Scientific Journal of Impact Factor(SJIF): 3.134
e-ISSN(O): 2348-4470
p-ISSN(P): 2348-6406

International Journal of Advance Engineering and Research Development

Volume 1,Issue 12, December -2014

PROPERTIES AND APPLICATION OF COMMERCIAL MAGNETORHEOLOGICAL FLUID – A REVIEW

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Abstract — *Magneto rheological fluids have been investigated to be of much importance due to their magnetic field dependent properties. The rheological and magnetic properties of several commercial magneto rheological (MR) fluids are presented and discussed. These fluids are compared using appropriate figures of merit based on conventional design paradigms. Some contemporary applications of MR fluids are discussed. The emphasis has been laid on studying applications of MR fluids that can be incorporated in mechanical systems as such MR brakes and MR dampers. These applications illustrate how various material properties may be balanced to provide optimal performance.*

***Keywords**- Magneto rheological fluids, MR fluid properties, MR fluid dampers, MR fluid brakes.*

I. INTRODUCTION

Magneto rheological fluids have been investigated to be of much importance due to their magnetic field dependent properties. The magnetorheological response of MR fluids results from the polarization induced in the suspended particles by application of an external field. The interaction between the resulting induced dipoles causes the particles to form columnar structures, parallel to the applied field. These chain-like structures restrict the motion of the fluid, thereby increasing the viscous characteristics of the suspension. Thus the behavior of controllable fluids is often represented as a Bingham plastic having a variable yield strength (e.g., Phillips, 1996). In this model, the flow is governed by Bingham's equations:

$$\tau = \tau y\ (H) + \eta\ \gamma\&, \tau \geq \tau y \qquad (1)$$

at stresses τ above the field dependent yield stress τy. Below the yield stress (at strains of order 10-3), the material behaves viscoelastically:

$$\tau = G\,\gamma\ , \tau < \tau y \qquad (2)$$

where G is the complex material modulus. It has been observed in the literature that the complex modulus is also field dependent (Weiss, Carlson and Nixon, 1994; Nakano, Yamamoto and Jolly, 1997). Perhaps the most significant of these departures involves the non-Newtonian behavior of MR fluids in the absence of a magnetic field (Kormann, Laun and Klett, 1994).

II. PROPERTIES OF COMMERCIAL MR FLUID

Magnetic, rheological, tribological and settling properties of four commercial MR fluids are discussed. The basic composition of these four fluids is given in Table 1.

Commercial mr fluid	% iron by volume	Carrier fluid	Density (gm/l)
MRX-126PD	26	Hydrocarbon oil	2.66
MRX-140ND	40	Hydrocarbon oil	3.64
MRX-242AS	42	water	3.88
MRX-336AG	36	Silicon oil	3.47

2.1 Magnetic properties

Understanding the magnetic properties of MR fluids is important for designing MR fluid-based devices.In many such devices, the MR fluid represents the largest magnetic reluctance within the magnetic circuit. These magnetic properties may also prove useful in providing insight into the character and formation of particle structures within the fluid.

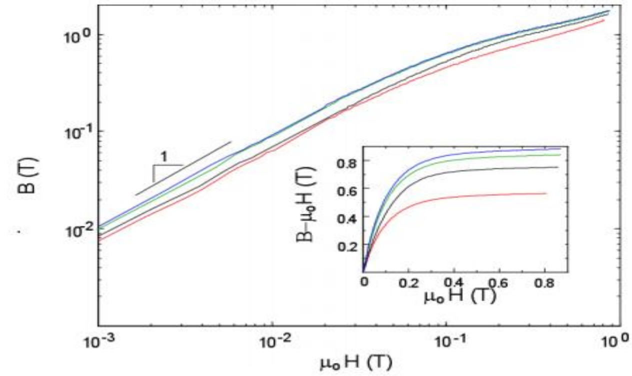


Figure1. Flux density within MR fluids as a function of applied field Inset: Intrinsic induction as a function of applied field. Ascending order of the plots corresponds to increasing iron volume fraction.

