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Magneto Rheological Dampers — A New Paradigm in Base Isolation Techniques in Earth Quake Engineering

S. Suresh Babu
Kongu Engineering College, Perundurai , Tamil Nadu, India

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MAGNETO RHEOLOGICAL DAMPERS - A NEW PARADIGM IN BASE ISOLATION TECHNIQUES IN EARTH QUAKE ENGINEERING

S. SURESH BABU
Professor,
Department of Civil Engineering,
Kongu Engineering College,
Perundurai – 638 052, Tamil Nadu, India.

ABSTRACT

Over the past three decades, a great deal of interest has been generated regarding the use of structural protective systems to mitigate the effects of dynamic environmental hazards, such as earth quakes and strong wind, on Civil Engineering structures. These systems usually employ supplemental damping devices to increase the energy dissipation capability of the protected structure. One of the most promising new devices proposed for structural protection is Magneto rheological (MR) fluid dampers because of their mechanical simplicity, high dynamic range, low pressure requirements, large force capacity and robustness, this class of devices has been shown to mesh well within application demands and constraints to offer an attractive means of protecting Civil infrastructure systems against dynamic loading.

The focus of the paper is to develop a fundamental understanding of large scale MR dampers for the purpose of designing and implementing these “smart” damping devices in large- scale structures for natural hazard mitigation.

Key words: MR dampers, MR fluids, Base Isolation devices, ER Dampers.

INTRODUCTION

One of the most successful means of protecting structures against Seismic events is 'BASE ISOLATION'. Seismic Base isolation mitigate the risk to life and property from strong Earth quakes [Carlson J.D (1994)]. In base isolation Systems, non linear devices such as Lead-rubber bearings, friction pendulum bearings or high damping rubber bearings are often used. The benefit of these types of bearings is that the restoring Force and adequate damping Capacity can be obtained in one device. However, because the dynamic characteristics of these devices are strongly non-linear, the vibration reduction is not optimal for a wide range of input ground motion intensities.

Because the performance of highly sensitive equipment in Hospitals, Communication Centers, and computer Facilities can be easily disrupted by moderate acceleration levels and even permanently damaged by higher excitations [Spencer Jr., et.al., 1997], efforts have trained towards the use of Isolation for protection of buildings contents. Ex: Base isolation Systems have been employed in a semiconductor Facility in Japan to reduce micro vibration from a nearby high speed Train rail [Kyle C, et.al., 2001]

Recent revisions to the Uniform Building Code (ICBO -1997) mandate the accommodation of larger base displacements and the consideration of a stronger Maximum Credible Earthquake (MCE), indirectly suggesting the need for supplementing damping devices. However, the addition of damping to minimize base displacements may increase both internal deformation and absolute accelerations of the gains for which base isolation is intended [Dyke SJ, et.al., 1996a & Dyke SJ, et.al., 1996c]. In general, protection of the contents of a structure is achieved through minimization of structural acceleration.

Seeking to develop isolation systems that can be effective for a wide range of ground excitation, hybrid control strategies, Consisting of a passive Isolation system combined with actively controlled actuators, have been investigated by a number of researchers. The advantages of hybrid base isolation systems are high performance in reducing vibration, the ability to adapt to different loading Conditions, Control of multiple vibration modes of the structure and so on.

As a paradigm shift among base Isolation system employs semi active control devices, often called 'Smart' dampers include Magneto Rheological (MR) Fluids (MR Dampers) and Electro Rheological (ER) Fluids (ER Dampers).

MR Fluids and devices

Magneto rheological fluids (or simply "MR" fluids) belong to the class of controllable fluids. The essential characteristic of MR fluids is their ability to reversibly change from free-flowing, linear viscous liquids to semi-solids having controllable yield strength in milliseconds when exposed to a magnetic field.

This feature provides simple, quiet, rapid response interfaces between electronic controls and mechanical systems. MR fluid dampers are relatively new semi-active that utilize MR fluids devices to provide controllable damping forces.

