A Look at the Problems And Solutions in the Production and Application of Magnetorheological Data.

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Abstract

This review of MRF (magnetorheological fluids or MR fluids) brings out the challenges in methods of preparation, difficulties encountered in storage and use, and possible solutions to overcome the challenges.
Magnetorheological fluid in the rheological fluid domain has found use due to its ability to change its shear strength based on the applied magnetic field. Magnetorheological fluids are composed of magnetizable micron-sized iron particles and a non-magnetizable base or carrier fluid along with additives to counter sedimentation and agglomeration.
Magnetorheological fluids can respond to external stimuli by undergoing changes in physical properties thus enabling several improved modifications in the existing technology enhancing their application versatility and utility. Thus, magnetorheological fluid, a rheological material whose viscosity undergoes apparent changes on application of magnetic field, is considered as a smart material. Such materials can be used for active and semi-active control of engineering systems.
Many studies on the designs of systems incorporating MR fluids, mainly for vibration control and also for other applications including brakes, clutches, dynamometers, aircraft landing gears, and helicopter lag dampers, have emerged over last couple of decades. However, the preparation as well as the maintenance of magnetorheological fluids involves several challenges. Sedimentation is a major challenge, even when stored for moderate periods of time. A comprehensive review is made on the problems confronted in the preparation of magnetorheological fluids as well as sustenance of the properties, for use, over a long period of time. Other problems encountered include agglomeration and in-use thickening (IUT) as well as rusting and crusting. Of interest is the mitigation of these problems so as to prepare fluids with satisfactory properties, and such solutions are reviewed here. The control of magnetorheological fluids and the applications of interest are also reviewed.
The review covers additives for overcoming challenges in the preparation and use of magnetorheological fluids that include incrustation, sedimentation, agglomeration, and also oxidation of the particles. The methodology to prepare the fluid along with the process for adding selected additives was reviewed. The results showed an improvement in the reduction of sedimentation and other problems decreasing comparatively. A set of additives for addressing the specific challenges has been summarized. Experiments were carried out to establish the sedimentation rates for compositions with varying fractions of additives.
The review also analyzes briefly the gaps in studies on MR fluids and covers present developments and future application areas such as haptic devices.

Keywords: Smart materials, Magnetorheological fluids, Magnetorheological damper, Active vibration control, Agglomeration, Sedimentation, In-use thickening, Additives

Introduction

The ability to change properties in a controlled manner under application of stimulation such as a variable current, magnetization, heat, force, stress and deformation have made smart materials such as magnetorheological fluids (MRF) attractive for wide ranging applications. Magnetorheological materials including fluids belong to a class of smart materials called rheological materials that change their properties as a function of magnetic field, much like their electrical counterparts, electrorheological (ER) materials. Discovered in 1948 by Rabinow (Rabinow, 1948), MR materials have since been studied and broadly categorized as magnetorheological fluids, magnetorheological elastomers, and magnetorheological foams (Carlson & Jolly, 2000). Of the three, magnetorheological fluids have been studied extensively and deployed the most in a variety of applications. This versatility is due to the rapid field responsiveness of magnetorheological fluids, noiseless operation, relative insensitivity to small quantities of dust or contaminants, and ease of control. The work done by Rabinow and Winslow (Winslow, 1947) in establishing the force transmissions characteristics of MR and ER (electrorheological) fluids respectively had paved the way for developing systems incorporating these fluids. Carlson et al. (Carlson et al., 1996) researched into the possibilities of using magnetorheological fluids for developing commercial devices. The shear strength of commercially available MRF varies from 0–100 kPa under the effect of the magnetic field. In valve mode, in the Magnetorheological damper (MR Damper or MRD), the MR fluid flows between two-fixed poles, which are parallel to each other. When the fluid flows between them, due to the applied magnetic field, the magnetic particles align themselves in a chain form (on state) which is easily reversible on field removal (off state). The control of the physical change of the fluid from liquid to semi-solid by the magnetic field makes the fluid a reliable member in applications such as active vibration control and brakes.

The limitations of sedimentation, stability issues, and temperature effects were impediments to development and commercialization of MR devices. Progressively, researchers were able to confront these impediments and develop solutions that could promote the effective utilization of the MR devices. The operability of these devices with low voltage and the advent of efficient control systems have accelerated their evolution and facilitated the implementation of magnetorheological fluids in numerous applications. Some of the applications include dampers, clutches, brakes, seismic isolators, exercise equipment and limb prosthetics (Jolly et al., 1998; Carlson, 2007). The knowledge of the challenges faced in magnetorheological fluid preparation and usage provide inputs for taking prophylactic measures against them and resolving them with varying degrees of efficacy. Presented here is a broad overview of the problems and challenges faced in the preparation of reliable magnetorheological fluids. A review of the common compositions, preparation, and a few applications are included. A brief insight into some gaps in research and development as well as future trends is also provided.

Composition of magnetorheological fluids

Magnetorheological fluids comprise three main components: magnetic particles, carrier fluid, and additives. Magnetic particles used are often carbonyl iron of 99% purity because carbonyl iron particles have a high magnetic permeability and high saturation magnetization (Ashtiani et al., 2015a). Carbonyl iron particles are obtained by chemical vapor deposition of iron pentacarbonyl. The shape of the carbonyl iron particles used is usually spherical as it reduces effects of wear on the walls of the container or device inside which the magnetorheological fluids operate. However, fiber shaped particles have shown better yield stress and low OFF state viscosity as compared to spherical particles (Vicente et al. (Vicente et al., 2011); Chen et al. (Jiang et al., 2011)). The concentration of carbonyl iron particles ranges from 20 to 40% by volume, and the size is normally maintained between 3 and 5 μm averaging around 4.25 μm. Very low size may not enable the magnetorheological fluids to develop high yield stress while very large size of the iron particles could cause erosion and friction issues.

The carrier fluid used is mineral oil, silicone oil, or any other synthetic oil which has low viscosity (Jiang et al., 2011).

The carrier fluid should also not chemically react with iron particles. The carrier fluid is selected based on the intended application of the magnetorheological fluid. For polishing application, water is a suitable carrier fluid, while for vibration control, silicone oil is the preferred choice owing to its properties like high viscosity index, low friction characteristics, high shear strength, and high flash point (Ashtiani et al., 2015a).

Additives added are usually surfactants either to prevent agglomeration of the magnetic particles or to inhibit the rate of settling of magnetic particles (Bombard et al., 2009). The use of additives is an important criteria as the particles owing to their high density have a tendency of sedimentation or settling down which if not resolved could render the device ineffective.

Additives like grease, a thixotropic agent (Premalatha et al., 2012), emulsifiers Tween-80 and Span-80, used to improve sedimentation stability (Zhang et al., 2009), and Stearic acid, an organic acid that increases the density of the carrier fluid (Ashtiani et al., 2014), have all been used to achieve sedimentation stability. A summary of the additives used and purpose are shown in Table 1. The properties of a typical MR fluid are summarized in Table 2.

General preparation of magnetorheological fluids

The preparation of magnetorheological fluids includes two components: solid phase and liquid phase. The solid phase consisting of magnetic particles is coated with additives like guar gum in a certain composition such that the volume to mass ratio of the particles increases. The liquid phase comprises the carrier fluid to which additives are added, in a particular manner and proportion in order to increase the density of the carrier fluid.

The solid phase is then added to the liquid phase and mixed thoroughly for a certain period of time.

The resulting mixture is then left undisturbed to observe the settling characteristics of the magnetic particles.

Addition of stabilizers and additives often overcomes the problem of sedimentation.

The ,magnetorheological fluid is like a homogeneous solution of solid phase in a liquid phase where the solid phase particles behave as small magnets in the presence of a magnetic field and align along the magnetic field lines forming long chains. In the OFF state, the particles normally re-disperse in the solution. The change in apparent viscosity of the magnetorheological fluids in the presence of magnetic field is the working principle ofMR-based devices.

Challenges in preparation and use of magnetorheological fluids

There are several challenges in the preparation and use of magnetorheological fluids. Some of the challenges and the techniques of solving them are reviewed in the ensuing sections.

