and sedimentary stability. Jiang[8], *et al.* prepared a type of dimorphic MR fluid by adding wire-like iron nanostructures into the conventional CI based MR fluid. They found that the Fe wires additives can greatly enhance the stress strength of the dimorphic MR fluids comparing with the conventional MR fluids.This feature has inspired the design of a large variety of power transmission devices based on the use of MR fluids, such as brakes and clutches[9,10]. In the present study, MR fluid has been synthesized to avoid agglomeration and for this purpose oleic acid and tetramethylammonium hydroxide surfactants are used.

Huang[11], *et al.* presented theoretical design of a cylindrical MRF brake assuming annular space between circumference of disk and electromagnet filled with MR fluid, and braking torque due to shearing of that MR fluid. Li and Du[12] experimentally investigated torque characteristics of designed disc MR brake operating at low speeds. Bydon[13] described the construction and operation of Lord's MR brake, which offers maximum 5.65 Nm torque at operating speed 1000 rpm. The brake was restricted to be operated within temperature ranging between -30 °C to 70 °C. Park[14], *et al.* presented a theoretical design

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of MRF brake required for automotive applications. Sukhwani and Hirani[15] designed a MRF brake for high rotational speed up to 2000 rpm. They considered the effect of MR gap on the performance of MR brake. Nguyen and Choi[16] considered minimization of zero-field friction heat in theoretical design of automotive magnetorheological brake to optimize the brake performance. In the present work, flywheel based MR brake experimental set up has been designed and developed. Experimental study on brake filled with synthesized MR fluid has been performed.

1.1 Synthesis

A typical MR fluid consists of CI particles (diameter 2-4 µm, purity 96 % and 80 % by wt), additives (approx. 1 % by wt) and base oil provides a yield stress of about 40-45 kPa under a magnetic field of 0.4 T[3]. In this research work MR fluid consisting of 19.5 % by wt silicone oil, 0.25 % by wt oleic acid, 0.25 % by wt tetramethylammonium hydroxide and 80 % by wt carbonyl iron powder (SIGMA ALDRICH 12310, 99 % purity and mean size of particle 150 µm) has been prepared by the method of mechanical mixing. To get high yield strength, large sized particles (0-150 µm compared to commonly used particle size 2-4 µm) have been employed. Generally larger size particle gives higher yield strength of MR fluid[17].

Shah[18], *et al.* has reported that larger sized particles provide 15 times higher yield stress compare to that of the small sized particles. Further it has been also reported that on mixing smaller and larger particles with different weight fractions, the Bingham yield stress value increases by a factor of three compared to that of the large sized particle dispersed fluid [18].

To synthesize MRF, following steps have been followed:

(a) CI particles (80% by wt) were mixed with oleic acid (0.25% by wt) for 30 minutes at 400 R.P.M in the stirrer.
(b) After that tetramethylammonium hydroxide (0.25% by wt) was poured and mixed for 30 minutes at 400 R.P.M in the same stirrer.
(c) Then servo medium e.g. silicone oil (19.5% by wt) was poured in small amounts gradually (4% by wt) after every 30 minutes and mixed for 3 hrs at 450 R.P.M in the same stirrer.

To check the MR effect synthesized MRF was kept in magnetic field by applying current in the coil, as shown in Fig. 1. A mild steel bolt was dipped into MR fluid mixture and then pulled back at a height of upper level of electromagnet core (AWG 25 and number of turns: 1000) to observe the agglomeration stability of MR fluids. Figure 1 shows the chain strength of synthesized MR fluid and MRF 241ES for the same magnetic fields (same wire, same size electromagnet, same number of turns and same value of D.C. current 1.32A). This initial observation indicates higher strength of synthesized MR fluid chain compared MRF 241ES chain (commercially available maximum strength MRF). Synthesized MR fluid does not agglomerate, which prove that oleic acid and tetramethylammonium hydroxide reduce the group formation of chain particles. Whereas water based MRF 241ES show inconsistent performance, which vary due to evaporation of water mixed in MRF241 ES.

