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Effect of Sedimentation on Torque Transmission in the Larger Radius Magnetorheological Clutch

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***Abstract*—**Sedimentation of magnetorheological (MR) fluid affects its working. MR fluid is a smart fluid that has unique qualities such as quick responsiveness and easy controllability. It is used in the MR damper, MR brake, and MR clutch. In this work effect of sedimentation on torque transmission in the shear mode operated MR clutch is investigated. A test rig is developed to test the impact of sedimentation on torque transmission in the MR clutch. Torque transmission capability of MR clutch has been measured under two conditions to confirm the result of sedimentation. The first experiment is done just after filling and the other after one week. It has been observed that transmission torque is decreased after sedimentation. Hence sedimentation affects the working of the MR clutch.

***Keywords*—**Clutch, magnetorheological fluid, sedimentation, torque.

I. Introduction

MR clutches are developed to replace conventional clutches and torque converters [1]. They are non-conventional clutches that use the MR fluid, a smart fluid with quick response, easy controllability, smooth operation, and reversible characteristics with applied magnetic field [2]. Clutches, brakes, and locking devices are examples of shear mode operation [3]-[6]. Researchers have studied and developed the MR fluid-based products, but some technical problems get the desired output. Some researchers used magnetic particles of different diameters (1.25 and 7.9 μm) to enhance the MR fluid's yield strength [7]. In literature [8], the MR fluid's field-dependent viscosity decreases at a higher shear rate. There are three essential constituents of MR fluids, i.e., magnetic particles, base fluid, and additive or surfactant. Magnetic particles of MR fluid form a chain-type structure when the external field is applied. The strength of MR fluid increases due to the formation of the magnetic particle chain. Hence MR fluid can change its phase from liquid to semi-solid and semi-solid to liquid reversibly. MR fluid's rheological property, such as yield strength and viscosity, varies with the applied magnetic field.

The sedimentation of the magnetic particles is some significant issue to use MR fluid. It is due to the high density of particles than the carrier medium. Hence redistribution of magnetic particles is necessary for the proper functioning of MR fluid. Sedimentation is a significant problem for the devices that use MR fluid for a long time, as in MR damper [9]. However, the attention on sedimentation over the working of MR fluid rotating devices is significantly less. Some research works are using MR fluid for the torque transmission [10], [17] in the shear mode MR clutch, but sedimentation is missing. MR fluid is kept between the two parallel discs oriented perpendicularly to the shaft axis. When a magnetic field is applied, a chain of magnetic particles is formed. Formed chains restrict the flow of fluid and develop a force that is responsible for torque transmission. Hence, it is vital to study MR fluid particles' sedimentation effect on the MR clutch's torque transmission. The novelty of this research work is to investigate the impact of sedimentation of MR fluid on torque transmission in the MR clutch. MR clutch is designed and fabricated to conduct the experiments. MR fluid, synthesized, characterized and compared with rheological characterization, shows higher strength with higher weight percentages of magnetic particles. The test-setup is developed to test the MR clutch action. Scanning electron microscopy (SEM) is used for particle shape and size analysis. After day one and after a week, the transmission torque change is presented in results and discussion.

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II. Design of MR Clutch

MR clutch has two basic designs: disc-shaped and cylindrical or bell-shaped clutches. In the disc-shaped clutch, the MR gap's orientation is perpendicular to the axis of the shaft. The MR gap's direction is parallel to the shaft axis in the cylindrical or bell-shaped clutch. In this research disc-shaped, MR clutch operated in shear mode is designed and developed to test the transmission torque. Fig. 1 shows the schematic of the proposed MR clutch. The components of the developed MR clutch are shafts (1) MR clutch disc (2) cover (3), core (4) and coil (5). MR fluid is filled in the 0.5 mm gap created between the two parallel plane discs whose radius is 50 mm. The electromagnetic core consists of copper wire (SWG 22) with 300 turns. The copper coil is connected to the DC power source. Two brackets have been designed to support the whole MR clutch assembly.