In this paper, following the introduction of the essential characteristics of MR fluids, the visco-plasticity models are described MR fluid field-dependent besides the civil engineering characteristics and shear thinning/thickening effects. The advantages of MR fluids and devices in applications are discussed and comparisons of MR fluid dampers for civil engineering applications are introduced.

Magneto Rheological (MR) Fluids

The initial discovery and development of MR fluids can be credited to Jacob Rabinow (1948,1951) at the US National Bureau of Standards in the late 1940s. These fluids are suspensions of micron-sized, magnetizable particles in an appropriate carrier liquid. Normally, MR fluids are free flowing liquids having a consistency similar to that of motor oil. 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 parallel to the field, as shown in Fig 1.

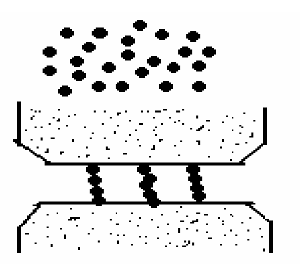

Fig.1. MR fluids

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 only in a few milliseconds.

A typical MR fluid contains 20-40% by volume of relatively pure, soft iron particles, e.g., carbonyl iron; these particles are suspended in mineral oil, synthetic oil, water or glycol. A variety of proprietary additives similar to those found in commercial lubricants are commonly added to discourage gravitational setting and promote particle suspension, enhance lubricity, modify viscosity, and inhibit wear. The ultimate strength of the MR fluid depends on the square of the saturation magnetization of the suspended particles. The key to a strong MR fluid is to choose a particle with a large saturation magnetization [Carlson J.D (1994)]. The best available particles are alloys of iron and cobalt that have saturation magnetization of about 2.4 tesla. Unfortunately, such alloys are prohibitively expensive for most practical applications. The best particles are simply pure iron, as they have a saturation magnetization of 2.15tesla. virtually all other metals, alloys and oxides have a saturation magnetization significantly lower than that of iron, resulting in substantially weaker MR fluids.

Typically, the diameter of the magnetizable particles is 3 to 5 microns. Functional MR fluids may be made with larger particles; however, particle suspension becomes increasingly more difficult as the size increases [Carlson J.D (1994)]. Smaller particles that are easier to suspend could be used, but the manufacture of such particles is difficult. Commercial quantities of relatively inexpensive carbonyl iron are generally limited to sizes greater than 1 or 2 microns. Significantly smaller ferromagnetic particles are generally available as oxides, such as the pigments commonly found in magnetic recording media. MR fluids made from such pigment particles are quite stable because the particles are typically only 30 manometers in diameter. However, because of their lower saturation magnetization, fluids made from these particles are generally limited in strength to about 5kPa and have a large plastic viscosity due to the large particle surface area.

Three types of MR fluids manufactured by the LORD Corporation are commercially available. Table 1 presents the main properties of these three types of MR fluid: MRF-132LD(oil based), MRF-240BS (water-based), and MRF-336AG (silicone oil-based). MR fluids exhibit a significant shear thinning effect because of both the addition of suspension agents and changes in the magnetic particle microstructure during shear MR fluids have an approximately linear magnetic property when the applied magnetic field is small. As the magnetic field increases, a gradual magnetic saturation is observed; consequently, the MR fluid yield stress saturates due to its direct relationship with the magnetic field.

