Magnetorheology: Applications and Challenges

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What do shock absorbers, artificial joints, and earthquakes have in common? Magnetorheological (MR) fluids. MR fluids are an example of field-controllable materials, whose rheological properties can be dramatically altered by applying large magnetic fields (Ginder, 1996). Apparent suspension viscosities can be increased by several orders of magnitude for applied magnetic flux densities on the order of 1 Tesla (e.g., on the order of the field near a completely magnetized piece of iron). Their flow behavior is typically described as that of a classical Bingham fluid—a material with a yield stress that does not flow unless the applied stress exceeds the yield stress. For MR fluids, the yield stress is an increasing function of the applied field strength. Reported initially by Rabinow (1948), these materials have finally begun to see successful commercial applications, such as in shock absorbers and artificial joints (Table 1). Other applications, including earthquake dampers, are likely to appear in the near future.

Table 1: Current and Potential Applications of MR Fluids.

Application	Reference
Current Applications:	
Automotive clutch	Sakai (1988)
Brakes for exercise equipment	Carlson and Sproston (2000)
Polishing fluids	Kordonsky and Golini (2000)
Seat dampers	Carlson and Sproston (2000)
Prosthetic knee damper	Carlson and Sproston (2000)
Actuator systems	Lewis (1999)
	Carlson and Sproston (2000)
Shock absorbers	Corbett (2000)
Potential Applications:	
Engine mounts	Hartsock et al. (1991)
	Ginder (1996)
Earthquake damper	Dyke et al. (1996)
Automotive clutches	Hartsock et al. (1991)
	Ginder (1996)
MR Elastomer dampers	Ginder (1996)
	Davis (1999)

The effect of an applied magnetic field on the steady-shear rheological properties of an MR fluid is illustrated in Figure 1, where the apparent fluid viscosity is plotted as a function of shear rate for different magnetic field strengths. With no applied field, the fluid is essentially Newtonian with a shear rate-independent viscosity. When an external magnetic field is applied, the viscosity at small shear rates increases; the larger the field strength, the larger the viscosity. The same data are replotted in the inset of Figure 1 as shear stress as a function of shear rate, illustrating the Bingham-like response with a field strength-dependent yield stress (i.e., a nonzero shear stress as the shear rate approaches zero).

MR fluids are composed of magnetizable particles (e.g., iron particles), typically on the order of 1–10 μm in diameter, dispersed in a liquid. The dramatic change in rheological behavior when the field is applied is tied to an equally dramatic change in the suspension microstructure (Figure 2). Upon the application of the field, the particles magnetize with their north and south poles oriented with the field. The particles then attract one another, north pole to south pole, forming fibrous aggregates aligned with the applied magnetic field. The field-induced rheological changes arise because of the extra work required to disrupt these aggregates. The structure formation process is quite rapid—forming on the order of milliseconds for concentrated suspensions—and reversible—the structure rapidly disappears under flow when the field is removed. The rheological changes, intimately tied to the structural changes, are also very rapid.

These materials are distinct from ferrofluids (Rosensweig, 1982, 1997) that are composed of much smaller magnetic particles (diameters on the order 1–10 nm). Because the particles are so small, Brownian motion disrupts the formation of large, fibrous structures, resulting in only very small changes in the viscosity when an external magnetic field is applied. MR fluids, however, are quite similar to electrorheological (ER) fluids (Gast and Zukoski, 1989; Jordan and Shaw, 1989; Halsey, 1992; Parthasarathy and Klingenberg, 1996). These materials, composed of polarizable particles dispersed in nonconducting liquids, show a dramatic increase in viscosity when external electric fields are applied, along with the formation of fibrous aggregates. To date, MR fluids appear in commercial applications while ER fluids do not, primarily because of the superior field-induced rheological properties of MR fluids, and the poor long-time stability of ER fluids.