The MR clutch works when the magnetic field is applied; motion transfer occurs from the input shaft to the output shaft. It is due to chain formation by the MR fluid particles in the direction of the magnetic field. The external DC power source controls the input current. The characteristics of MR fluid can be explained by the Bingham rheology model [10].

$$\tau = \tau_0 + \eta\dot{\gamma} \tag{1}$$

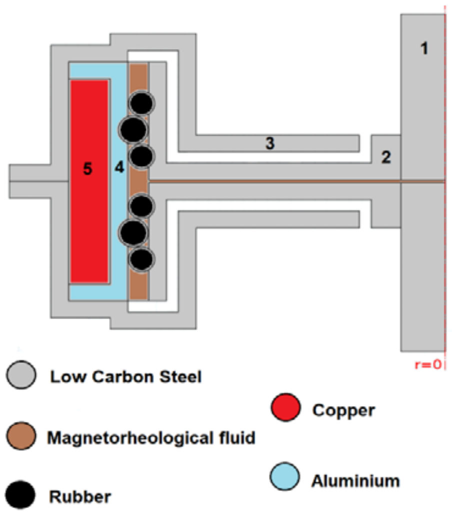


Fig. 1 2D axisymmetric schematic of the proposed MR clutch

MR fluid has three main components, i.e., magnetic particle, base fluid, and additives [11]. The magnetic particle is selected to achieve higher yield stress, good stability, and higher magnetic saturation. The particle shape and size of the magnetic particle play an essential role [12]. Magnetic particles of MR fluid are scattered when there is no magnetic field. These magnetic particles form a chain-like structure in the presence of the magnetic field. In this research, carbonyl iron is selected as magnetic particles. The base fluid provides fluidity in the MR fluid. Mainly silicone oil, mineral oil, and water are used as the carrier liquid. Additives are used in MR fluid to improve the property such as dispersion stability and sedimentation stability. Oleic acid, grease, and graphite flakes are used as an additive in MR fluid [13], [14]. The mechanical mixing method has been used to prepare the sample MR fluid. Table I shows the components of MR fluid, which are given below. Table II shows the percentage composition (% w/w) of elements used to prepare MR fluid samples. Carbonyl iron particles have been mixed with oleic acid for 30 min at 400 rpm by a mechanical stirrer. Then silicone oil has been added to the mixture and stirrer for the next 2 hours, and finally, MR fluid is prepared.

TABLE I
COMPONENT OF MR FLUID

No.	Components	Product no. (Sigma-Aldrich)	Specification
01	Carbonyl Iron	44890	5-9 µm grain size and density 7.86 g/ml
02	Silicone oil	50384	viscosity 150 mPa.s
03	Oleic acid	O1008	density of 0.89 g/ml

TABLE II
PERCENTAGE COMPOSITION (% W/W) OF MR FLUID COMPONENTS

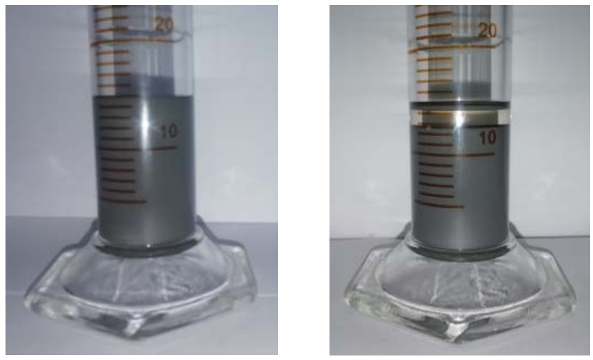
Sample	Carbonyl Iron	Silicone oil	Oleic acid
MRF 30	30	68.5	1.5
MRF 60	60	39	1
MRF 70	70	29.25	0.75
MRF 80	80	19.5	0.5

MR fluid sample has been used and filled in the test tube up to 15 mm height to study the sedimentation effect, as shown in Fig. 2. The sedimentation stability is calculated from the sedimentation ratio (S) as in (2) [13]:

$$S = \frac{x}{X} \times 100\% \tag{2}$$

X and x are the initial full length of MR fluid and the length after the MR fluid sedimentation correspondingly.