Formation of hard cake

This is a defect in magnetorheological fluids during operations that lead to the formation of a hard cake because of agglomeration of iron particles and remnant

Table 1 Additives used in MR fluid to reduce the problems of sedimentation, wear, and agglomeration and improve dispersability

S no.	Additive	% of additive	Purpose
1	Guar gum ((Wu et al., 2006); (Chen et al., 2005)), poly(methyl methacrylate) (Cho et al., 2004), carboxymethyl cellulose, polyethylene oxide, synthetic hectorite, xanthan gum (Carlson, 2002a)	0.5–1% by volume	Coating of iron particles to reduce the density consequently reducing sedimentation
2	Polyvinyl butyral (Jang et al., 2005)	0.5–1% by volume	Coating of iron particles to reduce the density and to improve anti-corrosion characteristic
3	Tetramethylammonium hydroxide (Ashtiani et al., 2014), fibrous carbon (Sukhwani & Hirani, 2007), Aerosil 200, arabic gum (Turczyn & Kciuk, 2008)	0.25–1% by weight	Surfactants to coat the iron particles and subsequently reduce agglomeration of particles
4	Olefin polymer emulsifier, Tween-60 and Tween-80, Span-60 and Span-80 (Zhang et al., 2009)	1–2% by weight	Emulsifiers used to improve sedimentation stability of MR fluid.
5	Grease (Premalatha et al., 2012), colloidal clay ((Foister et al., 2003); (Hato et al., 2011); (Munoz, 1997)), fumed silica (Iyengar & Foister, 2002)	3–5% by weight	Thickeners used to reduce sedimentation of magnetic particles
6	Lecithin (Powell et al., 2013)	2% by weight	Surfactant used to mitigate the settling rate of the magnetic particles
7	Oleic acid (Sarkar & Hirani, 2013), zinc dialkyldithiophosphate, organo molybdenum (Foister et al., 2003), sodium nitrite (Carlson, 2002a)	1–3 % by volume	Anti-friction and anti-wear additives to reduce erosion
8	Magnetic nanoparticles (Portillo & Iglesias, 2017), iron naphthalate, iron oleate (Grunwald & Olabi, 2008),	1–6% by volume	Dispersants used to disperse the magnetic particles in the carrier fluid
9	Stearic acid (Ashtiani et al., 2014), sodium stearate, lithium stearate (Grunwald & Olabi, 2008)	1–3% by weight	Thixotropic additive used for increasing the density of the carrier fluid in order to improve sedimentation stability
10	Cholesteryl chloroformate (Mrlík et al., 2013)	1–3% by weight	Improves thermal stability and sedimentation stability of the MR fluid
11	Polystyrene (Fang et al., 2008)	1–2% by weight	Coating of the iron particles to reduce agglomeration and to improve sedimentation stability
12	N-glucose ethylenediamine triacetic acid (GED3A) (Cheng et al., 2010), polyvinylpyrrolidone (Phule, 1999), aluminum distearate, thiophosphorus, thiocarbamate (Sukhwani & Hirani, 2007)	0.25–2 % by weight	Improves sedimentation stability

Table 2 Properties of typical MR fluids

Property	MR fluid
Suspended particle	Iron (carbonyl/electrolytic), ferrites
Particle size	3–10 μm
Suspending fluid	Nonpolar and polar liquids
Required field	0.2–0.5 T
Off state viscosity (Pa s)	0.1–1
Density (g/cc)	3–5
Reaction time	15–25 ms
Max. yield stress	50–100 kPa
Working temperature range	− 50 to 150 °C
Device excitation	Electromagnets or permanent magnets

magnetization. The cake remains even after the magnetic field is turned off resulting in non-homogeneous behavior of the magnetorheological fluids. As magnetic dipole forces together with Van der Waal's forces existing between the particles create a strong bond, a large amount of mechanical energy is required to breakdown the chain structure of the agglomerates (Ashtiani et al., 2015a). Shear rates of a large magnitude are necessary for the fluid to flow even in the OFF state. Lopez-Lopez et al. (López-López et al., 2006) made use of a surfactant to anti-agglomerate the hard cake. Nanoparticles of silica were used to create re-dispersion to a certain extent in the off state. However, in the ON state, the gel gave way and the particles dropped down in a cluster creating separation difficulties. Thus, a surfactant should not only be able to separate the particles in OFF state but also be able to withhold the force as a result of strong magnetic field for large number of cycles.

Surfactants have also been used to delay the time of settling of the particles and to facilitate re-dispersion (Kuzhir et al. (Kuzhir et al., 2009), Bossis et al. (Bossis et al., 2008), Bombard et al. (Bombard et al., 2009)). Oleic acid and tetramethylammonium hydroxide have been used as surfactants (Chiranjit Sarkar et al. (Sarkar & Hirani, 2013)) to mitigate the clustering of the iron particles.

In order to slow down the sedimentation process of the magnetic particles, thickeners have been added to the magnetorheological fluids (Weiss et al. (Weiss et al., 1997)). Some of the materials used as thickeners are fluorocarbon grease (Iyengar et al. (Iyengar et al., 2010)), colloidal clays (organoclays) (Foister et al. (Foister et al., 2003); Hato et al. (Hato et al., 2011); Munoz et al. (Munoz, 1997)), and fumed silica (Iyengar and Foister (Iyengar & Foister, 2002)). It was observed that the magnetorheological fluids when suspended with synthetic clay exhibited considerably low settling rate.

On the other hand, silica particles added in low volume fractions (2–3%) brought down the settling rate but displayed abrasive tendencies towards damper seals and walls (Foister et al. (Iyengar & Foister, 2002)).

Lecithin was tried as another surfactant to overcome hard cake formation. It mitigated the settling rate of the particles, but reduced the permeability of the magnetorheological fluids significantly, thereby, reducing its performance (Powell et al., 2013). Thixotropic agents and carbon fibers have been used to separate the magnetic particles by forming strand or chain like structure that encompasses and traps the particles and separates them (Zhang et al., 2009).

Coatings were also considered as an alternative to surfactants. Jang et al. (Jang et al., 2005) experimented by using the polyvinyl butyral coating on the iron particles. It showed improved anti-corrosion characteristic of the magnetorheological fluids, apart from reducing particle density, thereby preventing the formation of hard cake.

PMMA (poly(methyl methacrylate)) coating on the iron particles considerably reduced sedimentation as a result of decrease in particle densities owing to encapsulation of the iron particles by PMMA (Cho et al (Cho et al., 2004)). The use of magnetic nanoparticles (up to 3% volume) along with particles (up to 32 % volume) suspension displayed excellent stability, avoiding the hard cake formation (Iglesias et al.) (Iglesias et al., 2012).

Nanoparticles occupy the voids between the micro particles and form regular chains on application of magnetic field. This increases the yield stress of the fluid (Ashtiani et al., 2015a). Portillo (Portillo & Iglesias, 2017) experimented with the shear stress and strain rate of the fluids where nanoparticles were added to the magnetorheological fluids. It was found that the shear stress was greater in the sample with nanoparticles compared to the one without nanoparticles. It was discovered that the nanoparticles formed a "halo" around the magnetic iron particles and thus helped in preventing agglomeration and aided in re-dispersion. Addition of nanoparticles also showed an increase in magnetic field induced variation in viscosity and offered a better solution to sedimentation problems as against surfactant addition.

Clumping effect

This effect arises as a result of very high magnetic field for a long time that causes the entrapment of particles in the form of chains letting the carrier fluid flow freely. These chains adhere to each other as they come together. Shear deformation then causes shear thinning behavior. It is noted that clumping is different from agglomeration as the former occurs at high currents causing iron particles to be locked in position along the magnetic field lines. The carrier fluid is, however, able to move freely leaving behind the iron particles. When force is applied on the iron particles that are locked in place, they come together and form a cluster. It can be said that clumping may be causing agglomeration. However, agglomeration can result even at low currents due to remnant magnetism of iron particles. Hard cake is a phenomenon that involves agglomeration of iron particles which then sediment owing to increase in density. Thus, clumping could be a cause for hard cake formation as well. In a study by Huang et al. (Huang et al., 2012), it was demonstrated that the squeezing force required shows an increasing trend with the increase in magnetic field, when the clumping effect in an MR damper was absent. However, in the presence of clumping effect, the squeeze force exhibits no such ascent, thereby, diminishing the effectiveness of the damper.

Fluid particle separation

Fluid particle separation occurs as a result of the compression in squeeze mode when the particles or liquid separate out radially perpendicular to the direction of compressive force.

