The response of excited magneto-rheological fluid along field direction

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Abstract. This paper describes an experimental study on the characteristics of an excited magneto-rheological fluid in the field direction using a self-developed two-plate rheometer. The effects of B-fields and shearing are investigated. The normal force can be built up by B-fields and further increased by imposing an additional shear action. The rate at which the normal force changes in response to an increasing B-field and shearing is quite rapid. In addition, the shear-enhanced normal force can be sustained even when the shear is stopped. An explanation based on chain rotation and slippage effects is proposed.

1. Introduction

Major studies on the characterization of magneto-rheological fluids (MRFs) have focused mainly on field-dependent shear responses in the direction perpendicular to that of the magnetic field. Engineering applications that utilize field-dependent rheological properties have evolved in the areas of active control damping [1], polishing/grinding processes [2, 3], flexible fixtures [4] and medical devices [5]. The response of MRF along the field direction (i.e., the normal direction) has recently attracted attention. De Vicente et al. [6] carried out studies on the normal force generated by an excited MR fluid with a commercial controlled-stress parallel-plate rheometer. The MRF tested had 50% volume fraction of carbonyl iron particles in silicone oil. The relative susceptibility and saturation magnetization of the particles were 131 and 1990 kA/m, respectively. They claimed that the normal force can only be generated where two criteria are satisfied: a) the B-field must exceed a critical value; and b) the MRF must be under shear strain. The normal force will increase with the shear strain up to a maximum value, then decrease with any further increase in the shear strain. Liu et al. [7] observed that the excited MRF did not rise until the B-field applied had been increased to around 13 mT. See and Tanner [8] reported that the normal force of MRF can be generated by a B-field even where there is no shear action. The home-made specimen MRF was a suspension of 80% by weight 4 to 6 µm carbonyl iron powder in a paraffin oil. Tests with gaps of 0.8, 0.9 and 1.0 mm were performed with a commercial controlled-strain rheometer. The effect of different gap sizes was reported not significant. The normal force increases with a magnetic field as B^2 and if a shear is imposed, the normal force will decrease. The normal force will continue to fall with an increase in the shear strain until it eventually settles at a steady value. The value at which it settles depends on the
magnitude of the shear rate and is lower at higher shear rates. These phenomena, whereby the normal force is increased by a B-field and reduced by a shear, are respectively attributed to stronger elongated aggregates and the breaking of MR particle chains under shear strain. Laun et al. [9] recently proposed that the relationship between the normal force and the B-field can be expressed as $F_N \propto B^{2.4}$, and found that the normal force can be increased with shear. Their tests were performed with constant shear rates and a fixed gap of 0.8 mm width using a commercial controlled-torque rheometer. The specimen MRF was a hydrocarbon-based suspension of 50% micron-sized magnetisable carbonyl iron particles. This paper presents the results of a recent study on the normal forces measured in excited MR fluids using a self-constructed rheometer. The first set of experiments was mainly aimed at analyzing the B-field effect; no shear was imposed. The other set of experiments was conducted under steady shearing conditions.

2. Experiments

2.1. Materials

The MR fluid tested, MRF-140CG from Lord Corp., mainly consisted of 3 components [10] that included micron-sized magnetizable particles, hydrocarbon-based oil and other additives, such as suspending agent, thixotropes, anti-wear and anti-corrosion additives, and friction modifiers. Its viscosity was 0.280±0.07 Pa-s and particle concentration was 85.44% by weight. The particle size was in the approximate range of 0.88 to 4.03 µm, as measured by SEM.

2.2. Test rig

A parallel-plate rheometer was constructed to measure the characteristics of the MR fluids, as shown in Fig. 1. Fig. 2 is a schematic diagram of the rheometer.