Magnetic induction curves, or B-H curves, of the four commercial MR fluids are shown in Figure 4. As can be seen, the MR fluids exhibit approximately linear magnetic properties up to an applied field of about 0.02/µo A/m, where µo =4πe -7 T-m/A is the permeability of a vacuum. In this region, the differential permeability (the slope of B(H)) of the MR fluids is relatively constant. These permeabilities vary between 5 and 9 times that of a vacuum. The magnetic properties of MR fluids vary significantly from the properties of most bulk ferromagnetic properties in that ferromagnetic induction can typically be linearized over a much broader range of applied field and the corresponding permeabilities are several orders of magnitude greater. MR fluids begin to exhibit gradual magnetic saturation beyond the linear regime. Complete saturation typically occurs at fields beyond 0.4/µo A/m. The intrinsic induction or polarization density (B-µo H) of an MR fluid at complete saturation is φJs Tesla, where φ is the volume percent of particles in the fluid and Js is the saturation polarization of the particulate material (Jolly, Carlson and Muñoz, 1996). For example, a fluid containing 30% iron (Js=2.1 Tesla) saturates at about (0.3)(2.1)=0.63 Tesla. Little or no hysteresis can be observed in the induction curves. This superparamagnetic behavior is a consequence of the magnetically soft properties of the iron used as particulate material in these fluids and the mobility of this particulate phase.

2.2 Rheological properties

The rheological properties of controllable fluids depend on concentration and density of particles, particle size and shape distribution, properties of the carrier fluid, additional additives, applied field, temperature, and other factors. The interdependency of all these factors is very complex, yet is important in establishing methodologies to optimize the performance of these fluids for particular applications. The magnetorheological effect of the four MR fluids was measured on a custom rheometer using a 46 mm diameter parallel plate geometry set at a 1 mm gap. In the parallel plate geometry, shear rate varies linearly across the fluid sample with the maximum shear rate occurring at the outer radius. The rheometer is capable of applying greater than 1 Tesla through the fluid sample. Figure 2 shows the shear stress in the MR fluids as a function of flux density at a maximum shear rate of 26 s-1. At such a low shear rate, this shear stress data is approximately equivalent to the fluid yield stress as defined in Eq. (1). At low flux densities, the fluid stress can be seen to exhibit a power law behavior. The approximate power law index of 1.75 lies in the range of low to intermediate field behavior predicted by contemporary models of magnetorheology. Both linear models and models accounting for nonlinear magnetic effects such as particle saturation (Ginder, Davis and Elie, 1995; Jolly, Carlson and Muñoz, 1996) predict quadratic behavior at very low flux densities. The non-linear model proposed by Ginder, Davis and Elie (1995) predicts a power law index of 1.5 at intermediate fields. Beyond flux densities of about 0.2-0.3 Tesla, the effects of magnetic saturation are revealed as a departure from power law behavior. The stress response ultimately plateaus as the MR fluids approach complete magnetic saturation. As can be seen, the flux density at which this saturation occurs increases as the iron volume fraction in the fluid increases. Figure 2 shows the shear stress in the MR fluids as a function of flux density at a maximum shear rate of 26 s^{-1}.

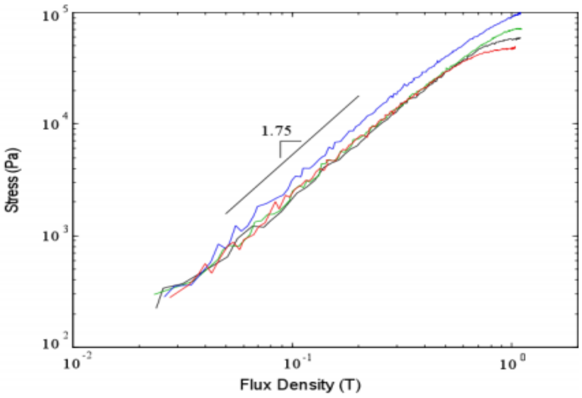
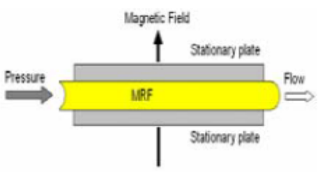
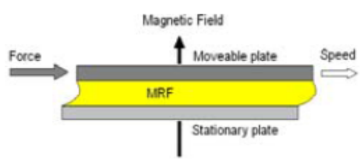
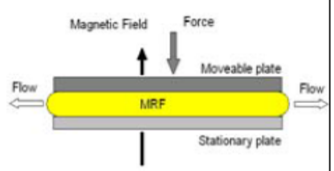


Figure 2. Fluid shear stress as a function of magnetic flux density at a maximum shear rate of 26 s-1.