Chain strength of the synthesized MR fluid has been measured by ANTON PAAR (MCR-52) Rheometer. Figure 2 shows the shear stress of the synthesized MR fluids at different magnetic flux densities.

(a) (b)

Figure 1. Chain structure of MR particles of (a) Strong particle chain of synthesized MR fluid and (b) Weak particle chain of MRF241ES.

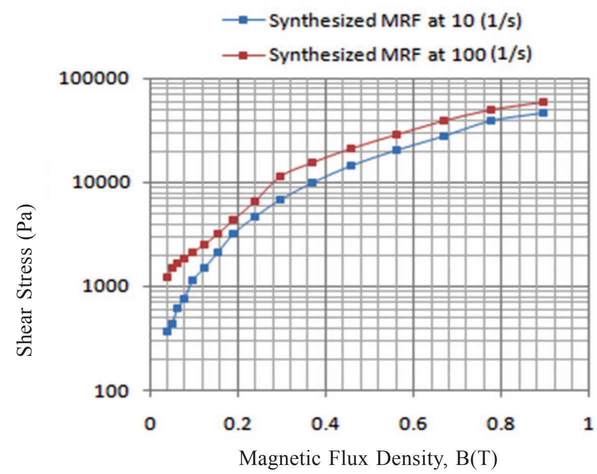
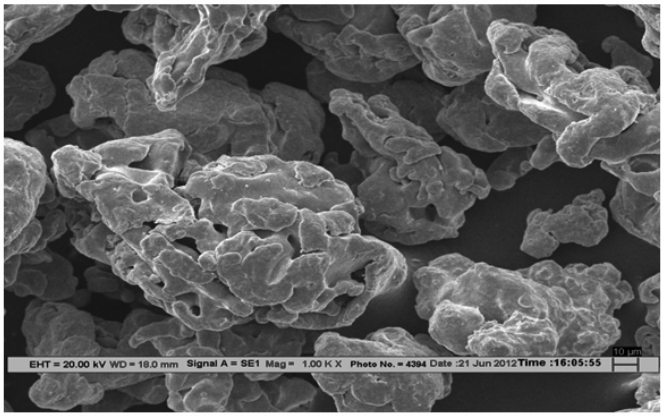


Figure 2. Shear Stress of synthesized MR fluid at various magnetic flux densities.