Fig. 2 shows the sedimentation rate of the MR fluid sample in which it started to sediment with time, and after a week, it gets stable.



(a) (b)

Fig. 2 Effect of sedimentation in MR fluid (a) after day one and (b) after a week

III. EXPERIMENTAL TEST RIG

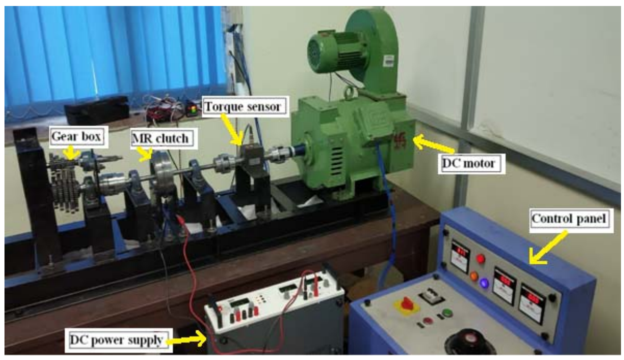


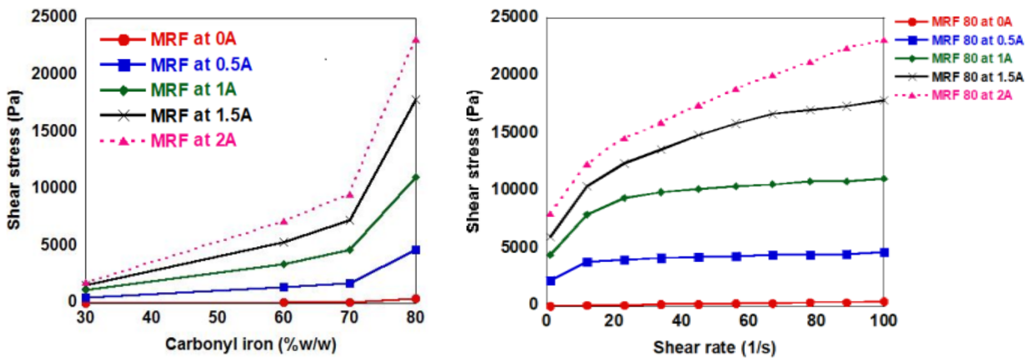
Fig. 3 Experimental test rig for testing the MR Clutch

An experimental test rig is developed to test the designed MR clutch with prepared MR fluid, as shown in Fig. 3. A DC motor (5 hp and 1500 RPM) with a speed controller is used as the prime mover. A DC-regulated power supply with the output voltage (0-440 V DC) and output current (0-10A DC) is assembled with a speed controller. A torque sensor is placed in between the DC Motor and fabricated MR clutch to measure the transmission torque. The bearing bracket and jaw coupling are used to support the assembly. Torque data are shown by the display, which is connected to the torque sensor. A gearbox (Gear ratio: primary -1.142:1) is associated with the output shaft by jaw coupling and bearing bracket. External DC power supply (30V and 2A) is used to supply current to the MR clutch's electromagnet. When the DC supply is OFF, no magnetic field is observed, and hence no torque transmission. The magnetic field is activated when DC supply is ON. The yield strength of MR fluid increases due to the magnetic field, and thus transmission of torque from the input disc to the output disc is started in the MR clutch.