MR Fluid Models

A simple Bingham visco-plasticity model, is effective at describing the essential field-dependent fluid characteristics. In this model, the total shear stress T is given by

$$T = T_o \ (H) \ Sin \ y = n \ y \qquad (1)$$

where
T0 = yield stress caused by the applied field;
H = magnitude of the applied magnetic field;
y = Shear strain rate
n = Field – independent plastic viscosity

Note that the fluid post-yield viscosity is assumed to be a constant in the Bingham model. Because MR fluids exhibit shearing thinning effect. In this model, the constant post-yield plastic viscosity in the Bingham model is replaced with a power law model dependent on shear strain rate.

$$T = T_o \ (H) + k \ (y)^{1/m} \ Sin \ (y) \qquad (2)$$

where
H, k = Fluid parameters and m , k >0

Comparing the above equations, the equivalent plastic viscosity of Herschel – Bulkley model is $n = k \ (\Upsilon)^{1/m-1}$

It is noted that the equivalent plastic viscosity decreases as the shear strain rate increases when m>1 (shear thinning). Further more, this model can also be used to describe the fluid shear thickening effect when m<1 [S. Sureshbabu, 2003]

Advantages of MR Fluids and Devices in Practical Applications:

There are basically two types of controllable fluids -MR fluids and ER fluids. The primary advantage of the MR fluids stems from their high dynamic yield strength due to the high magnetic energy density that can be established in the fluid. Energy density in MR fluid is limited by the magnetic saturation of iron particles. For a typical iron-based MR fluid, the maximum energy density is 0.1 Joule/cm3. ER fluids, on the other hand, are limited by the dielectric breakdown, and the maximum energy density is only about 0.001 Joule/cm3. This is the main reason that the yield strength of MR fluids is larger by an order of magnitude than that of ER fluids; however, their viscosity is almost the same. A yield stress close to 100kPa can be obtained for MR fluids with magnetic suspensions containing power of carboxyl iron [Dyke S J et al., 1996], whereas 2-5kPa appeared to be the maximum yield stress for an ER fluid. A high dynamic yield stress allows for small device size and high dynamic range. Carlson and Spencer indicated that the minimum amount of active fluid in a controllable fluid device is proportional to the plastic viscosity and inversely proportional to the square of the maximum yield stress. For a comparable mechanical performance, the amount of active fluid needed in MR devices will be two orders of magnitude less than that required in ER devices, resulting in much smaller devices [Housner G W et al,1994].

MR fluids can operate at temperatures from -40 to 150C with only slight variations in yield stress. This arises from the fact that magnetic polarization is not strongly influenced by temperature. Additionally, MR fluids are not sensitive to impurities commonly encountered during manufacturing and usage. Furthermore, because surfactants and additives do not affect the magnetic particle polarization mechanism, it is easier to stabilize MR fluids against particle/carrier separation, even though the particles and carrier liquid have a large density mismatch. Antiwear and lubricity additives can generally be included in MR fluids to enhance stability, seal life and bearing life since electro-chemistry does not affect the magneto-polarization mechanism.

From a practical implementation perspective, although the total energy requirements for the ER and MR devices are almost equal, only MR devices can be easily driven by low-voltage, current-driven power supply outputting only ~1.2 amps. ER devices, on the other hand, require a high-voltage power source (~2000-5000 volts) which may not be readily available, especially during strong earthquake events. Moreover, such a high voltage may pose a safety hazard. Table 2 provides a summary of the key properties of both ER and MR fluids [Spencer J R et al., 1997b].

MR devices and MR fluid dampers

The maximum force that an MR damper can deliver depends on the properties of MR fluids, their flow pattern, and the size of the damper. Virtually all devices that use MR fluids can be classified as operating in: (a) a valve mode, (b) a direct mode, (c) a squeeze mode, or a combination of these modes. Diagrams of these basic modes of operation are shown in Fig.2. Examples of valve mode devices include servo-valves, dampers, shock absorbers and actuators. Shear mode devices include clutches, brakes, chucking and locking devices, dampers and structural composites. While less well-understood than the other modes, the squeeze mode has been used in some small-amplitude vibration dampers [Spencer J R et al., 1997].

