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Properties and application of magnetorheological fluids

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Materials

ABSTRACT

Purpose: This paper presents basic properties of the magnetorheological fluids (MR) and their development in recent years. A variety of still growing practical applications in mechanical devices are presented.
Design/methodology/approach: The theoretical research results of the properties and applications obtained in the past decades and progressed in recent years are reviewed.
Findings: It is very clearly and well understood from the presented paper that replacement of the traditional devices with active, smart system better adapted to the environment stimulus are necessary. Many of them will include MR fluids as active component.
Research limitations/implications: MR fluids with excellent properties can be applied in various fields of civil engineering, safety engineering, transportation and life science. They offer an outstanding capability of active control of mechanical properties.
Practical implications: A very useful material for the engineers engaged in the design of brakes, dampers, clutches and shock absorbers systems.
Originality/value: This article describes an up-to-date MR materials development and their application in civil engineering. The advantage of the smart systems over nowadays solutions becomes the direction of the researches and designing of 21st century devices.
Keywords: Smart materials; Magnetorheological materials; Magnetic properties; Shear stress

1. Introduction

Science and technology have made amazing developments in the design of electronics and machinery using standard materials, which do not have particularly special properties (i.e. steel, aluminum, gold).

Imagine the range of possibilities, which exist for special materials that have properties scientists can manipulate. Some such materials have the ability to change shape or size simply by adding a little bit of heat, or to change from a liquid to a solid almost instantly when near a magnet; these materials are called smart materials. Smart materials have one or more properties that can be dramatically altered. Most everyday materials have physical properties, which cannot be significantly altered; for example if oil is heated it will become a little thinner, whereas a smart material with variable may turn from a liquid state which flows easily to a solid. Each individual type of smart material has a different property which can be significantly altered, such as viscosity, volume or conductivity. The property that can be altered determines what type of applications the smart material can be used for [1].

Varieties of smart materials already exist, and are being researched extensively. These include piezoelectric materials, magnetorheostatic materials, electrorheostatic materials, and shape memory alloys. Some everyday items are already incorporating smart materials (coffeepots, cars, glasses) and the number of applications for them is growing steadily.

Magnetorheological materials (fluids) (MR) are a class of smart materials whose rheological properties (e.g. viscosity) may be rapidly varied by applying a magnetic field. Under influence of magnetic field the suspended magnetic particles interact to form a structure that resists shear deformation or flow. This change in the material appears as a rapid increase in apparent viscosity or in the development of a semisolid state.

Advances in the application of MR materials are parallel to the development of new, more sophisticated MR materials with better properties and stability. Many smart systems and structures would benefit from the change in viscosity or other material properties of MR. Nowadays, these applications include brakes, dampers, clutches and shock absorbers systems.

2. Properties of magnetorheological fluids

Typical magnetorheological fluids are the suspensions of micron sized, magnetizable particles (mainly iron) suspended in an appropriate carrier liquid such as mineral oil, synthetic oil, water or ethylene glycol. The carrier fluid serves as a dispersed medium and ensures the homogeneity of particles in the fluid. A variety of additives (stabilizers and surfactants) are used to prevent gravitational settling and promote stable particles suspension, enhance lubricity and change initial viscosity of the MR fluids. The stabilizers serve to keep the particles suspended in the fluid, whilst the surfactants are adsorbed on the surface of the magnetic particles to enhance the polarization induced in the suspended particles upon the application of a magnetic field.

Table 1.
Summary of the properties of MR fluids [1]

Property	Typical value
Initial viscosity	0,2 – 0,3 [Pa·s] (at 25°C)
Density	3 – 4 [g/cm^3]
Magnetic field strength	150 – 250 [kA/m]
Yield point τ_o	50 – 100 [kPa]
Reaction time	few milliseconds
Typical supply voltage and current intensity	2 – 25 V, 1–2 A
Work temperature	-50 do 150 [°C]

Typically, the diameter of the magnetizable particles range from 3 to 5 microns. Functional MR fluids may be made with larger particles, however, stable suspension of particles becomes increasingly more difficult as the size increases. Commercial quantities of relatively inexpensive carbonyl iron are generally limited to sizes greater than 1 or 2 microns. Smaller particles that are easier to suspend could be used [2,3], but the manufacture of such particles is difficult. Significantly smaller ferromagnetic particles are generally only available as oxides, such as pigments commonly found in magnetic recording media.