Ismail et al. (Ismail & Aqida, 2014) studied the behavior of fluid when subjected to compressive forces and concluded that fluid separates from the particle phase changing the particle chain structure as well as causing pressure build up due to an increase in resistance to compressive force developed. The strength distribution of the fluid also drops which leads to reduction in squeeze force. It was observed to occur in fluids of low viscosity, low compression speed, and high applied current among which viscosity was the major factor causing fluid particle separation. Hence, the viscosity of fluid should be sufficiently high when the fluid is subjected to compressive force in order to prevent fluid particle separation.

Oxidation of particles

Oxidation of particles is a chemical process that usually occurs in the presence of air and moisture. This causes rusting of iron particles used in the magnetorheological fluids which may severely affect the performance of magnetorheological fluids. Magnetization of the particles decreases as a result of exposure to atmosphere and high temperature which increases the off state viscosity because of increase in solid volume. It was also speculated that oxidation may be a cause for in use thickening of the magnetorheological fluids owing to prolonged usage for a long period of time (Wahid et al., 2016). Young-Min Han et al. (Goncalves et al., 2005) studied the effects of using corroded iron particles to synthesize magnetorheological fluids and its performance in MR devices. It was observed that the shear stress values were very low and the response time was very high. Also, the particles that had undergone corrosion for a longer period of time exhibited even lower shear stress values. Performance of an MR device depends directly on the shear stress values. Higher values of shear stress denote good performance whereas lower values of shear stress imply poor performance of an MR device. Solutions to the oxidation problem include organic coatings (Jang et al., 2005) as well as electro-less nickel plating (Ulicny & Mance, 2004) on the iron particles which reduce the exposure of iron particles to atmosphere for long duration. Carlson [69] used sodium nitrite as rust inhibitor in magnetorheological fluid instant mix.

Stability

Stability is the resistance of magnetorheological fluids to withstand sedimentation and agglomeration of magnetic particles. Sedimentation stability is the property of the magnetorheological fluids to resist sedimentation such that the magnetic particles remain suspended homogeneously within the fluid system. Agglomerative stability is the ability of the fluid to remain dispersed and not agglomerate in the absence of magnetic field. Sedimentation stability increases by 92% on adding 3% by weight of stearic acid (Rabbani et al., 2015). Dispersibility of the iron particles can be improved by addition of iron naphthalate and iron stearate (Olabi & Grunwald, 2007). Studies by Wu et al. (Wu et al., 2006) on the effect of guar gum addition in order to enhance sedimentation stability of the magnetorheological fluids showed that only 2–3% sedimentation occurs in a period of 3 months. Jang et al. (Jang et al., 2015) added magnetic γ-Fe_2O_3 nanoparticle additives to micrometer-sized CI-based magneto-rheological fluids to improve the yield stress and lessen the sedimentation of the fluid.

Sedimentation is typically controlled by the use of thixotropic agents and surfactants such as xanthan gum, silica gel, stearates, and carboxylic acids. The thixotropic networks disrupt flow at very low shear rates exhibiting high viscosity, but thins as the shear rate is increased. Network of swollen strands are formed by stearates when used with synthetic and mineral oils that serve to entrap particles and immobilize them.

Nanoclay when added to magnetorheological fluids also brings down sedimentation. Grease as an additive to improve sedimentation stability was attempted by Premalatha et al. (Premalatha et al., 2012). Although it showed good results, it could not encapsulate the magnetic particles as well as guar gum. Thixotropic additives such as sodium stearate and lithium stearate (Olabi & Grunwald, 2007) have been used to enhance the sedimentation stability of the carrier fluid. Ashtiani et al. (Ashtiani et al., 2014) performed test using stearic acid as an additive. Stearic acid was added to the carrier fluid which then formed a gelatinous network that enhanced the density allowing it to trap the magnetic particles and prevent sedimentation. Particle sizes also determine stability of the magnetorheological fluids to a large extent. Particles smaller than a micrometer do not produce sufficient yield stress for the operation of the magnetorheological fluids.

Ierardi et al. (Ierardi & Bombard, 2009) showed that fine grained particles exhibit higher yield stress whereas a mixture of fine and coarse grains show lower OFF state viscosity. Lopez-Lopez et al. (López-López et al., 2006) prepared the magnetorheological fluids with particles of size 100 nm but discovered that the yield stress was considerably low and could not cause significant damping action. Magnetic Gradient Pinch valve, a new MR valve with circular controllable apertures with a reversible jamming mode operation of magnetorheological fluids by Carlson et al. (Goncalves & Carlson, 2009), could make use of large particle sizes that would not affect the performance of the magnetorheological fluids. MR brakes make use of large size particles for synthesis of magnetorheological fluids in order to generate the necessary shear stress (Sarkar & Hirani, 2013). Bombard et al. (BombardA et al., 2003) established the fact that a mixture consisting of carbonyl iron particles of different sizes improves the rheology of the magnetorheological fluids by increasing the yield stress and decreasing the OFF state viscosity. Bell et al. (Bell et al., 2007), de Vincente et al. (Vicente et al., 2011), and Jiang et al. (Jiang et al., 2011) have demonstrated that the sedimentation stability as well as yield stress enhancement takes place by incorporating nano and micro wires instead of spherical particles.

Choi et al. (Choi et al., 2006) discovered that the dispersion stability of the fluid is improved by coating the particles with polymers. Apart from the geometry and size of the particles, the concentration of the particles also influences the stability of the magnetorheological fluids. The concentration is usually determined by the application for which the magnetorheological fluids are being used. Typical values for the concentration vary from 20 to 40% by volume for a size of 3–5 μm while the particles of size greater than 100 μm cause wear, friction, and erosion. However, particles sizes up to 120 μm have been used in applications needing large shear force, such as in brakes (Sarkar & Hirani, 2013).

Temperature effects

Temperature effects on magnetorheological fluids have caused alteration in viscosity as the latter is dependent on temperature. The operating temperature for magnetorheological fluids may range from − 20 °C to 150 °C depending on the application. Beyond this temperature range, it is observed that the viscosity of magnetorheological fluid is not controllable and the semi-active control is compromised. Chen et al. (Chen et al., 2015) studied the effects of temperature on magnetorheological fluids and proposed a relation between the two variables. It is noted that shear stress is not affected in the optimum working (100 °C) range but shows an irregular variation beyond 100 °C. Viscosity being proportional to shear stress is affected by temperature. Also, temperature rise to a very high value can cause oxidation effects which could cause significant spalling of the iron particles. Gordaninejad et al. (Sahin et al., 2009) have explained the effect of temperature on MR effect based on Bingham plastic model. Mohammad Meftahul Ferdaus et al. (Ferdaus, 2014) have demonstrated the decline of viscosity with rise in temperature using Lord Corporation's MR damper. Altering the position of electromagnet and external magnet were tried to reduce temperature effects with some improvements.

Sealing issues

Sealing issues in magnetorheological fluids mainly result due to drop in viscosity of oil generally due to increase in temperature. The solutions to overcome temperature effects on the magnetorheological fluids solve these issues. Cylindrical seals have been used to overcome leakage of fluid occurring because of sudden changes in viscosity (Bajkowski et al., 2007). Seal damage due to particle shape and certain additives may also result in leaks.

Time response

Time response of magnetorheological fluids is a crucial factor necessary for semi-active control. It depends on the type of application for which the magneto rheological fluid is being used. For a MR damper, Koo et al. (Koo et al., 2006) had conducted several experiments to determine the parameters affecting the magnetorheological fluids in a MR damper. It was observed that the current bears no influence on the response time while an increase in the piston velocity causes an exponential decrement in the response time. This was attributed to the compliance inherent in the system either at the test fixtures or in the damper, which was later established experimentally. As compliance increases, the response time also increases. Werely et al. (Yoo & Wereley, 2002) compared electrorheological and magnetorheological fluids valves for time response. It was found that the response time of electrorheological valves was better than the MR valves.

However, high voltage requirement and relatively low controllable range limits the use of electrorheological valves. On the other hand, MR valves although exhibiting relatively slow response have better controllability.

