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Nondimensional scaling of magnetorheological rotary shear mode devices using the Mason number

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ABSTRACT

Magnetorheological fluids (MRFs) exhibit rapidly adjustable viscosity in the presence of a magnetic field, and are increasingly used in adaptive shock absorbers for high speed impacts, corresponding to high fluid shear rates. However, the MRF properties are typically measured at very low ($\dot{\gamma} < 1000\ \text{s}^{-1}$) shear rates due to limited commercial rheometer capabilities. A custom high shear rate ($\dot{\gamma} > 10{,}000\ \text{s}^{-1}$) Searle cell magnetorheometer, along with a full scale rotary-vane magnetorheological energy absorber ($\dot{\gamma} > 25{,}000\ \text{s}^{-1}$) are employed to analyze MRF property scaling across shear rates using a nondimensional Mason number to generate an MRF master curve. Incorporating a Reynolds temperature correction factor, data from both experiments is shown to collapse to a single master curve, supporting the use of Mason number to correlate low- and high-shear rate characterization data.

1. Introduction

Magnetorheological energy absorbers (MREAs) have been successfully implemented in semiactive crashworthy systems to protect occupants against impact, shock and blastloads, especially to protect the lumbar region of the human spine [1–3]. Shear rates in these MREAs typically range up to 25,000 s^{-1} or higher. However, data from low shear rate (up to 1000 s^{-1}) characterization tests are typically extrapolated up to these high shear rates because of the dearth of high shear rate data. Both MR yield stress and fluid viscosity have been shown to vary with temperature [4,5]. Furthermore, MRFs are highly shear thinning materials, so they exhibit a significant reduction in viscosity as shear rate increases [6]. For these reasons, a wide variety of fluid characterization tests, which vary temperature, shear rate, and applied magnetic field are currently required to adequately determine the performance of a given MR fluid utilized in certain devices and environments, and consequently, predictive models such as the Herschel–Bulkley (HB) constitutive model typically employed to characterize measured rheological behavior must rely on a huge data set of characterization tests to be useful across the entire range of expected operating conditions. It is desireable therefore to reduce the overall amount of data required for determination of the MR fluid behavior, while maintaining the ability to accurately predict any off-nominal change in performance.

The objective of this study is to use a nondimensional Mason number incorporating temperature dependent parameters to scale fluid performance data between a custom Searle-type magnetorheometer, capable of high quality test measurements at shear rates up to 10,000 s^{-1}, and a practical shear mode rotary vane magnetorheological energy absorber (RVMREA), which operates at shear rates over 25,000 s^{-1}, to assess the performance of a commercially available magnetorheological fluid (LORD Corporation MRF-140CG) over this range of shear rates. Thus, a limited set of test data is shown to provide enough information for the critical design of RVMREAs operating over this shear rate range (0–25,000 s^{-1}).

1.1. Magnetorheological fluid

A magnetorheological fluid (MRF) consists of magnetizable particles suspended in a nonmagnetizable carrier fluid. Commercially available MRFs use carbonyl iron spheres on the order of 1–10μm in diameter as the magnetizable particles, either a silicon- or hydrocarbon-based oil as the carrier fluid, and various additives to improve stability and settling rate.

In the absence of an applied magnetic field, the particles are randomly dispersed and will move with the fluid as it flows. When exposed to a magnetic field, the particles form chains parallel to the magnetic field lines and the MRF "solidifies." These two

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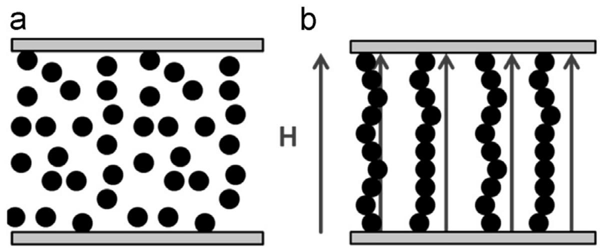

Fig. 1. States of magnetorheological fluid: (a) in the absence of field, the particles flow freely, (b) particles form chains that resist flow in the presence of magnetic field.

conditions of MRF, called "passive" and "active" respectively, can be seen in Fig. 1. The particle chains resist fluid motion until a certain yield stress is reached, beyond which fluid motion will occur, called post-yield flow [7].

In practical MRF devices, the magnetic field is produced by a controllable electromagnet. In this way the applied magnetic field, and thus the yield stress, can be continuously and instantaneously adjusted (response time < 15 ms), so that an appropriate amount of energy can be dissipated within the MREA. A well-developed MRF used in production devices will have a yield stress from 30 to 100 kPa at magnetic saturation.