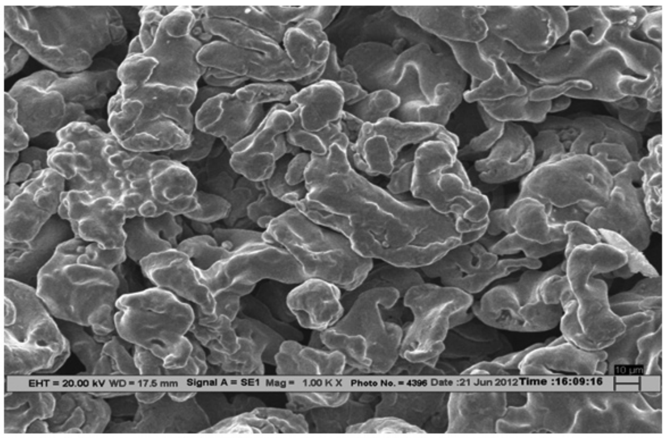
2. CHARACTERIZATION

2.1 Morphologies of Synthesized MR Fluid

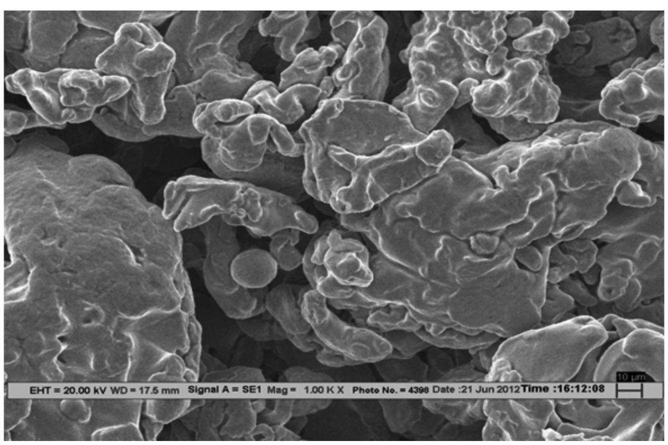
Figure 3 shows characteristic morphologies of pure CI (Fig 3(a)), CI-oleic acid particles (Fig. 3(b) and CI-oleic acid-tetramethylammonium hydroxide (Fig. 3(c). SIGMA-ALDRICH 12310 product has different sizes of iron particle. They are 5-25 % in the range of less than 45 µm, 65-85 % between 45 µm to 150 µm and 10 % between 150-212 % µm. Figure 3(a) also shows the various distribution of size of iron particles. Fig. 3b and Fig. 3c show the layer of oleic acid and tetramethylammonium hydroxide on the iron particles. The ratio of magnetic strength to cost for larger size particles is higher than that of smaller size particles, but the rate of sedimentation of the larger particles is on higher side. To get the benefit of the both particle sizes, mixed mode MR particles has been synthesized and characterized for brake applications.



(a)



(b)



(c)

Figure 3. SEM images of (a) pure CI particle, (b) CI-oleic acid particle and (c) CI-oleic acid-tetramethylammonium hydroxide particle.

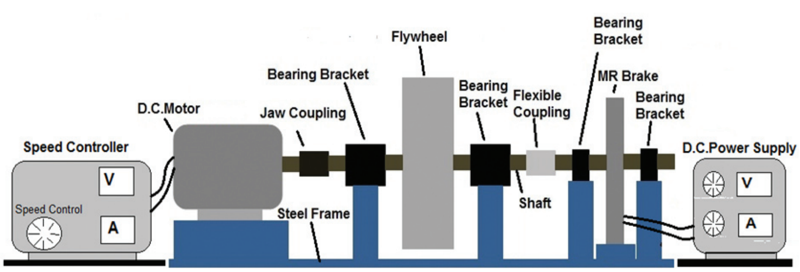


Figure 4. Schematic diagram of the MR brake setup.

2.2 Design and Development of Experimental Set Up

Sketch of the MR brake test set up is shown in Fig. 4. It consists of DC motor with speed controller. A flywheel is connected between the DC Motor and MR brake through bearing bracket, jaw coupling and flexible coupling. A DC power supply is used to apply the current to the electromagnet of MR brake.

Figure 5 shows the experimental setup of MR brake. DC motor (2 H.P and 1500 R.P.M) and DC power supply (30 V and 5A) are used in the test set up. The mass and inertia of the flywheel are 20 kg and 0.42 kgm^2, respectively. A toggle switch is used to control the motor ON/OFF and MR Brake ON/OFF. The experimental torque is conducted to explore the torque output of the prototype MR brake using synthesized MR fluid and MRF 241ES. The output torque is determined by dividing the power loss of the DC Motor with the angular speed of the shaft measured at different applied coil current. Stopping time of the brake (on-state and off-state) has been analyzed using the two different MR fluids at different speed.

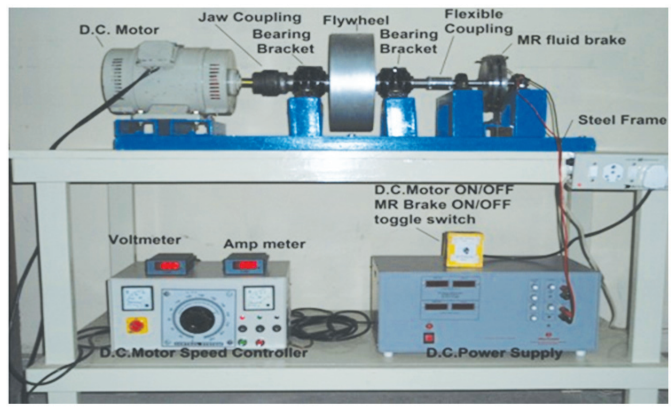


Figure 5. Experimental setup of MR brake.