![Figure 1 Photograph of the self-constructed rheometer.](image1)

![Figure 2 Schematic diagram of the self-constructed rheometer.](image2)

The setup included five major parts: a fixture for the MRF, a mechanical input, an electromagnetic circuit, a compression load cell and a data acquisition system. The fixture for the MRF consisted of two parallel plates. The shear rates specified in this paper were calculated on the basis of the radius of the plate, 20.5 mm. The lower plate was attached to a linear motor that adjusted the size of the gap between the two plates. There was also a laser sensor used to monitor the movement of the lower plate and ensure a gap of a constant width during tests. Shear actions were exerted by a D.C. servo motor with a 7700 gear head attached to the shaft of the upper plate. An optical encoder was used to measure the speed of the motor. An electromagnetic circuit with 3,700 turns of coil providing about 4 mT to 1 T was designed using ANSYS and a magnetization curve of MRF-140CG. The radius of the magnetic
poles was 20 mm. This was smaller than the plates for 1 mm in diameter used to facilitate an evenly distributed field inside the MR fluid. A gaussmeter was used to measure the B-field. Because the gaussmeter probe inserted directly into the MR fluid could not be used to measure the real B-field inside the MR fluid [9], it was inserted into the gap between the upper pole and the upper plate. A calibration was carried out before the experiments were conducted. The values of B-fields at a position measured by the gaussmeter and calculated using ANSYS, respectively, were quite close. The ANSYS results showed that the B-field inside the MR fluid was about 35% higher than the value measured at the aforementioned position. Hence, the B-fields specified in this paper are the adjusted values from the measurements. Fig. 3 shows a typical FEA result, illustrating the difference between the B-fields in the air gap and the MR fluid. The spatial homogeneity of the magnetic field across the MR fluid is also shown in this figure. A compression load cell was fixed underneath the shaft of the lower plate to measure the normal force of the excited MRF. The major measurements, i.e., the normal force, were calibrated with standard weights before the experiments were carried out. The calibrated results are shown in Fig. 4. Signals from both the load cell and the incremental encoder of the motor were captured by two Agilent 34970A data acquisition units and recorded in a computer for subsequent analyses.

Figure 3 FEA results showing the difference between the B-fields in the air gap and the MR fluid, and the spatial homogeneity of the field across the MRF.

Figure 4 Calibration of normal force measurements using standard weights.

2.3. Measuring procedures
Two sets of experiments were performed to study the responses of the MRF along the field direction. One set of experiments was carried out with a steadily rotating upper plate to impose shear on the specimen fluid and the other set of experiments was conducted without shear. The specimen MR fluid contained in its original bottle was shaken vigorously and de-gassed in a vacuum before use. A controlled volume of MR fluid was injected onto the lower plate using a clean syringe. The lower plate was then elevated to form a gap of 1 mm between the plates, which was monitored by the laser sensor.
Pre-shearing produced by rotating the upper plate with 2.2 s\(^{-1}\) was applied to the MR fluid for 10 minutes to ensure good dispersion. To start with, the readings for the load cell under zero field and zero shear strain conditions were recorded for the first 3 mins. The desired field was then applied and the normal force data were captured from the load cell with a sampling rate of 10 Hz for 27 mins. The captured data were then averaged and compared with the B-fields. The experiment was carried on without turning off the B-fields for the shear test. The normal force was first recorded for 3 mins. A shear rate of 0.1 s\(^{-1}\) was subsequently imposed for 22 mins. The motor was then turned off, i.e., there was no shear, and the normal force was again recorded for another 5 mins. After the experiments, the MR fluid was demagnetized by applying an inverse impulse B-field. The experiment was repeated for other B-fields of 270, 405, 540, 675 and 810 mT.