In-use thickening (IUT)

Magnetorheological fluids when subjected to a large number of cycles of loading exhibits an increase in OFF state viscosity at high stress and high shear rate. The OFF state force also shows an increasing trend. This turns the fluid into a paste that renders the MR damper unsuitable for semi-active control. Carlson et al. (Chrzan & Carlson, 2001) performed experiments to identify the nature of IUT and identified probable reasons behind IUT. Spalling of small scale particles, oxides, etc., from the surface of micro particles formed a network-like structure over prolonged usage causing secondary bonding between particles. This secondary bond enhances the viscosity of the magnetorheological fluids in the OFF state. Some solutions to this problem include the use of hardness enhancing additives and anti-wear or anti-friction additives in a small percentage, 0.5 to 2% by volume (Gonclaves et al.) (Goncalves et al., 2005). A good magnetorheological fluid should be able to resist IUT phenomenon which could otherwise drastically affect the damping performance of magnetorheological fluids. Jie Ding et al. (Ding et al., 2011) has also suggested that IUT phenomenon may be a result of shear thickening mechanisms owing to formation of hydro clusters at high shear stresses. Solutions to IUT include using spherical particles and eliminating use of rough particles which may form flakes or spall causing IUT.

The use of additives like fumed silica, surface coatings, and antioxidants have mitigated IUT (Foister et al., 2003; Munoz, 1997).

Erosion

Erosion occurs due to friction between particles in fluid flow. It was observed that the carbonyl iron particles undergo a structural change because of shock or friction or both. Erosion leads to irreversible thickening of the suspension degrading the performance of magnetorheological fluids (Ashtiani et al., 2015b).

Magnetorheological fluids can also lead to erosion of the container walls in which they operate. However, the use of spherical-shaped iron particles with prescribed hardness has helped in mitigating problems of erosion by magnetorheological fluids.

Addition of anti-friction additives reduces the effect of erosion. Anti-friction additives used include oleic acid (Kumbhar et al., 2015), zinc dialkyldithiophosphate, and organomolybdenum (Foister et al., 2003).

Yield stress

Yield stress is a property which should be high for magnetorheological fluids to be used as dampers. Rabbani et al. (Rabbani et al., 2015) have established the relationship between temperature, magnetic field strength, and the maximum yield stress. Arrhenius analogy was applied along with their own adjustments. It was observed that as the magnetic field strength is increased, the maximum yield stress shows a significant increase. However, with an increase in temperature, both yield stress and viscosity declined. When the temperature was decreased, no significant increase in yield stress was seen showing that the decline in yield stress with increase in temperature is irreversible. This happens as the gel structure of the fluid is disturbed on increasing temperature which brings down yield stress. However, reduction of temperature does not re-construct the gel structure which explains why the yield stress does not show an increase with reduction of temperature. It was also noted that the effect of temperature is secondary to magnetic field strength.

Interior wall incrustation

After long time storage, it is observed that the magnetorheological fluids forms a crust and adheres to the walls of the container. This renders the fluid unsuitable for further use. The probable reasons for the crust formation are the agglomeration of the particles followed by adhesion on the container walls. The adhesion may be an effect of guar gum. It was observed that the crust hardens with time. This may be because of the removal of oil from the crust as a result of evaporation. It was observed by Zhang et al. (Zhang et al., 2012) that nanoparticles which float partially on the liquid surface and provide some weak adsorption sites lead to enhanced evaporation.

Instabilities of a pressure driven flow

The problem of particle clogging in MR devices subjected to non-uniform magnetic field was suspected to occur because of instabilities arising when the flow of magnetorheological fluids is pressure driven (Rodríguez-Arco et al., 2013). Pressure-flow rate curves for the magnetorheological fluids flow through a tube subjected to non-uniform magnetic field were plotted as shown in Fig. 1.

It was observed that a local minimum is obtained at a particular speed and the flow becomes unstable in the range of imposed speeds corresponding to the decreasing branch of the curve. Steady state flow is noticed at speeds corresponding to the increasing part of the curve. The curve showed different trends as result of the competitive effects of hydrodynamic dissipation and interaction between the aggregates and the tube walls. The interaction forces between particles and tube walls decrease with increasing speed as the particles do not get sufficient time to get concentrated in the region of high magnetic field. The shape of the pressure-flow rate curves indicates the range of speeds where the instabilities occur. So, the operating speeds are kept outside the range of instabilities in MR applications.

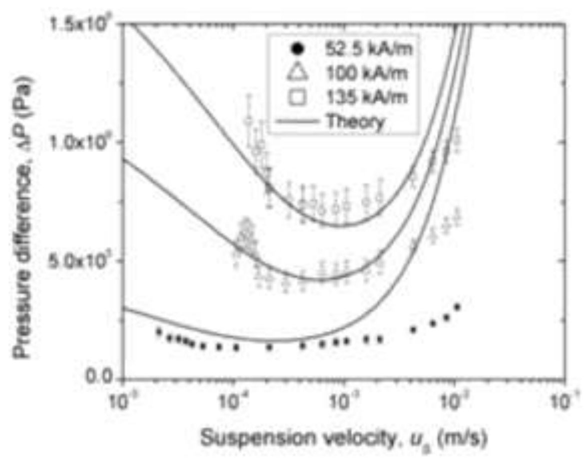

Fig. 1 Pressure flow rate curves at different magnetic fields ((Rodríguez-Arco et al., 2013) Rodríguez-Arco et al.)

Challenges in control of magnetorheological fluids and devices

The versatility of magnetorheological fluids to be changing its apparent viscosity and rheological properties is accomplished through control of the magnetic field, which may be semi-active or active depending the way the control is achieved.

Passive control

Passive control of devices involves control of vibrations and shocks by using natural or artificially engineered systems like polymers, springs, and fluids. In passive control, vibration isolation is at certain selected points or for a designed range of frequencies. Beyond the designed range, passive control is rendered ineffective. Examples of passive dampers are gas charged systems, spring mass absorbers and isolators, hydraulic piston cylinder arrangements, and polymeric vibration mounts (Rao, 1990).

Vibration absorber is a spring mass system designed to absorb vibrations of certain excitation frequencies that is affixed at the point where the level of vibrations is to be alleviated. The vibration absorber exerts an equal and opposite force in response to the excitation force as a result of which the main mass is left undisturbed. Thus, the vibration absorber transfers the excitation on the main mass to itself, conserving energy of the system in the process (Malik, 1990).

Vibration absorbers are implemented by attaching a resonant mass which counteracts the incoming vibration to the original mass. The resonant frequency of the vibrating structure should be at least 20% away from the tuned frequency of the absorber. Practical range of operation is determined by the size of the absorber. The operating range will be large if the absorber mass is large and will be small if the absorber mass is small. Also, the amplitude of vibration will be small only if the absorber mass is large. Thus, if the weight of the absorber is reduced, the effectiveness of the absorber will be compromised.

Narrow bandwidth is the major limitation of passive vibration absorbers which if increased also increases the weight. Beyond the designed range, the absorber is ineffective. Passive vibration absorber is useful when the excitation frequencies are nearly constant (Kelly, 2012).

Anti-resonance force isolators are types of vibration isolators that have a spring and force generator. The dynamic force produced in the force generator is opposed by spring force at anti-resonant frequency.

Other passive vibration isolators include tuned mass dampers which dissipate the oscillatory energy and negative stiffness isolators that isolate low excitation frequencies including soft elastomeric and rubber pads that inherently require relative large deflections while absorbing the energy of vibration.

Semi-active control

Semi-active control implies control of vibration in which the stiffness of the vibrating system can be adjusted to isolate unwanted variable frequency excitations.

MR converter (MRC) was one of the first devices that made use of magnetorheological fluids developed by Kordonsky 1993 which provided controllable hydraulic resistance. MR shock absorbers as well as MR seals were some of the early devices employing magnetorheological fluids.

Karnopp et al. (Karnopp et al., 1974) suggested one of the earliest semi-active suspensions that could be almost as effective as an active suspension. The advantages of semi-active devices were that in function it could behave as an active device. However, if the power to device failed, it could still act as a passive device. Thus, it overcame the limitation of passive dampers and had the advantage of an active suspension.

Ashour et al. (Ashour et al., 1996) discussed the basic properties of magnetorheological fluids for their potential applications in vibration control problems. Exercise machines were some of the earliest applications of magnetorheological fluids.

Karnopp (Young-Tai et al., 2005) introduced the sky-hook controller which exhibited satisfactory vibration control. Using skyhook control along with Preisach hysteresis model for predicting vibration isolation, Choi et al. demonstrated better control in time and frequency domain compared to conventional models.