Applications

The ability to electronically control the rheological properties of MR fluids (with an electromagnet) has numerous applications (Hartsock et al., 1991; Ginder, 1996; Carlson and Sproston, 2000). Many applications exploit this phenomenon in either damping or torque transfer scenarios. Proposed applications range from shock absorbers and other damping devices, to clutches, brakes, actuators and artificial joints. Some of these applications are now commercial (Table 1). Advantages of MR devices over conventional

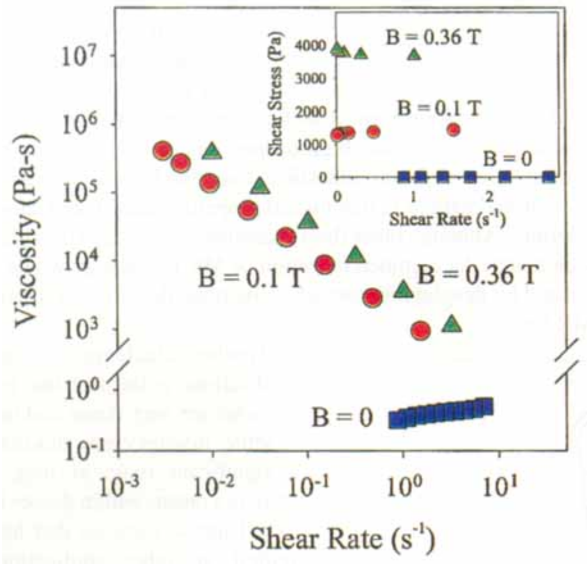

Figure 1. Apparent viscosity as a function of shear rate for an MR fluid composed of carbonyl iron particles (50 μm dia) in silicone oil (10 vol %) for different applied magnetic field strengths (Rankin et al., 1999; Rankin, 2000).
Inset: shear stress as a function of shear rate.

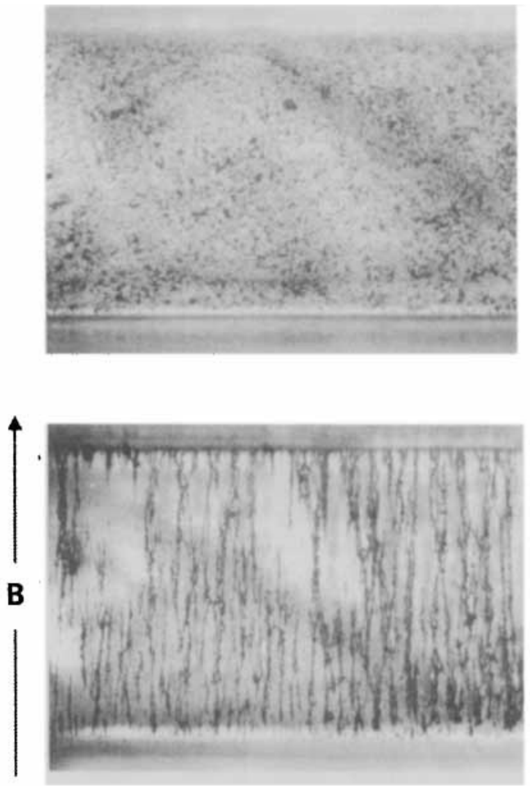

Figure 2. MR suspensions (2 vol. %, 50 μm dia. iron particles in silicone oil) before and after applying a magnetic field.

approaches include faster responses, improved performance, simplicity of design, and, in some cases, reduced cost.

MR shock absorbers and other dampers operate as follows: In a conventional fluid-filled damper, a piston translates through a cylinder as a result of the motion or vibration is to be damped. The piston forces fluid through one or more channels; the viscous dissipation of this flow dissipates the energy of vibration. In an MR shock absorber, the viscosity of the fluid can be varied by applying a magnetic field so that the damping characteristics of the design can be altered. Using feedback control, the magnetic field can be continually adjusted to provide optimum damping.

The Lord Corporation (Cary, NC) has developed a commercial seat damper for the cabs of large trucks (Carlson and Sproston, 2000). The damper reduces the vibration experienced by the driver, thus reducing driver discomfort and fatigue. Carrera (Atlanta, GA) has developed cockpit-controlled MR shock absorbers for race cars. With these systems, the driver can adjust the damping without having to physically replace shock absorbers. Delphi Automotive Systems (Troy, MI) has developed a semiactive MR shock absorber system (Corbett, 2000). This system improves not only the ride of an automobile, but handling and overall vehicle control, in part because it can be integrated with the automobile's ABS system. These shock absorber systems are slated to appear on the Cadillac Seville in 2002.