3. Results and Discussion

3.1. Normal force of excited MR fluid

Figure 5 depicts the changes in the normal force as the B-field was increased. The trend is similar to the results of See et al. [8]. The particles aggregated due to the field effect and formed a columnar structure, pushing the two plates apart. The laser sensor showed that there was an increase of about 20 \(\mu\)m in the size of the gap under 600 mT. The normal force attained in low magnetic fields, i.e., < 200 mT, was not quite stable and repeatable. However, under relatively high fields, i.e., > 300mT, the normal force results were quite stable. This indicates that the internal structure under low B-fields is non-deterministic. Normal force measurement data can be fitted by the power law \(\sigma_{\text{normal}} \propto B^{2.245}\). See et al. [8] and Laun et al. [9] also modeled their results using power-law curves with respective exponents of 2.6 and 2.4. The theoretical model developed by Shkel et al. [11] has an exponent of 2. This significant increase in the normal force of excited MRF without shearing is genuine. However, de Vicente et al. [6] reported that the normal force of excited MRF without shearing is too small to be measured. The different conclusions reached in these two studies may be due to the differing field strengths and MR fluids used.

3.2. Response of the normal force with steady shear

The normal responses of MRF under different B-fields and a constant shear rate of 0.1 s\(^{-1}\) are shown in Fig. 6. For the initial 180 s, the specimen MRF was under a constant B-field only, with no shear. Once shear was applied at the 180\(^{\text{th}}\) second, the normal force increased rapidly by about 100%. This phenomenon is similar to that reported by de Vicente et al. [6]. Nevertheless, it does not accord with the results reported by See and Tanner [8], in which the normal force declined only under shearing action. Figure 6 shows that the normal force was roughly constant throughout the shearing period. While the shear was stopped at the 1,500\(^{\text{th}}\) second, the normal force remained constant. Laun et al. [9] have recently reported similar results in which although there was a significant increase in the normal force under shear strain, the normal force dropped once the shear was stopped. De Vicente [6] used an analogue of a theory developed for ER fluids by Martin and Anderson [12] to explain the increase in the normal force of excited MRF due to shear. When a particle chain is tilted and forms an angle, \(\theta\), with the field direction, a resisting torque is generated. The torque is a function of \(\sin(2\theta)\). When the aggregates/chains of the excited MRF are tilted, magnetic torques are generated to resist the further increase in the shear strain. As a result, this leads to an upward force. For large shear strain values, i.e., large tilted angles (2\(\theta\) > \(\pi/2\)), the increased normal force will drop. However, as shown in Fig. 6, the increased normal force remained almost constant in our experiment. This can be explained by the occurrence of slippage at the interface between the plate and the MR fluid. Hence, when the shear was applied solely by rotating the top plate, the MR particle chains became slightly deformed and experienced a resisting torque that led to an increase in the normal force. As the shear action continued, the tilted angles of the chains increased with the shear strain. Once the slippage occurred, the tilted angles became constant and there was no further increase in the normal force. The normal force remained unchanged even with a further increase in the shear strain. All the tests were under a
constant shear rate of 0.1 s$^{-1}$. Based on the typical values of the relevant parameters including the magnetic flux density (1T), the magnetic field inside the MRF ($H_o=1$ A/m), the viscosity (0.28 Pa-s), $\mu_r (4\pi\times10^{-7}$ Vs/Am), $\mu_{oil}$ (1), the Mason number [13] was calculated to be much less than unity which thus shows that the structure of the MRF remained intact. During the last 5 mins. of the experiment, the shear was stopped. The normal force still remained unchanged because the MRF structure had not changed. The normal force vanished only when the B-field was turned off, i.e., the MRF structure relaxed.

Figure 5 Normal force of the excited MRF fitted with power law curves.
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\sigma = 6E-05B^{2.982} \\
\sigma = 8E-06B^{2.245}
\]

Figure 6 Constant shear rate of 0.1 s$^{-1}$ applied at 180 s. Shear was stopped for the last 5 mins. (large signs)

4. Conclusion
The phenomenon whereby the normal force of an MRF is increased using B-fields is confirmed with a power law having an exponent of about 2. The normal force can be increased further by imposing shear actions on the excited MRF. The amount of the increase due to shear is quite significant. In the experiments carried out, a 100% increase was recorded under a shear rate of 0.1 s$^{-1}$. The shear-enhanced normal force can be sustained even when the shear is stopped. Hitherto, no firm conclusions can be drawn to explain the different results produced in similar studies. More comprehensive studies should be carried out to elucidate the mechanism.

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