Magnetorheological measurements with consideration for the internal magnetic field in samples

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Abstract. The magnetically induced yield stress in a sample of suspension of magnetic particles is associated with formation of a field-oriented structure, the strength of which depends on the degree of particles magnetization. This factor is largely defined by the actual magnetic field strength in the sample. At the same time it is common practice to present and analyze magnetorheological characteristics as a function of the applied magnetic field. Uncertainty of an influence function in magnetorheology hampers interpretation of data obtained with different measurement configurations. It was shown in this paper that rheological response of magnetorheological fluid to the applied magnetic field is defined by the sample’s actual (internal) magnetic field intensity, which, in turn, depends on sample geometry and field orientation all other factors being equal. Utilization of the sample’s actual field as an influence function in magnetorheology allows proper interpretation of data obtained with different measuring system configurations. Optimization of the actual internal field is a promising approach in designing of energy efficient magnetorheological devices.

1. Introduction

The magnetorheological effect constitutes a change in rheological properties of a suspension of magnetic particles, also known as a magnetorheological (MR) fluid, upon the application of a magnetic field and is commonly associated with the magnetically induced fluid yield stress. The yield stress appears due to the magnetization of particles followed by their magnetic dipole-dipole interaction and formation of a field oriented structure. In shear flow such a magnetized fluid exhibits elevated effective viscosities as well as normal stresses.

Historically, these rheological characteristics are measured, presented and analyzed as a function of applied magnetic flux density \(B\) or applied magnetic field strength \((H=\frac{B}{\mu_0})\), where \(\mu_0\) is permeability the vacuum [1,2]. At the same time, an effective magnetization of particles and therefore the magnitude of measured rheological parameters are defined by the actual magnetic field intensity in the sample. In general, the internal magnetic field intensity \((H_i)\) in the sample is commonly presented as follows:

\[
H_i = H - DM
\]  \(1\)

where \(H\) is the applied magnetic field intensity, \(D\) is a demagnetization factor and \(M\) is material magnetization.
The demagnetization factor is introduced to account for the magnetic field created by the material magnetization and directed opposite to the applied field. The magnitude of the demagnetization factor depends on sample geometry (aspect ratio) as well as the field and the sample mutual orientation. For example, it may change from 0 to 1 when a high aspect ratio magnetic plate is oriented along or perpendicular to the magnetic field. Taking into account the relatively high MR fluid magnetization, the influence of the demagnetization factor on a sample’s internal magnetic field intensity and consequently on rheological response of magnetorheological fluid to the applied magnetic field can be significant. As it is shown in this presentation, utilization of the internal magnetic field intensity in samples as an influence function in magnetorheology allows one to avoid misinterpretation of rheological data and provides basis for generalization of data obtained with different measurement configurations. Optimization of the actual internal field can also be a promising approach in designing of energy efficient magnetorheological devices.

2. Problem configuration

A configuration with shear flow oriented normal to a magnetic field is utilized in most MR fluid applications as well as in magnetorheological measurements. Usually, the sheared layer is thin, has relatively high aspect ratio and the field-shear orientation is realized in two ways as depicted in figure 1. The configuration $B_z$ is characteristic to such application as magnetorheological finishing (MRF®) [3] and the configuration $B_y$ is widely used in magnetically controlled clutches, dampeners, etc [4]. It is reasonable to expect that MR fluid magnetization as well as rheological response on applied magnetic field for configurations $B_z$ and $B_y$ will differ due to effect of the demagnetization factor on the actual (internal) field in the sample. A comparative study of these two cases was performed both numerically and experimentally.

![Figure 1. Shear flow and magnetic field mutual orientations.](image1)

![Figure 2. Schematics of configurations for magnetic modeling and rheological measurements.](image2)

By virtue of the fact that adequate instrumental measurements of the magnetic field intensity inside the very thin samples (thickness of 0.2 mm) are unrealizable, the internal field was computed using finite
element analysis (FEA). As discussed below, the 3D magnetic modelling and the sample’s internal field intensity calculations were performed in strict compliance with the design of experimental hardware and the sample geometry used in rheological measurements. The experimental hardware constituted two rotational rheometers schematically depicted in figure 2, where the schematic a) renders the configuration \( B_z \), and the schematic b) renders the configuration \( B_y \) as shown in figure 1. Black areas in figure 2 represent samples of MR fluid and arrows show magnetic field orientation.

MR fluid relative magnetic permeability required for simulation was derived from measurements of the initial magnetic susceptibility of the fluid. The measurements were conducted with a Bartington MS2B magnetic susceptibility system. An assumption was made that the susceptibility remains constant for the initial part of the magnetization curve that is in the range of relatively low magnetic field intensities where modeling was performed. All computations and rheological measurements were conducted for the relative magnetic permeability of 2.8, which corresponds to the silicon oil-based MR fluid with 45 vol. % concentration of ~3.5 micron in size carbonyl iron particles (BASF).