III. OPERATIONAL MODES OF MR FLUID

Table 2, MRF operational modes

Operational mode	Valve mode	Shear mode	Squeeze mode
Functional principle			

The modes of operation for MR fluid devices are flow mode (fixed plate mode, valve mode), shear mode (clutch mode), squeeze mode (compression mode) and any combination of these three. Diagrams of the three basic modes of operation are shown in Fig. 1. In the flow mode, MR fluid is made to flow between static plates by a pressure drop, and the flow resistance can be controlled by the magnetic field which runs normal to the flow direction. Examples of the flow mode include servo- valves, dampers, shock absorbers and actuators. In the shear mode, the MR fluid is located between surfaces moving (sliding or rotating) in relation to each other with the magnetic field flowing perpendicularly to the direction of motion of these shear surfaces. In the squeeze mode, the distance between the parallel pole plates changes, which causes a squeeze flow. In this mode relatively high forces can be achieved; this mode is especially suitable for the damping of vibrations with low amplitudes (up to a few milli metres) and high dynamic forces. The squeeze mode has been used in some small-amplitude vibration dampers.

IV. MR FLUID DEVICES

4.1 Brakes and clutches

MR fluid-based brakes and clutches generally work in the shear mode but may also work in the flow mode. The MR fluid rotary brake made by Lord Corp. is a controllable rotary resistance element that is compact, smooth acting and low power consuming. An MR fluid brake that has been used for cycling and stair-climber types of aerobic exercise machine is shown in Fig. 9. The brake is 92 mm in diameter and provides a maximum dissipative torque of 7 N m for speeds of up to 1000 r/min. The maximum mechanical energy dissipated is 700 W, while the maximum required electrical power supply is 10 W (0.8 A at 12 V) . They are used in conjunction with velocity feedback where the torque is controlled in real time such that the user is forced to maintain a desired target speed proŽ le. Their simplicity and ease of control make them a very cost-effective choice for a wide variety of applications ranging from controllable exercise equipment to precision active tension control.

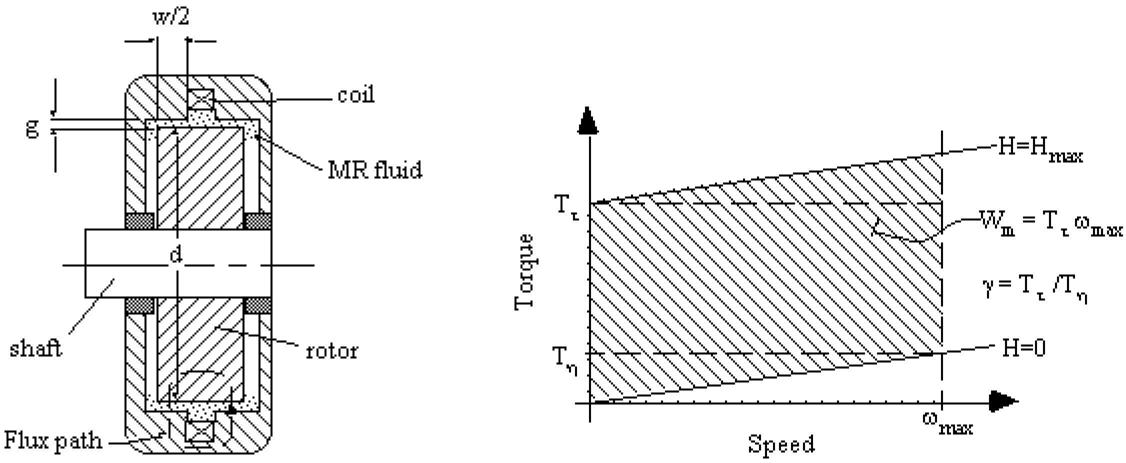


FIGURE 3.- MR fluid rotary brake

4.2 MR dampers

MR fluid dampers are characterized by large damping force, low power consumption, etc. and may be used in various vibration control systems. A small MR fluid vibration damper made by Lord Corp. is a type of damper working in the squeeze mode that is being used for real-time, active control of damping in numerous industrial applications. This damper may also be used as a locking device. The damper functions by moving a small steel disc or bafle in a chamber of MR fluid. Primary controlled motion is axial although secondary lateral and flexing motions may also be accommodated. Damping forces of 0–200 N are produced in the primary direction. The maximum stroke is §3 mm, and the response time is less than 10 ms. The Rheonetic linear damper shown below is designed for use as a secondary suspension element in on- and off-highway vehicles . This application is a damping control unit and is one of the first applications of MRF in the automotive industry. A magnetic coil integrated into the piston of the damper generates a magnetic field and this magnetic field regulates the MRF flow resistance within the damper.