1.2. Mason number and apparent viscosity

Classic work by Mason and colleagues showed that a nondimensionalized ratio of dominating physical forces described particle behavior in shear and electric fields, and influenced following researchers to use a similar ratio [8]. This dimensionless group came to be known as the Mason number. A minimized expression for a Mason number is shown below as the ratio of hydrodynamic force to polarization force.

$$Mn \equiv \frac{F^H}{F_0} = \frac{\text{hydrodynamic}}{\text{polarization}} \tag{1}$$

Building on this framework, a Mason number for MRFs was developed based on the fluid shear rate and suspension magnetization [9]. Because the magnetization, M, is a nonlinear function of magnetic field strength within each particle, an appropriate polarization force term was a function of particle magnetization [10].

While the research by Klingenberg et al. [9] applied the same expression as for the hydrodynamic force as the original work, given as

$$F^H = 6\pi\eta_c a^2\dot{\gamma} \tag{2}$$

where η_c is the carrier fluid viscosity, a is the particle radius, and $\dot{\gamma}$ is the shear strain rate, they calculate the polarization force term as a modified point-dipole which accounts for nonlinearities in particle magnetization, M_p. Realizing that the magnetic moment is related to the average magnetization of a single spherical particle, m, by

$$m = \frac{\pi}{6}\sigma^3 M_p \tag{3}$$

where σ is the particle diameter, and that the bulk suspension magnetization, $\langle M\rangle$ is related to the particle magnetization by the solids loading fraction, ϕ, given by the equation

$$M_p = \frac{1}{\phi}\langle M\rangle \tag{4}$$

Klingenberg et al. [9] derive the magnetic polarization force to be the expression shown below:

$$F_0 = \frac{\pi}{48}\frac{\mu_0\sigma^2\langle M\rangle^2}{\phi^2} \tag{5}$$

where μ_0 is the permeability of free space, $4\pi \times 10^{-7}$[V s/A m].

An expression for Mason number in an MRF is given as

$$Mn(\dot{\gamma}, M) = \frac{9}{2}\frac{\eta_c\phi^2}{\mu_0\mu_c}\frac{\dot{\gamma}}{\langle M\rangle^2} \tag{6}$$

where μ_c is the carrier fluid permeability. The Mason number given by Eq. (6) reduces the abscissa of the experimental characterization plots to a nondimensional expression, but in order to achieve the data collapse to a master curve it is helpful to also nondimensionalize the ordinate. An accepted way to do this is to use apparent viscosity, the ratio of total shear stress by shear rate, and normalize this value by the high shear rate viscosity in the absence of applied field, as shown in the following equation:

$$\hat{\eta} = \eta_{app}/\eta_\infty \tag{7}$$

When experimental measurements of MR fluid apparent viscosity are plotted versus Mason number, the curves for various shear rates and magnetic field strengths collapse to a single function. Originally validated using low shear rate ($\dot{\gamma} < 1000\ \text{s}^{-1}$) measurements, it was later shown to hold true in high shear rate operation [6] in carefully controlled laboratory experiments. It is proposed here that this nondimensional analysis can be effectively extended to model practical MREA devices under real-world conditions.

The experimentally measured variables are the shear rate, $\dot{\gamma}$, torque, M, and suspension magnetization, $\langle M\rangle$, and using this nondimensional group allows for disparate experimental data to be modeled as a single curve, greatly expanding the useable information about MR fluid behavior over a wide range of operating conditions.

It is worth mentioning that there are a number of other Mason numbers modified to account for surface friction and flow channel topography [11], suspensions of magnetizable particles in nonconducting media versus nonconducting particles in ferromagnetic media [12], and particle sizes in inverse ferrofluids [13]. Another study points out that there is an inconsistency in the choice of the characteristic particle dimension in Klingenberg's Mason number, specifically the use of particle radius, a, in the hydrodynamic force term of Eq. (2) and particle diameter, σ, in the magnetostatic force term of Eq. (3). The adjusted Mason number, Mn^*, would therefore be $Mn^* = 32{\cdot}Mn$ [14]. This definition of Mason number is used for the remainder of this study.

The rotary vane MREA is designed as a crash protection device, so it is expected to operate at high shear rates ($\dot{\gamma} \geq 25,000\ \text{s}^{-1}$), approximately $25\times$ greater than can be achieved on commercial rheometers. We replace dynamic viscosity with the apparent viscosity, η_{app}, defined as the instantaneous ratio of the shear stress to the shear rate, and write the two term Bingham plastic model as shown below:

$$\eta_{app} = \frac{\tau_y}{\dot{\gamma}} + \mu \tag{8}$$

This requirement of using normalized apparent viscosity is because an MRF with a higher solids loading will be stronger due to a higher available yield stress, but the off state viscosity will also be larger. Therefore, a direct comparison across solids loading can be achieved by such a normalization. By relating the bulk suspension magnetization to the polarizing force through volume fraction in Eqs. (3) and (4), the Mason number implicitly accounts