LQ (linear quadratic) control, PID (proportional integral differential) control, and sliding mode were other control techniques to demonstrate semi-active control.

Although semi-active control provides fast response and has relatively low power requirements, efficient modeling and prediction of its high nonlinear dynamic nature is a challenge.

Active control

Active control of vibration is the continuous sensing of the incoming excitation and subsequent application of counteractive forces to nullify the disturbances. It is the superimposition of secondary vibrations on the primary sources to obtain a minimum residual signal.

Collete et al. (Collette et al., 2011) stated the advantages of active vibration control over passive control in that the active vibration isolation strategies eliminate the tradeoffs observed in passive control. In passive control with damping, amplitude of vibrations is reduced at lower frequencies, but it causes degradation of isolation at high frequencies. This tradeoff between damping and isolation is termed as first trade off. The second tradeoff is between the insensitivity to external force and isolation at frequencies below resonant frequencies. Three practical realizations of sky hook spring are obtained by locating the inertial reference on the equipment, on the ground, and by mounting an intermediate mass on a piezoelectric actuator which is connected to the equipment by an elastomer layer. It is suggested that the stiffness of the practical realizations of the isolator can be modified by using different sensors and actuators. Comparisons between soft, medium, and stiff strategies are also covered. Soft strategies offer isolation at wide range of frequencies but are very sensitive to external disturbances. Medium strategies have relatively low dynamic stiffness and are not sufficiently robust to external disturbances. Stiff strategies are insensitive to external disturbances but may lead to instabilities as the ground gets strongly coupled to the equipment.

Active control is used mainly in precision machining applications or sensitive fabrication and in damping vibrations in large structures such as in telescope mounts, where the system should be vibration free.

Active vibration control is implemented in smart structures consisting of smart sensors and actuators with a control unit that can apply corrective action without manual interference (Rao, 1990).

Some control algorithms used for implementing active vibration control are now reviewed.

Bang–bang controller or hysteresis controller or on–off controller (Obrien, 2007)

A Bang-Bang controller makes use of a feedback controlling element that switches instantly between two states generally ON and OFF. Any system possessing hysteresis characteristics can be implemented using Bang-Bang controllers. Discrete controllers are variable structure controllers as the output is discontinuous.

Linear quadratic regulator (Bemporad et al., 2002)

System dynamics are represented by liner differential equations for which the solutions are obtained based on linear quadratic Gaussian problem where the cost is a quadratic function. Linear quadratic regulator is a feedback controller used for active control.

Limitations of active control are that the control fails completely when the components of the system fail. Also, the design of active control is complex and its implementation is expensive.

Models used for analysis of MR damper

Modeling of MR dampers can be divided into parametric and non-parametric. Parametric modeling involves use of physics to represent the system in the form of spring, dashpot and body mass and subsequent analysis of the system dynamics. The model assumes certain parameters. The error between the theoretical results obtained on using the assumed parameters and experimental values are minimized by applying suitable correction to the parameters. Non-parametric modeling includes analytical expressions to represent the behavior of the system in the form of functions followed by the use of certain logic and fitting techniques to determine the empirical constants (Wang & Liao, 2011). Parametric models include rheological laws that explain the fluid behavior.

Some of the parametric models are:

1. Bingham viscoplastic model (Braz-César & Barros, 2013)

Bingham model is used for explaining the rheology of non-Newtonian fluids that flows only if yield stress is reached. It assumes that magnetorheological fluids are rigid until a certain yield stress is reached. The main advantage is that Bingham model is very simple to use and it gives sufficiently accurate values. However, it gives efficient results only for low shear rates and post-yield region of magnetorheological fluids and it cannot explain velocity nonlinearity.

The governing equation is: $\tau = \tau_y(H) + \eta\dot{\gamma}$
where
τ = total shear stress
$\tau_y(H)$ = magnetic field-induced shear stress
η = coefficient of viscosity
$\dot{\gamma}$ = shear rate.

2. Bouc-Wen model (Braz-César & Barros, 2013)

Bouc-Wen model is used to express nonlinearity and hysteresis behavior of fluids. This model could describe the force-displacement relationship well along with hysteresis behavior. However, this model fails to fit inertial effect caused by low damping force attenuation phenomenon. Also, this model is relatively complex.

The governing equations are:

$R = \alpha kx + (1 - \alpha)kP$

$= A - \beta| \ ||P|^{n-1} \ P - \gamma \ |P|^n$

where

R = restoring force

k = stiffness coefficient

α = ratio of post yield to pre yield stiffness

P = hysteresis displacement

γ, A, n, and β are parameters that control hysteresis shape.

3. Herschel-Bulkley model (Chooi & Oyadiji, 2009)

Herschel-Bulkley model expresses the relationship between shear stress and shear strain rate in a nonlinear manner. Bingham model is a special case of Herschel-Bulkley model. This model is relatively complex for solving analytically and hence demands use of numerical methods to solve. Despite having few drawbacks, Herschel-Bulkley model takes care of shear thinning and shear thickening effects at high shear rates.

The governing equation is:

$\tau = \tau_y(H) + (\eta \dot{\gamma})^{1/m}$

where

τ = total shear stress

$\tau_y(H)$ = magnetic field induced shear stress

η = coefficient of viscosity

$\dot{\gamma}$ = shear rate

m = index which depends upon whether post yield flow is shear thinning or shear thickening.

Synthesis of magnetorheological fluids

The synthesized magnetorheological fluids with the following compositions by weight fraction of constituents used in the preparation is shown summarized at Table 3.

The magnetorheological fluids consisted of electrolytic iron particles as the magnetic particles, silicone oil as the carrier fluid, and guar gum and stearic acid as additives. The morphology of the electrolytic iron particles obtained through SEM technique is shown in Fig. 2.

Figure 2 shows the morphology of electrolytic iron particles. The particles are mostly of distorted rod-like structure along with few other shapes and sizes.

Procedure followed for preparation is as follows:

1. Electrolytic iron particles were mixed and coated with guar gum for 30 min at 400 rpm in stirrer.
2. Stearic acid was mixed with silicon oil and stirred for 30 min under 400 rpm using a stirrer.
3. The electrolytic iron solution was added to silicon oil solution with constant stirring periodically.
4. The MRF after preparation was stirred continuously for 5 h for obtaining a stable solution.
5. Each sample was taken in separate test tubes named A, B, and C and kept for analyzing anti-sedimentation property of MRF.

The three samples produced were observed over a period of time for sedimentation and separation of constituents. The results are show at Fig. 3a, b.

Table 3 Composition of MR fluid by weight fraction of constituents used in the preparation

Sample	Constituents		
	E.I powder (electrolytic iron) (%)	Additive (stearic acid + guar gum) (%)	Silicone oil (%)
A	60	3	37
B	30	0	70
C	30	3	67

Results and discussions on sedimentation

The experimental results clearly show the effect of additives (stearic acid and guar gum) on anti-settling properties of magnetorheological fluids. The sample A having 60% by wt. electrolytic iron particles with additive concentration of 3% by wt. was found to be having the least sedimentation rate. Comparing sample B and C, sample C with additives added took 9 h more than sample B to sediment. This clearly shows that addition of additives partially overcomes the sedimentation