IV. Results and Discussion

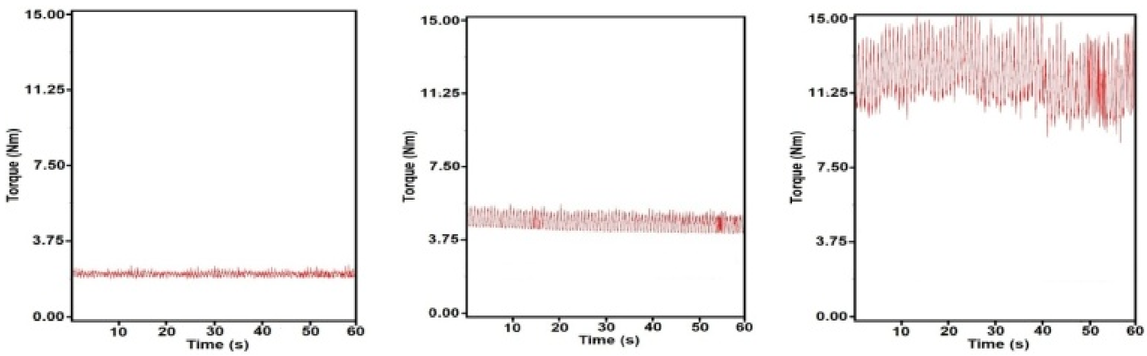
MCR 102 rheometer is used to characterize MR fluid at the shear rate 0-100 (1/s). To observe the effect of weight percentage of carbonyl iron on shear stress of different MR fluids a plot is presented in Fig. 4 (a). It shows the plot of shear stress with varying percentages of carbonyl iron weight used in prepared MR fluids at a fixed shear rate (100 1/s). It indicates that as the weight percentage of carbonyl iron increases, MR fluids' shear stress increases. This trend is the same for both kinds of MR fluids at different weight percentages of magnetic particles. Since MR fluid containing carbonyl iron with 80% w/w shows higher yield strength than other weight percentages (30% w/w, 60% w/w, and 70%, w/w) of carbonyl iron as shown in Fig. 4 (a); hence, carbonyl iron with 80% by w/w based MR fluid (MRF 80) is used in the torque transmission test. Fig. 4 (b) compares shear stress at the different shear rates for prepared MR fluids. Four different MR fluid samples have been tested at input current of 0, 0.5, 1, 1.5, 2 amperes (A). The value of yield stress increases with an increase in input current.

The experiments have been conducted to measure the transmission torque of fabricated MR clutch at 250, 750, and 1500 rpm using MRF 80 to confirm the shear stress results at low and high shear rates. The experimental torques has been shown at 0A, 1.0A, and 2.0A coil current in Fig. 5. The figure shows the transmitted torque results taken by MR fluid just after its preparation. While Fig. 6 shows the torque transmission test after seven days of the MR fluid kept inside the MR clutch. Both tests were taken over the same MR fluid held inside the MR clutch. It shows that transmittable torque increases as the current increases for MRF 80 for all rpm. When tested at day 1 of sample preparation, the maximum torque 15 Nm is found at 2A, while 1.9 Nm at 0A and 250 rpm. Fig. 6 shows that the maximum value of torque obtained is 11.25 Nm at 2A and 250 rpm after a week. It has been observed that at higher rpm, transmission torque has decreased. These results prove the shear thinning effect of MR fluid on transmission torque [15], [16]. The higher amount of transmitted torque is found at lower rpm in both cases. The experimental results of transmitted torque indicate the effect of sedimentation. It may be due to the erosion of magnetic particles that increase MR fluid's thickening and increase sedimentation rate [11].



(a) (b)

Fig. 4 Comparative results of carbonyl iron (%w/w) used with shear stress at a fixed shear rate (100 1/s) for (a) different MR fluid samples and (b) shear stress with the shear rate for MRF 80



(a1) (a2) (a3)