MR fluids made from such pigment particles are quite stable because the particles are typically only 30 nanometers in diameter. However, because of their lower saturation magnetization, fluids made from these particles are generally limited in strength to about 5 kPa and have a large plastic viscosity due to the large surface area. Main parameters of these fluids are presented in table 1.

In the absence of an applied field, MR fluids are reasonably well approximated as Newtonian liquids. For most engineering applications a simple Bingham plastic model is effective at describing the essential, field-dependent fluid characteristics. A Bingham plastic is a non-Newtonian fluid whose yield stress must be exceeded before flow can begin [4]. Thereafter, the rate-of-shear vs. shear stress curve is linear. In this model, the total yield stress is given by (1):

$$\tau = \tau_o(H) + \eta\,\dot{\gamma} \qquad (1)$$

where:

τ_o - yield stress caused by applied magnetic field, [Pa]

H - magnetic field strength, [A/m]

$\dot{\gamma}$ - shear rate, [s^{-1}]

η - plastic viscosity, [Pa·s]

Lots of modern, complex models of magnetorheological fluids are developed [5,6].

Normally, MR fluids are free flowing liquids having a consistency similar to that of motor oil (Fig. 1).

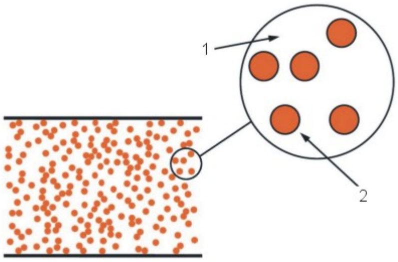

Fig. 1. MR fluid model without outer magnetic field (1 – carrier liquid, 2 – suspended magnetizable particles)

However, in the presence of an applied magnetic field, the iron particles acquire a dipole moment aligned with the external field which causes particles to form linear chains aligned to the magnetic field, as shown in Fig. 2.

This phenomenon can solidify the suspended iron particles and restrict the fluid movement. Consequently, yield strength is developed within the fluid. The degree of change is related to the magnitude of the applied magnetic field, and can occur in a few milliseconds.

Typical magnetorheological materials can achieve yield strengths up to 50–100 kPa at magnetic field strength of about 150–250 kA/m. It was found that wall roughness on contact with the fluid is important for yield strengths, especially in low magnetic fields. For low strains prior to yield, the shear modulus of a MR fluid also shows a very large increase in an applied magnetic field. MR materials eventually reach a saturation point where increases of magnetic field strength do not increase the yield strength of the MR material. This phenomenon typically occurs around 300 kA/m. The effect of magnetic saturation on the strength of MR materials can be studied by using finite element analysis.

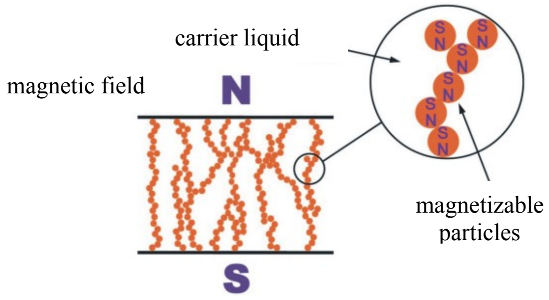

Fig. 2. MR fluid model in the outer magnetic field

The MR effect is immediately reversible if the magnetic field is reduced or removed. Response times of 6.5 ms have been recorded.

MR materials that have been already developed are stable in temperature ranges from –50 to 150°C. There are slight changes in the volume fraction and hence slight reductions in the yield strength at these temperatures, but they are small.

Also size and size distribution of the suspended particles affect the change in properties of the MR fluid when placed in a magnetic field.

Magnetorheological materials exhibit some advantages over typical electrorheological materials. In contrast to electrorheological materials, MR fluids are more useful because the change in their rheological properties is large, larger that in ER fluids, so an increase of yield stress are 20-50 times stronger. Unlike ER materials, they are also less sensitive to moisture and contaminants, and thus MR materials are candidates for use in dirty or contaminated environments. They are also unaffected by the surface chemistry of surfactants as ER materials are. The power (50 W) and voltage (12–24V) requirements for MR materials activation are relatively small compared with ER materials.