To date, several MR fluid devices have been developed for commercial use by the LORD Corporation. Linear MR fluid dampers have been designed for use as secondary suspension elements in vehicles. MR fluid rotary brakes are smooth-acting, proportional brakes which are more compact and require substantially less power than competing systems. MR fluid vibration dampers for real-time, active-control of damping have been used in numerous industrial applications.

In civil engineering applications, the expected damping forces and displacements are rather large in magnitude. Therefore, MR dampers primarily operating under direct shear mode or squeeze mode are employed. Some examples of recently developed MR dampers are given. These dampers are capable of meeting real-world requirements and are presently either in commercial production or in production prototype trails.

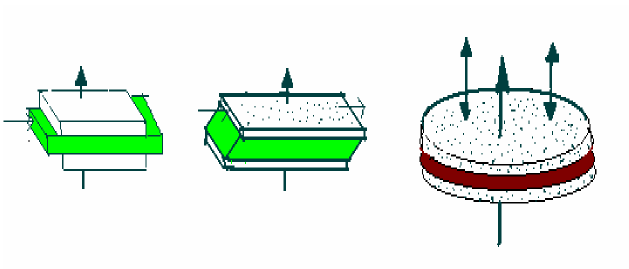

Fig.2. Basic operating modes for controllable fluid devices.. (a).Valve model (b). Direct Shear model (c). Squeeze model

CONCLUSION

Magneto rheological (MR) fluids are "smart" materials with rheological properties that can be substantially, but reversibly, altered in milliseconds when exposed to a magnetic field. The Herschel-Bulklely visco-plasticity model has been shown to be effective in describing the MR fluid field-dependent characteristics and shear thinning/thickening effects. Note that the Herschel-Bulkley model reduces to the well-known Bingham model when the fluid parameter m=1. Compared with electrorheological (ER) fluids, MR fluids have a higher yield stress and are insensitive to impurities and temperature. Moreover, MR devices are readily driven by common low-voltage power supplies. These advantages make MR fluids an devices more attractive in practical applications.

To date, several types of MR fluid dampers have been developed for commercial use or are under various stages of development. Previously reported laboratory studies using small-scale commercial MR dampers have indicated the promise of applying MR technology for vibration mitigation. However, there are still many challenges to be met before MR dampers may be implemented in large-scale structural vibration control applications. In the following chapters, topics on large scale MR damper modeling, testing and control are addressed, intending to provide fundamental insight into the behaviour of MR fluid dampers.

Table 1. Properties of three different MR Fluids

MR Fluid	MRF – 132LD	MRF-240BS	MRF-336AG
Fluid Base	Synthetic oil	Water	Silicone oil
Operating temperature(^{0} C)	-40--150	0-70	-40 –150
Density(g/cc)	3.05	3.818	3.446
Weight percent solids	80.74%	83.54%	82.02%
Coefficient of thermal expansion (volume,1/·c)	0.55-0.67*10^{-3}	0.223*10^{-3}	0.58*10^{-3}
Specific heat@25·c(j/g·c)	0.80	0.98	0.68
Thermal conductivity(w/m·c)	0.25-1.06	0.83-3.68	0.20-1.88
Flash point(·c)	>150	>93	>200
viscosity@10s $^{-1}$ /50s $^{-1}$ (pa. sec)	0.94/0.33	13.6/5.0	8.5/-

Table 2. Summary of the properties of ER & MR fluids

Property	MR fluids	ER fluids
Max. yield stress	50-100kPa	2-5Kpa
Maximum Field	~250 kA/m	~4 KV/mm
Apparent plastic viscosity	0.1-10Pa-s	0.1-1.0Pa-s
Operable temp range	-40-50·c	10-90·c
Stability	Unaffected by most Impurities	Cannot tolerate Impurities

Density	3-4g/cm^3	1-2g/cm^3
	10 -10 s/Pa	10 -10 s/Pa
Maximum energy density	0.1 joules/cm^3	0.001 joules/cm^3
Power supply(typical)	2-50v,1-2A	2000-5000V,1-10mA

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