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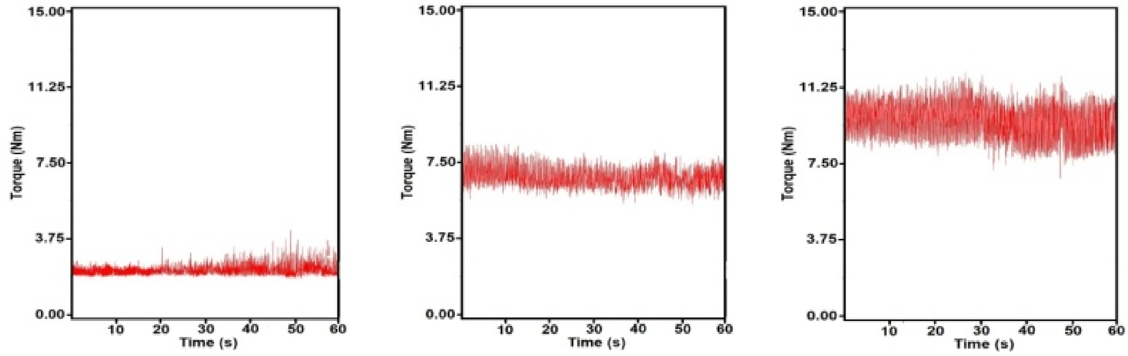
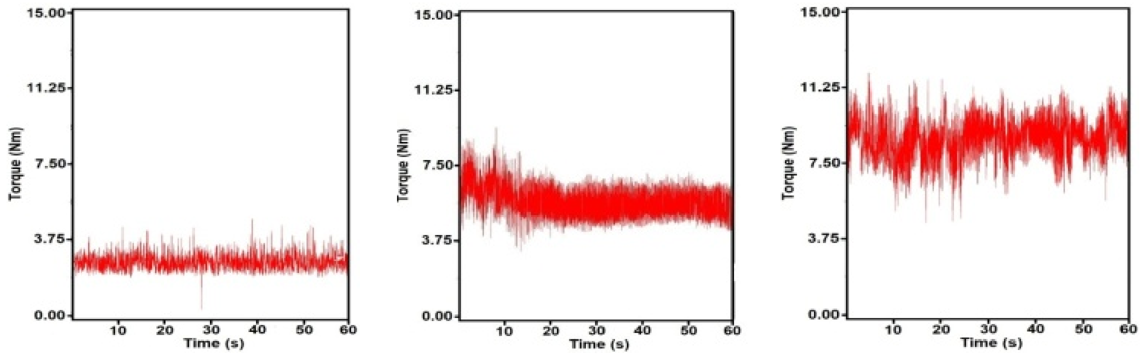
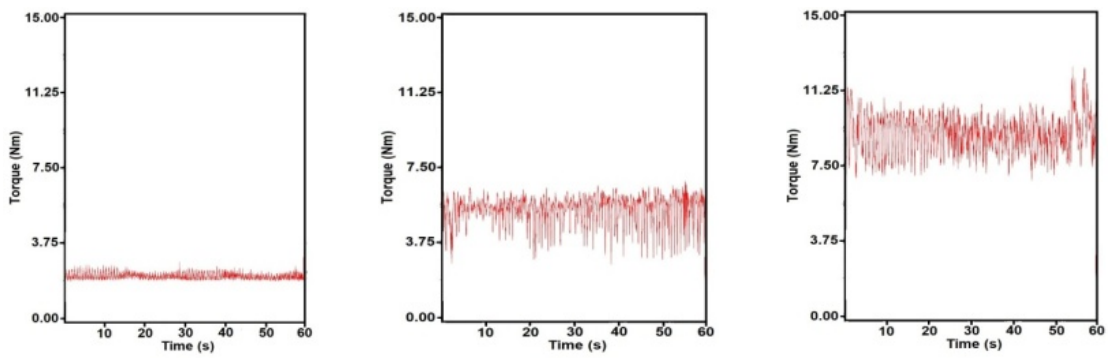


(b1) (b2) (b3)