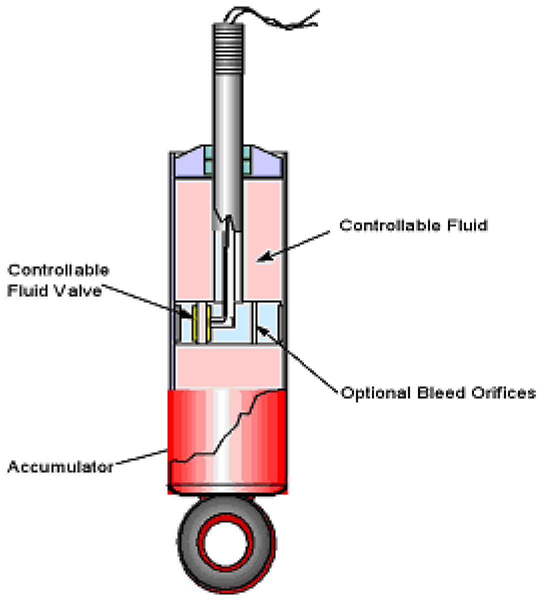


FIGURE.4- Functional principle of MRF damper

4.3 Polishing material

The key to MRF is a ribbon of abrasive-doped magnetic fluid that moves over a wheel and into contact with the surface of a spindle-mounted, rotating part. The fluid stiffens by four orders of magnitude in the contact zone, due to the presence of a magnetic field, turning from the consistency of honey to that of clay. Shear stresses between polishing abrasives in the fluid and the part surface cause material removal. The removal mechanism in MRF is unlike any other, and it results in a pit-free and scratch-free surface with high resistance to laser-induced damage.

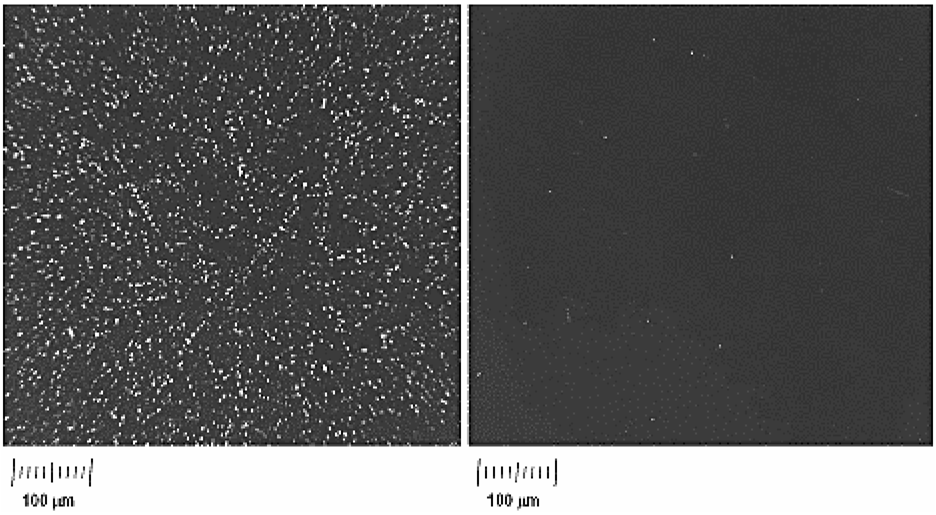


FIGURE.5-Dark field microscopy for acid-etched fused silica surfaces. A collaboration among Lawrence Livermore National Laboratory, Zygo Corp., and QED Technologies found that clean surfaces resulting from MRF are critical to enhanced UV laser damage resistance.

V. SUMMARY AND CONCLUSION

This paper presents the current status of MR devices and their applications in mechanical engineering. The key for MR fluid technology is to prepare high-performance MR fluids and to design for MR fluid devices in structures. There are some problems that should be noted when applying MR fluid devices in mechanical engineering. The first problem encountered when applying MR fluid devices is the settling stability of MR fluids. The heavy particles in an MR fluid are easy to settle down without suitable additives. However, high-performance commer- cial MR fluids, such as the MR fluids made by Lord Corp. have very little particle/carrier fluid separation under common flow conditions.

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