3. Application of magnetorheological fluids

Because the state of MR materials can be controlled by the strength of an applied magnetic field, it is useful in applications where variable performance is desired. Microprocessors, sensor technologies and increasing electronic content and processing speeds have created real-time control possibilities of smart systems used MR devices.

Beginning of the commercialization of MR technology was year 1995 and use of rotary brakes in aerobic exercise equipment. From this moment application of magnetorheological material technology in real-world systems has grown steadily.

During the past few years a number of commercially available products (or near commercialization) have been developed, e.g. [7-14]:

- linear MR dampers for real-time active vibrational control systems in heavy duty trucks,
- linear and rotary brakes for low-cost, accurate, positional and velocity control of pneumatic actuator systems,
- rotary brakes to provide tactile force-feedback in steer-by-wire systems,
- linear dampers for real-time gait control in advanced prosthetic devices,
- adjustable real-time controlled shock absorbers for automobiles,
- MR sponge dampers for washing machines,
- magnetorheological fluid polishing tools,
- very large MR fluid dampers for seismic damage mitigation in civil engineering structures,
- large MR fluid dampers to control wind-induced vibrations in cable-stayed bridges.

The MR brake operates in a direct-shear mode, shearing the MR fluid filling the gap between the two surfaces (housing and rotor) moving with respect to one another. Rotor is fixed to the shaft, which is placed in bearings and can rotate in relation to housing. Resistance torque in the MR brake depends on viscosity of the MR fluid that can be changed by magnetic field. MR brake allows for continuous control of torque. When there is no magnetic field the torque is caused by viscosity of carrier liquid, bearings and seals. MR brake is especially well suited for a variety of applications including pneumatic actuator control, precision tension control and haptic force feedback in applications such as steer-by-wire [15].

MR clutch similar to MR brake operates in a direct-shear mode and transfers torque between input and output shaft. There are two main types constructions of MR clutch: cylindrical and frontal. In the cylindrical model MR fluid works between two cylindrical surfaces and in frontal MR fluid fills gap between two discs. During work magnetic field produced by coils increases viscosity of fluid and causes transfer of torque form input to output shaft. Useful torque is available after 2-3 milliseconds from stimulation [1].

MR dampers are semi-active devices that contain magnetorheological fluids. After application of a magnetic field the fluid changes from liquid to semi-solid state in few milliseconds, so the result is an infinitely variable, controllable damper capable of large damping forces. MR dampers offer an attractive solution to energy absorption in mechanical systems and structures and can be considered as “fail-safe” devices.

4. Conclusions

Science and technology in the 21st century will rely heavily on the development of new materials that are expected to respond to the environmental changes and manifest their own functions according to the optimum conditions.

The development of smart materials will undoubtedly be an essential task in many fields of science and technology such as information science, microelectronics, computer science, medical treatment, life science, energy, transportation, safety engineering and military technologies.

Materials development in the future, therefore, should be directed toward creation of hyperfunctional materials which surpass even biological organ in some aspects. The current materials research is to develop various pathways that will lead the modern technology toward the smart system.

These fluids can reversibly and instantaneously change from a free-flowing liquid to a semi-solid with controllable yield strength when exposed to a magnetic field.

In the absence of an applied field, MR fluids are reasonably well approximated as Newtonian liquids. For most engineering applications, a simple Bingham plastic model is effective in describing the essential, field-dependent fluid characteristics.

MR technology has moved out of the laboratory and into viable commercial applications for a diverse spectrum of products. Applications include automotive primary suspensions, truck seat systems, control-by-wire/tactile-feedback devices, pneumatic control, seismic mitigation and human prosthetics.

In contrast to conventional electro-mechanical solutions, MR technology offers:

- Real-time, continuously variable control of
  - Damping
  - Motion and position control
  - Locking
  - Haptic feedback
- High dissipative force independent of velocity
- Greater energy density
- Simple design (few or no moving parts)
- Quick response time (10 milliseconds)
- Consistent efficacy across extreme temperature variations (range of 140C to 130 C)
- Minimal power usage (typically 12V, 1 Amp max current; fail-safe to battery backup, which can fail-safe to passive damping mode)
- Inherent system stability (no active forces generated)
- MR fluids can be operated directly from low-voltage power supplies. MR technology can provide flexible, reliable control capabilities in designs.

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