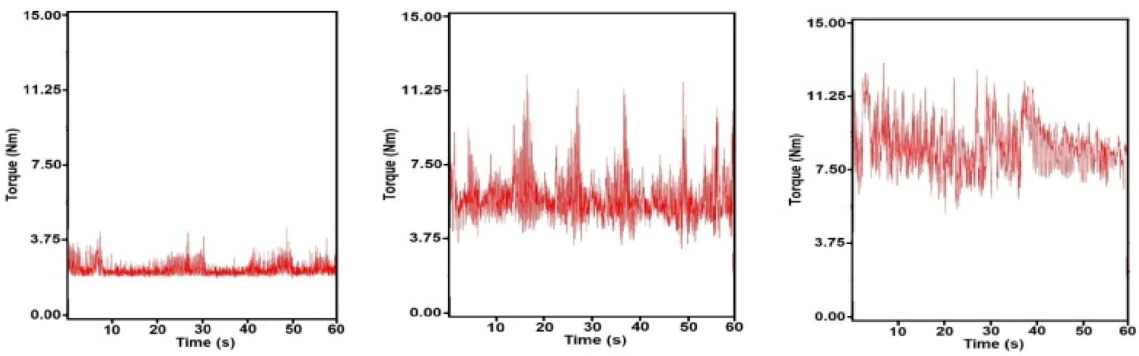


(c1) (c2) (c3)

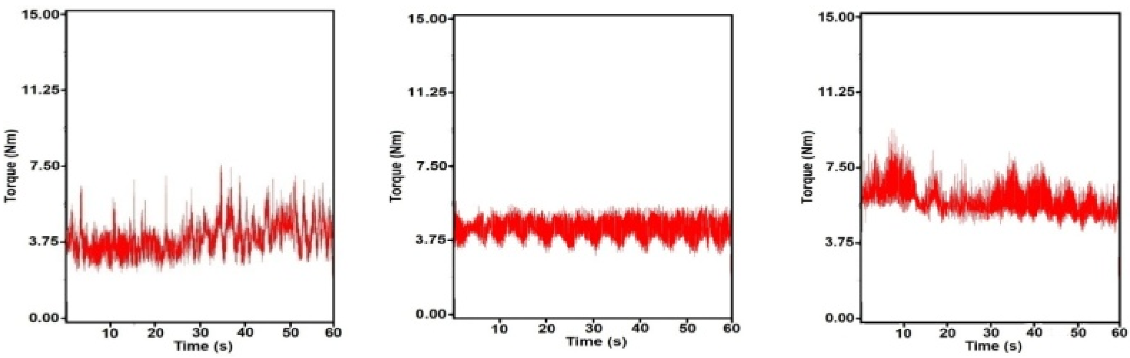
Fig. 5 Experimental torque (ET) plots of MR clutch at day one of MR fluid preparation at 250 RPM: (a1) 0A (a2) 1A and (a3) 2A; 750 RPM: (b1) 0A (b2) 1A and (b3) 2A; 1500 RPM: (c1) 0A (c2) 1A and (c3) 2A



(a1) (a2) (a3)



(b1) (b2) (b3)



(c1) (c2) (c3)

Fig. 6 Experimental torque (ET) plots of MR clutch after a week of MR fluid preparation at 250 RPM: (a1) 0A (a2) 1A and (a3) 2A; 750 RPM: (b1) 0A (b2) 1A and (b3) 2A; 1500 RPM: (c1) 0A (c2) 1A and (c3) 2A

V. CONCLUSION

In this research, MR fluid's sedimentation effect on the shear mode MR clutch's working efficiency is investigated. A test rig is developed to test the torque transmission in MR clutch. Rheological characterization shows that as the weight percentage of carbonyl iron increases, MR fluid's yield strength increases. The carbonyl iron with a weight percentage of 80 is selected to prepare MR fluid sample and test. The first test has been done on day one, and the second test has been done after a week. Experimental torque transmission result indicates that after a week, MR clutch's torque value decreases than day one. These results indicate the existence of sedimentation of MR fluid particles. It is also found that when sedimentation occurs, it reduces the working efficiency of MR clutch. This study helps us to improve the efficiency and durability of the shear mode MR clutch.

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