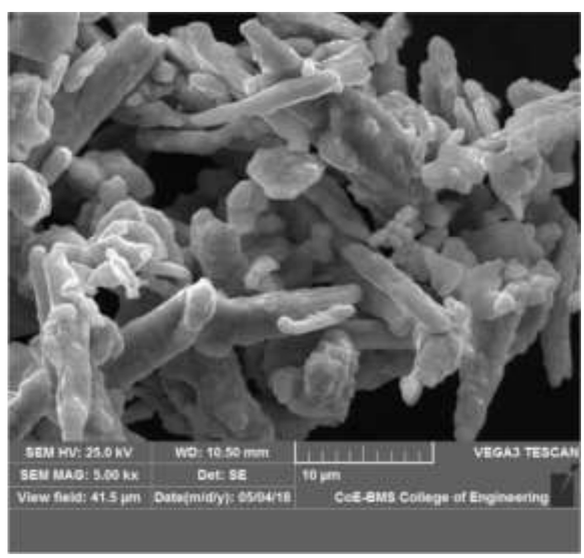

Fig. 2 Morphology of electrolytic iron particles

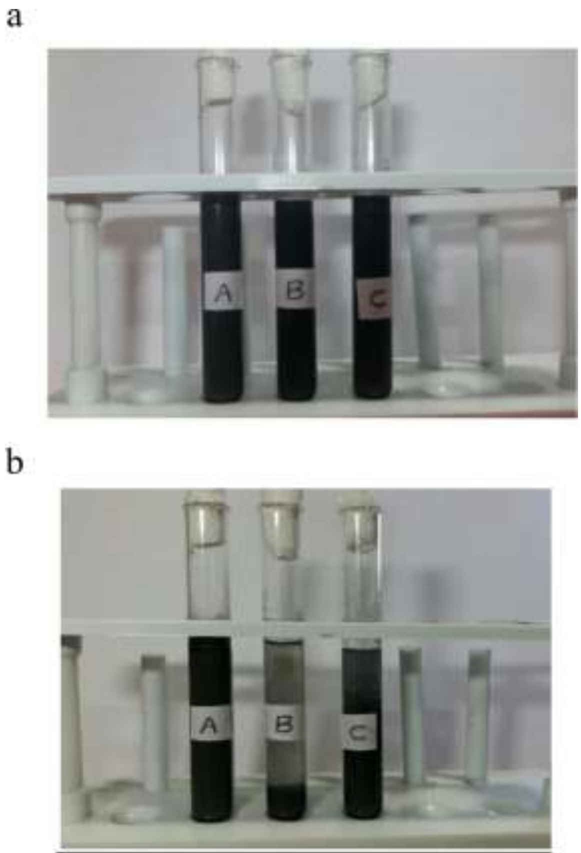

Fig. 3 a Three samples immediately after preparation showing no sedimentation. b Sample results after 15 h for the same three samples showing least sedimentation in sample A

problem due to density differences among suspended particles and carrier fluid.

After 2 to 3 months, the magnetorheological fluids formed interior wall incrustation inside the container as shown in Fig. 4a and b.

The morphology of the incrustation was obtained by SEM technique as shown in Fig. 5. The morphology shows the iron particles in a cluster with guar gum and stearic acid particles. Traces of oil between the particles are observed. The cluster indicates agglomeration of iron particles of varying shapes and sizes with guar gum particles dispersed around. The incrustation observed was perhaps due to the agglomeration of iron particles with moisture content and coating of these agglomerates with guar gum instead of individual particle coating resulting sedimentation after a long period. Silicone oil may have caused adhesion of particles to the container walls. The crust also indicates rusting of iron particles as a result of oxidation after 2 months due to exposure to atmosphere.

To prevent incrustation, the magnetorheological fluids are to be stored and sealed against moisture. The use of anti-corrosion additives such as polyvinyl butyral (Jang

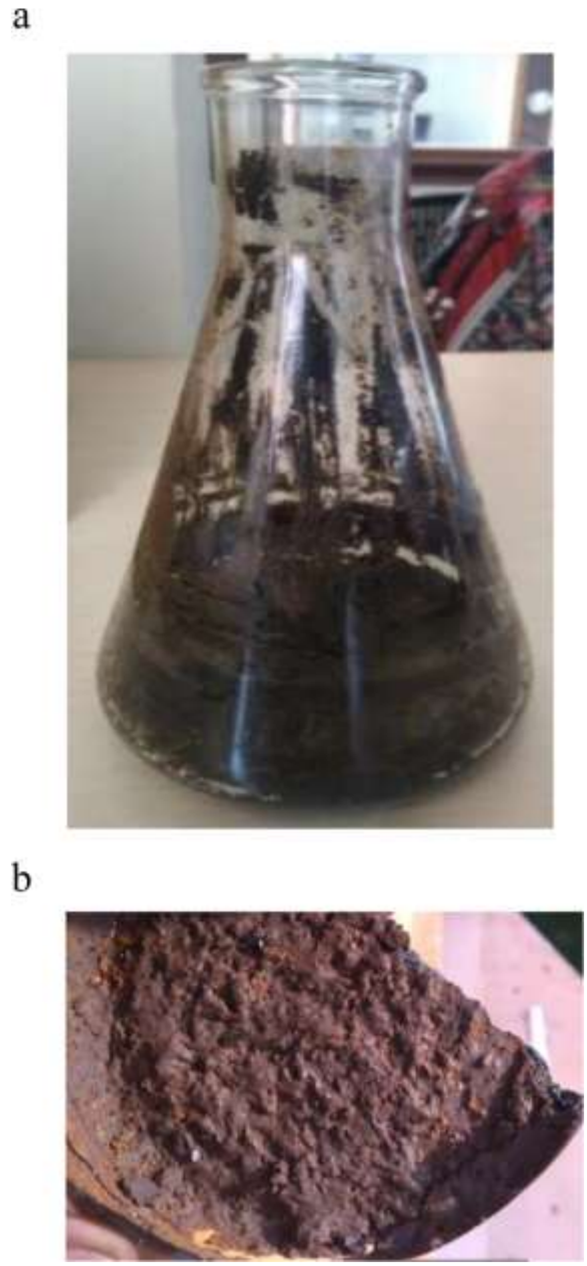

Fig. 4 a Interior wall incrustation. b Incrustation at the bottom of the container

et al., 2005) aids in mitigating rusting. Repeated periodical use of magnetorheological fluids reduces incrustation. During the course of review of the additive combination and process methodologies available for stabilizing MR fluids, experiments were conducted to establish the trends in sedimentation for both carbonyl iron as well as electrolytic iron with results suggesting that a reasonably acceptable combination of the additives were obtained for use in the MR damper designed and manufactured and currently under vibration testing for vibration damping by the a

b

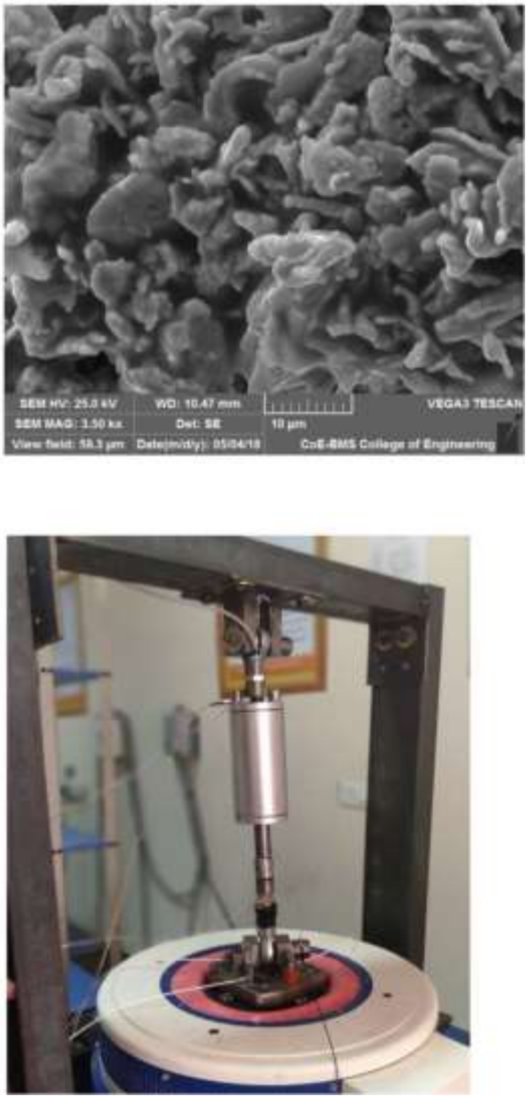

Fig. 5 a Morphology of the incrustation. b Damper test set-up where the batch of MR fluid is used

authors. The test setup of the MR damper currently under testing is shown in Fig. 5.

Applications of magnetorheological fluids

Magnetorheological fluids belong to the family of rheological materials. They have the ability to change from liquid state to semi solid state, within microseconds, under the influence of a magnetic field. Magnetorheological fluids mainly consist of base oil into which ferromagnetic particles like carbonyl iron and stabilizing agents are dispersed. The suspended particles normally remain randomly distributed in the oil. Under magnetization, they align together to form a chain like structure. This chain like structure not only increases the viscosity of the fluid, but also its yield strength.

Some applications of magnetorheological fluids follow.