3. Magnetic field modelling
A commercial software MagNet developed by Infolytica was used for simulations of magnetic field in the magneto-rheometer magnetic gap formed by pole pieces of electromagnet. First and foremost the results of magnetic modelling were verified with measurements of magnetic flux density in the empty gap using the Hall probe. A reasonable agreement between computed and experimental data was obtained.

Figure 3a shows an exemplary working space (solid 3D model) corresponding to the configuration \( B_y \) with high demagnetization factor of the sample. In this case MR fluid sample is defined in the form of thin disk (aspect ratio of 100) placed between electromagnet poles in such a way that its plane is normal to the magnetic field. An example of a computed map of magnetic field intensity distribution in the electromagnet’s gap containing a sample of MR fluid is shown in figure 3b.

![Figure 3a](image1)

*Figure 3a. Working space and a map of field intensity distribution for the configuration \( B_y \).*

It can be seen that the field strength (blue color) in the sample of MR fluid is significantly lower than the strength of applied field (light green color). In this particular case the field intensity was \( \sim 50 \) kA/m and \( \sim 120 \) kA/m respectively. In the case of configuration \( B_z \) (the model is not shown here) the sample in the form of a thin ring was placed in a radial tangential fringing magnetic field (see fig. 2a).
Some numerical results of calculations of the sample’s internal field intensity along with applied field intensity (in legend defined as air) for configurations $B_y$ and $B_z$ are presented in figure 4.

![Figure 4. Results of calculations of the intensity of magnetic field in the gap for the configurations $B_y$ and $B_z$.](image)

In the case of configuration $B_z$, with low demagnetization factor, the field intensity inside the sample is practically equal to the intensity of surrounding (applied) field for the whole range of applied magnetic flux densities. At the same time, the intensity of the sample internal field for configuration $B_y$, all factors being equal, is much lower than intensity of applied field.

2. Rheological measurements

Rheological measurements were performed with a commercial Anton Paar magnetorheometer Physica MCR 301. A standard plate-plate configuration with rotor diameter of 20 mm and working gap height of 0.2 mm was used to analyze the configuration $B_z$, as schematically shown in Fig 2b. To render case $B_y$, an attachment in the form of a magnetic unit with a radial fringing magnetic field and ring-plate geometry was used (see figure 2a). In both cases the Hall probe was arranged in the vicinity of the sample in order to monitor the applied magnetic flux density. A special anti-slip coating was applied to the working surfaces to provide not unreasonable and repeatable results. A proper calibration of units with standard Newtonian fluid provided unambiguous measurements. Yield stress measurements were conducted both in constant shear stress and constant shear rate regimes.

Results of the yield stress measurements shown in figure 5 demonstrate that the magnitude of yield stress in case $B_z$ significantly exceeds the yield stress for configuration $B_y$ at the same applied magnetic flux density. This experimental result is in a qualitative agreement with results of field modeling discussed above and supports the assumption that MR fluid yield stress is defined by the strength of the internal magnetic field in the sample. By this means, it is safe to say that MR fluid rheological response to applied magnetic field depends not only on applied field intensity and fluid magnetic properties but also on distinctive features of the actual conditions at which sample is magnetized. The use of the intensity of internal field in the sample as an influence function in magnetorheology allows obtaining unambiguous presentation of data derived from different measurement configurations. As it is shown in figure 6, all yield stress measurements for both $B_y$ and $B_z$ configurations are reasonably well rationalized when the internal field of the sample is used as the influence function. Alternatively, taking into account that the magnetization of a typical MR fluid saturates at the field intensity of $\sim 240$ kA/m [5], one would expect that optimization of the internal magnetic field in MR fluid, that is conditions at which MR fluid is magnetized in different magnetorheological devices or processes, may result in improvement of applications performance and efficiency.
3. Summary
Numerical modeling of magnetic field in the air gap containing a sample of MR fluid was performed for two configurations of magneto-rheometers, which design differed markedly in the geometry of the sample and the shear-field orientation. Results of modeling show that the actual magnetic field intensity in the sample depends among other factors on sample geometry and sample orientation with respect to the magnetic field. Since the strength of field induced structure in MR fluid depends on the internal field intensity, rheological measurements demonstrate expected dependence of the yield stress on magneto-rheometer configuration at all other conditions being equal. Utilization of the actual field in the sample as an influence function in magnetorheology allows generalization of data obtained with different measuring system configurations as well as their proper interpretation. Optimization of the internal magnetic field may result in design of energy efficient devices and processes based on the use of MR fluids.

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