MR damping devices can also be exploited in automotive and industrial engine mounts. Again, the rationale is to exploit the electronic control capabilities of the MR fluid properties to semiactively damp vibrations. Although such devices have been proposed, there are as yet no commercial applications.

There are numerous applications of MR dampers outside of the automotive industry. Large dampers may be utilized to reduce motion in such structures as buildings and bridges, for example, to damp vibration caused by earthquakes or wind (Dyke et al., 1996). The Lord Corp. has also recently commercialized an MR damper for a prosthetic knee, where the damper, sensors, control unit, and battery are all housed within the knee itself (Figure 3). The damper plays an important role in producing a smooth, natural gate (Carlson and Sproston, 2000).

Another class of MR applications exploits the torque transfer capabilities of these materials when placed between concentric cylinders or parallel disks. Such a geometry can be used in MR clutches and brakes (Ginder, 1996). Consider concentric cylinders with the space between them filled with an MR fluid. When one of the cylinders rotates with no magnetic field applied, little torque is transmitted to the second cylinder. However, when a field is applied to the fluid to make it much more viscous, a considerable fraction of the torque applied to the first cylinder can be transmitted to the second. In some cases, a sufficiently large field can cause the fluid to effectively solidify, making the second cylinder rotate with the same angular speed as the first.

One of the earliest commercial applications of this technology was the magnetic powder clutch utilized in Subaru's Electro Continuously Variable Transmission (Sakai, 1988). The Lord Corp. has also produced rotary MR brakes as resistance elements in exercise equipment (Carlson and Sproston, 2000). One can also imagine numerous automotive applications of MR clutches and brakes, some of which are currently being developed. However, none of these applications have reached the commercial stage.

MR technology can also be exploited in actuator systems. Consider a pneumatic actuator system in which air, delivered through tubes or pipes, can displace a piston of an actuator. The air flow is controlled by valves, which in turn are controlled by some means. MR technology enables a conceptually simpler system. Pumping an MR fluid through a tube can also displace a piston of an actuator. However, valves to control the fluid flow are unnecessary. By applying a large magnetic field to the fluid in one small area, the fluid can be effectively solidified, stopping its flow or redirecting it elsewhere. The Lord Corp. has also improved pneumatic actuator systems through the addition of MR brakes and dampers (Lewis, 1999; Carlson and Sproston, 2000).

MR fluids have also been utilized in the polishing industry. Kordonski and Golini (2000) describe a finishing process that employs an aqueous MR polishing fluid. The workpiece is held above a spinning wheel, with the MR fluid contained in-between by a magnetic field. The mechanical force exerted on the workpiece, and thus the rate of material removal, are controlled by the magnetic field strength. This method has the advantage that the polishing tool does not wear, as the MR polishing fluid can be recirculated and maintained.

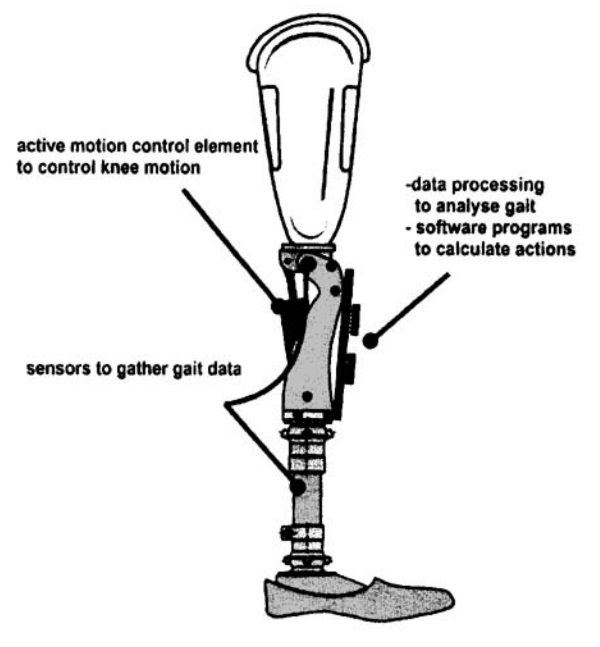

Figure 3. Prosthetic knee using a semiactive MR damper (Carlson and Sproston, 2000).