MR dampers

MR dampers make use of magnetorheological fluids inside a damper that is controlled by a magnetic field.

The change in magnetic field alters the damping characteristics of the damper which has several applications. MR dampers are used in automotive suspensions to semi-actively control the system in order to reduce the amount of vibrations being transmitted to the vehicle seats thereby enhancing passenger comfort.

The suspension generally consists of a shock absorber with magnetorheological fluids, sensor sets, and an ECU (electronic control unit). The MR damper behaves like a normal suspension system when the fluid is not subjected to the magnetic field. Under the influence of magnetic field, viscosity of the fluid changes, resulting in a change in damping force. The sensors monitor the road and vehicle conditions and feed the information to the ECU. The ECU then processes this data to provide the required damping force (Rodríguez-Arco et al., 2013).

MR dampers are also used in absorbing vibrations rendered by earthquakes. They operate within the resonating frequencies of buildings, making them earthquake proof (Stutz & Rochinha, 2011).

MR dampers have found potential use in prosthetic knees to absorb shocks and vibrations during motion as well as provide articulated motion akin to limb. A group of sensors determines the instantaneous state of the knee: knee angle, axial force, and moment and swing velocity. This facilitates the magnetorheological fluids to achieve the right viscosity to provide sufficient damping force. Similar applications include damping of vibrations in cable stayed bridges, household applications such as in washing machines, and exercising machines in fitness centers [http://www.lord.com/products-and Solutions/MR/custom-solutions.xml].

MR valves and orifices in hydraulic circuits

Hydraulic circuits using MR valves use magnetorheological fluids as the working fluid. The direction of the fluid flow inside the valve is perpendicular to the external magnetic field. The external magnetic field causes the fluid to change its viscosity. This makes the valve behave like a normal 2/2 way ON/OFF valve and thus achieve the required actuation (Grunwald & Olabi, 2008).

A conventional damper in a commercial cross stepper exercise machine was retrofitted with an external throttle valve, and the hydraulic fluid was replaced with magnetorheological fluids. It was shown that the resistance of the stroke of the foot pedals could be easily adjusted by varying the current to the coil in the throttle valve (Ashour et al., 1996).

Brakes

MR brakes are semi-actively controlled brakes that work by increasing the apparent viscosity of the magnetorheological fluids when powered ON.

Mode of operation of MR brakes is direct shear mode. MR brakes consist of a rotating disk, casing, and an electromagnetic coil. The magnetorheological fluids (OFF State) are filled between the disk and the casing.

When the coil is energized, it produces a magnetic field that makes the magnetorheological fluids more viscous with high yield stress. The high yield stress acts against the shear force from the rotor and reduces its speed (Rabinow, 1951).

Vibration isolation

Vibration isolation can be done for a large frequency range using magnetorheological fluids based vibration isolator. A semi-active MR mount was designed and tested successfully for large frequency range by Seung-Bok Choi et al. (Yang et al., 2017). The MR mount was developed to resolve the vibration issues in wheel loader cabins. ON-Off controller implement- ing FFT algorithm was used to control the vibration isolation mount. It was observed that the damping force generated could be enough to attenuate vibra- tions over a large frequency range.

Magnetorheological fluid-elastomer vibration isolator which is a composite of magnetorheological fluids in an elastomer was studied for various compressive oscillatory cycles by Gordaninejad et al. (York et al., 2007). It was observed that the MRF-elastomer composite isolator could isolate vibrations of large amplitudes and frequencies. MRF-elastomer composite isolator also performed better than squeeze mode type MRF damper.

The MRF brake and clutch can be used in vehicles, in automatic conveyer tables, in vibration control of cables, for prosthetic legs, and in rotation mechanisms such as a robot joint. An MRF damper has applications in automotive suspension system as well as vibration control of seismic, washing machine, flexible structures and mechanisms such as a vibration absorber of tall building or long bridge. An MRF mount can be useful to control unwanted vibrations which occur in most dynamic systems in which an MRF damper cannot be installed due to the lack of space such as in mount for a vehicle engine, a wheel loader, a precision platform, and a mount for a compact disk.

Research gaps, status, and future trends

For improved combination of additives to be more effective against sedimentation and agglomeration, Xue et al. (Xue & Sethi, 2012), based on earlier studies of the problem of aggregation and sedimentation in underwater mediation and medical applications, proposed using guar gum (GG) and xanthan gum (XG) in diluted single biopolymer water solution to stabilize particles for limited period of time by way of steric repulsion and increase in the viscosity of suspension. Further, specific concentrations of XG/GG weight ratio, for example, 1:19 of 3 g/L of total biopolymer concentration, were shown to significantly improve stability from sedimentation due to formation of XG/GG viscoelastic gel, increase in static viscosity, the yield stress of polymer at variance with the downward stress of iron particles, and the floatation tendency due to adsorption of polymers onto the surface of iron. When used separately, the water solution of each of GG and XG behaves viscous, but when mixed together, they form a viscoelastic gel solution preventing sedimentation for long periods. This combination of additives provides cues for further work in oil-based MR fluids.

Portillo (Portillo & Iglesias, 2017) used nanoparticles having an average size of around 7.8 nm with the ferrofluid carrier's solid concentration of 6.2% by volume. The results apparently showed no agglomeration. However, the MRF with the use of nanoparticles has not been tested for extensive cycling and periods of time to establish the efficacy in service. The effect of nanoparticles on fluid behavior in terms of viscosity, shear thinning, or thickening needs examination when used in cyclical operation system such as dampers.

Despite studies undertaken to characterize and to enhance performance of MR fluids, limited comprehensive approach is seen in efforts to improve field dependent yield stress, sedimentation mitigation, specific heat transfer properties, lubrication and wear patterns over service life, and fatigue behavior under prolonged repeated loading cycles (Choi (Choi & Han, 2013b)). Study of variables in combination and interaction of the variables such as fluid parameters is rare. These variables include particle size and shape, additives, viscosity of carrier fluid, conductivity, magnetic permeability of particles, and operating conditions including temperature, as well as, magnetization and the integrated system components and subsystems performing sensing and current output control such as in the case of semi-active and active magnetorheological fluid-based systems. Evolving standards in this domain for applications and benefits from large volume applications is yet to be charted. Such integrated research may be necessary to establish the long time response and behavior of magnetorheological fluids in integrated systems.

This research need arises from reliability considerations and the differences in the morphology of MR fluids arising from the requirement for properties specific to applications, such as smaller particles for dampers and larger particles for brakes and clutches (Sarkar (Sarkar & Hirani, 2013)) or varying particle sizes for better broad set of properties (Vicente et al., 2011; Bell et al., 2007). The effectiveness of magnetorheological dampers and devices will depend on real-time response to changing inputs. The response time of standalone MR fluid of 3 ms is seen commonly. But the response time of integrated systems change with varying fluid parameters, magnetization, and the integrated system components and subsystems performing sensing and control such as in the case of semi-active and active magnetorheological fluid-based systems. Such study is essential for accurately predicting the system behavior and the usefulness of the devices in rapidly changing environments such as automotive suspensions and airborne vibration isolation systems and to a more predictable degree in limb prosthetics and haptic applications.

Phu and Choi (Phu & Choi, 2019) reviewed MR fluid devices such as MRF brake, clutch, damper, and MRF mount with applications in vibration control of an automobile, vibration control of seismic, and several different rehabilitation prosthetics and suggested solutions for problems of block-up or agglomeration, where the fluid flow is restricted due to blockage by iron particles in applications of vibration control of an automobile, seismic disturbances, and several different rehabilitation prosthetics.

The devices are inherently complex due to moving elements, sealing requirements, packaging of electromagnetic circuit, and its controls. There is need for research to develop innovative designs to enhance reliability and simplify the packaging of the various parts with ease of assembly and dismantling for maintenance.

There are new areas of applications. But with emergence of newer areas, the need for comprehensive long-term multi-variable research is essential, but appears to be minimal.

Yin (Yin et al., 2018) proposed a solution to the problem of repeated X-ray exposure during procedures for medical catheter interventions, by using a MR fluid-based haptic robot-assisted master-slave system. The system has a MR fluid-based haptic interface to provide controllable haptic sensation to the catheter operator. Further, the intervention kinematics motions are captured to control the slave robotic catheter. Also developed is the slave catheter operating the mechanical system to manipulate the one to one motion of the surgeon performing the procedure through two-DOF motion consisting advance, retreat, and rotation including force feedback.