The measurement procedure has been discussed in the following.

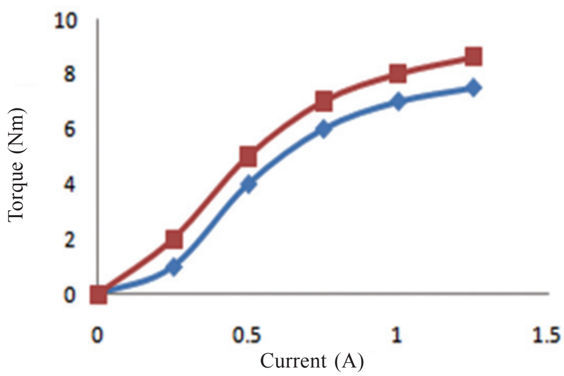
Step 1: Set the coil (of MR brake) current in DC power supply such as 0.5 A, 1 A and 1.5 A.
Step 2: Switch off the power supply.
Step 3: Run the DC motor at 1000 RPM.
Step 3: Turn off the DC motor by toggling switch in the middle position.
Step 4: Disk will stop within few seconds due to friction in the system. Measure this time using stopwatch.
Step 5: Run the DC motor once again at 1000 RPM.

Figure 6. Toggle switch.

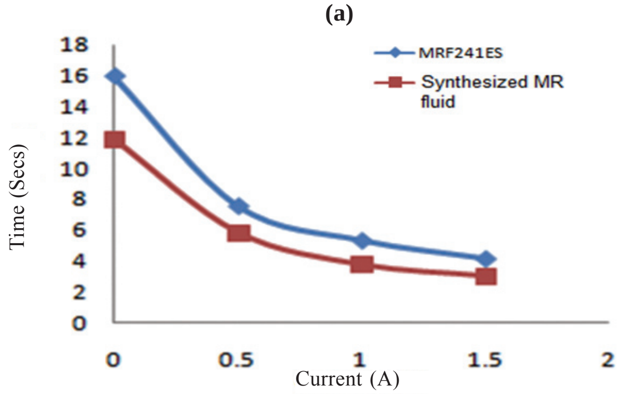
Step 6: Switch ON the MR brake by toggling switch towards the MR brake ON as shown in Fig. 6. This action will also turn off the DC motor. At this moment MR brake applies brake to the disk and disk stops within few second. Measure this time using the stopwatch.

3. RESULTS AND DISCUSSIONS

Figure 7 shows the braking torque of MR brake using two MRFs. It shows that the synthesized MR fluid has produced more braking torque as compared to MRF 241ES due to strong chain of synthesized MR fluid as discussed earlier. In stopping time analysis, rotor takes more time to stop due to inertia of flywheel when there is no braking action i.e. coils current is zero. As current increases less time required to stop the disk. Synthesized MR fluid takes lesser time compared to MRF 241ES which confirms the superiority of synthesized MR brake fluid.



(a)



(b)

Figure7. (a) Braking torque and (b) stopping time of MR brake using synthesized MR fluid and MRF 241ES.

4. CONCLUSIONS

The CI-based MR fluid prepared by mixing oleic acid and tetramethylammonium hydroxide as additives show superior performance. This synthesized MR fluid shows better chain strength and less agglomeration as compared to MRF 241ES fluid. The synthesized MR fluid gives 9 Nm torque and stops the motion of the disk in 11.85 sec (at zero coil current) and in 2.98 sec (at 1.5 A coil current). The flywheel inertia based MR brake setup can characterize MR fluids.

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