Challenges

With the proliferation of commercial applications over the last five years, one may begin to think that we are witnessing just the beginning of an explosion MR devices and applications. Indeed, numerous applications are currently in development, while other applications, such as MR elastomer dampers (Ginder, 1996; Davis, 1999), are in the research stage. There are certainly other uses for this technology that we simply have not thought of yet. However, wide range application of MR technology is impeded, if not restricted, by several limitations. Most, if not all of these limitations are associated with the fluids themselves, as opposed to the device design and manufacturing.

One of the most significant issues for commercializing any device is cost. Carbonyl iron particles, the type of iron particles preferred by application developers, are relatively expensive at \$6–7/lb (\$13–15/kg) in bulk. More cheaply produced iron particles tend to be irregular in shape, have wider size distributions, and simply do not perform as well. Some iron alloy particles actually perform better than carbonyl iron, but are significantly more expensive. It is apparent that more applications would quickly become commercial if the material cost could be reduced.

Not unrelated to the cost issue is the desire to obtain the largest field-induced change in viscosity with the smallest particle concentration and applied field strength possible. Simply, the material cost could be reduced by reducing the amount of iron employed. Unfortunately, the magnitude of the MR effect increases with particle concentration, and thus there is a trade-off between cost and performance. This trade-off currently prohibits some applications. The maximum achievable viscosity change caused by the magnetic field is itself a significant issue for some applications. For example, some high stress and high torque applications, such as MR automotive transmissions and MR automotive brakes, can require field-induced changes in rheological properties that exceed current capabilities. Although other fluid characteristics are also important, it is clear that the commercialization of MR technology would be facilitated by developing methods to increase the ultimate strength of MR fluids.

Another challenge in some applications is the fact that iron particles are very dense and tend to settle. In some cases, this is not a significant issue as long as there is a means within the device to redisperse particles that have settled. In other applications, such as earthquake dampers, the device may be unused for a long time and then be required to perform in an instant. Here, allowing time for the particles to be redispersed is not an option. One method for overcoming the problem of sedimentation is to disperse the particles, not in a Newtonian liquid, but in a material with a yield stress. Some surfactant systems and greases are potential candidates. Another option is to weakly aggregate the particulate suspension, containing the particles within a space filling particulate network. Both approaches can be used to overcome sedimentation, but unfortunately they significantly increase the fluid viscosity when no field is applied, making them unusable in some applications. Thus, overcoming sedimentation remains a challenge in MR technology.

The physical chemistry of the iron-laden suspensions is at the heart of several challenges. Iron oxidizes spontaneously, and in devices at elevated temperatures wherein the particles are exposed to the atmosphere, oxidation can be a problem. As the particles oxidize, they become less magnetizable, diminishing the MR effect. Colloidal forces acting between the particles can cause aggregation, which can negatively affect the fluid rheology in the absence of the applied field, can increase the rate of sedimentation, and can severely inhibit the ability to redisperse particles that have settled. Very little is known about these phenomena in MR fluids.

Each of the limitations and challenges described commands a better understanding of magnetorheology, particularly of the relationships between the particle and fluid properties and the suspension rheology. Such information is necessary for optimizing the response of devices, as the more Edisonian approaches appear unable to resolve existing issues. Better understanding is also necessary for developing models of MR behavior, which are important for attacking such engineering issues as handling the effects of viscous heating, optimizing device geometry and magnetic field distribution, and developing predictive capabilities for design and control strategies.

Despite these challenges, MR technology has been proven to be viable in numerous applications. Overcoming limitations will lead to improvements in fluid and device performance, as well as foster the development of new applications. Considering that most of the commercial progress has appeared in only the last five years—in a field that has been around for 50 years—it is likely that MR technology will progress substantially in the near future.

Acknowledgments

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