As the problem of sedimentation posed concerns, the focus shifted towards the magnetorheological elastomer (MRE) belonging to MR material family, which is a composite material with magnetic-sensitive particles arranged or embedded in a non-magnetic elastomers matrix (Carlson & Jolly, 2000). This MRE overcomes the problems faced by MR fluid such as deposition, sealing, and environmental issues, and hence, it was successful in controlling vibration. However, the development of MRE has posed difficulties in characterization and analysis due to the inherent inconsistency due to variables in preparation of MRE.

Kallio (Kallio, 2005) stated difficulties in use of MR elastomers in bonding, accurate characterization for modeling, and prediction due to variables in MRE preparation, curing, and room temperature vulcanizing. In compression, the mechanical behaviour is reported to be complex due to factors such as, static or dynamic loads, force, frequency, strain, magnetic field and directional variations in properties. The variations in the results reported is also perhaps due to the directions of applied load, magnetic field, and particle chains having significant effect on damping and stiffness, and therefore, there is need for further study. Lockette (von Lockette et al., 2008) examined the bimodal behavior of MRE and found inconsistency in the results compared to unimodal behavior. Wu et al. (Wu et al., 2009) found that dispersing of CIP needed surface modification and ball billing, but this had an effect of lowering the MR effectiveness. Increase in percentage of CIP resulted in phase separation reduced thermal stability, and it was concluded that a compromise is needed to balance the mechanical and MR properties in longer service life.

In a detailed review, Li (Li et al., 2014) 2014 summarized that though MRE overcomes some of the limitations of MRF such as settling and sealing problems, frequency shift characteristics rendering the MRE tunable, large modulus range, and faster response, the following are reported to be impediments to its extensive use:

- Inadequate studies in combined loading problems that is characteristic due to use of MRE.
- Versatilities of MRF renders them amenable to tunable design functionalities for applications such as brake systems, haptic devices, and polishing and predictable variable damping needs which are all perhaps better than MRE.
- MRE self-sensing capabilities are yet to be evolved fully.
- Inherent conflict exists in MRE characteristics as soft matrix provides large MR effect, but it is accompanied by lower load capability and durability and longer vulcanizing time requirements of few days.
- Relatively higher power requirements are specified with larger foot print of the device limiting the application areas.

Koo et al. (Koo et al., 2006) had established that low frequency applications such as in lower piston velocities resulted in minimal temperature effects in MR fluid systems. It implies that MR fluids may better suit low frequency operations such as in helicopters and automotive applications which is the area of research for the authors of this paper.

Magnetorheological fluids were assessed for efficient reduction in tool vibration. However, there is a lack of systematic published studies on the variation of properties in working environment for longer durations. Factors affecting the stability of MR fluid in operation are friction and temperature, and the resultant changes in properties over extended periods of time, fluids subjected to thickening after prolonged use, and settling of ferroparticles. These factors are a concern due to the degradation in the performance of the fluid being employed (Sam Paul et al.) (Sam Paul et al., 2015). The comprehensive analyses of methods to overcome these difficulties has not been found adequately researched in literatures. It has been reported that the increase in the percentage of iron particles has increased the effect of damping in turning, but the problem of sedimentation adds to its drawback (Sam Paul et al.) (Sam Paul et al., 2014).

Uttami et al. (Utami et al., 2018) investigated effects of long-term cyclic loading on MR fluid as well as on the MR Valve material surfaces over 1,70,000 cycles. In-use thickening was reported with exponential increase in the damping force and viscosity changes in both ON and OFF state. The reasons attributed by JD Carlson (Carlson, 2002b) for IUT was to the brittle oxidized layer of iron, carbides, and nitrides fracturing into particles of nanosize, under stresses developed due to loading. More important are the wear observed on the interior wall of the MR valve as well as change in shape of the carbonyl iron particles. The combined effect is the change in the MR fluid rheology that may render it unsuitable for further use. The thinning or reduction in number of suspended particles may be due to shear-induced migration, gravity force, and remnant magnetization on the interior of magnetic materials used to house the coil or MR valve and centrifugal forces which result in agglomeration and settling thus reducing the number of particles in suspension. Incrustation or clot on the inner walls after extended cycles restrict the flow paths and result in increase in damping force that may appear as IUT. Further, it was reported the viscosity of the used MR fluid at 0.1 Pa s after the fluid was subjected to 170,000 cycles is ten times lower than its viscosity before the long cyclic operation (1 Pa s). The experimental conditions and the damper designs are different in the two studies (Utami et al., 2018; Carlson, 2002b) with internal valve passage and meandering external valve respectively. Clearly, the exact mechanism of changes in rheological properties, damping force, and changes in ON state and OFF state viscosity as also the response to shear rate need a detailed research with use of such devices and the fluid variables over a longer period of use to ensure reliable operation.

Research to minimize the amount of fluids has led to innovative mechanical designs and fluid flow paths. Minimizing the MR fluid volume used is a factor for researchers due to its high cost (over $800 for 500 ml) when used in larger vibration isolation systems. Therefore, innovative fluid flow channel designs, coil arrangement, and permanent magnets to produce large range of damping force with minimal fluid have been researched such as several combinations of multiflow, multicoil double-tube shock absorber using both MRF and an ordinary fluid (Yuan et al. (Yuan et al., 2019)).

To improve the effectiveness of channel, with a larger magnetic zone to increase the magnetic field and reduce inductance and response time, MR dampers with two, three, and more coils under a small current and a larger damping force control strategy are proposed by Yuan (Yuan et al., 2019). The use of permanent magnets facilitates to enhance the range of magnetization along with variable coils by aligning or opposing directions of magnetic flux lines and consequently improves the range of the damping force. The permanent magnet also provides a fail-safe minimum magnetization and damping force in such designs.

There is insufficient multi-variable testing and research to establish MR fluids as the viable option forlong-term usage in service and often under harsh oper- ating conditions such as in industrial, automotive, andaerospace applications.

Future challenges

Vibration in mechanical system is still a hindrance and considered as a major concern even after considerable advancement in science and technology. In any mechanical system, amplitude of vibration will be less during initial stage and gradually increases as can be seen when machining progresses. Hence, less damping is required during the processing beginning stage and more damping will be required as the function of the work progresses. In such situation, a rheological damper where damping ability varied by adjusting the controlling parameters of damper as per the requirement through automated logic based on the real-time sensor inputs of the vibration and cutting parameters will prove to be effective. From the review of literature, it appears that research in varying the damping ability of rheological damper with many variables was not done so far. Also, from literature, it was revealed that smart material which has better efficiency in controlling vibration was not used along with active system. This applied research in magnetorheological damper will redefine the vibration reduction effectively and is expected to increase usage in future.

Conclusions

Magnetorheological fluid preparation for applications and the different additives and their use to improve performance of magnetorheological fluids was comprehensively reviewed. The challenges faced in the synthesis of magnetorheological fluids and their uses have also been categorized. The control of magnetorheological fluids and devices were also reviewed with some solutions to overcome the limitations in use of magnetorheological fluids. The models used to understand the behavior of magnetorheological fluids followed by applications of magnetorheological fluids in vibration damping and isolation are broadly visited. It is evident that managing the challenges in preparation and use with appropriate process, additives, and mixing has rendered MRF suitable for a variety of applications along with real-time control of the fluid behavior. Use of suitable viscoelastic model for the fluid and control methodologies in analyses and design make MRF useful for many applications including vibration alleviation. Apparently, further research is needed to improve the usage of MRF both in quality and low-cost quantities.

MRF continues to be researched and used, due to versatility in modes of operation, controllability, and better predictability of behavior through various nonlinear models in application areas for the MR fluid products in automotive, aerospace, prosthetics, and other medical domains. Many solutions in MRF preparation and additives have been researched to enhance the properties to mitigate problems encountered during use.

Polydimethylsiloxane (PDMS) commonly known as silicone oil has emerged as an acceptable carrier fluid for many applications. However, finding low-cost carrier fluid with favorable properties for MR fluids continues to be an area of research (Ashtiani et al. (Ashtiani et al., 2015a)). Research for low-cost solutions for MR fluid preparation would be a key driver for proliferation of MRF research-based solutions for many applications. Further, research to minimize the amount of fluids has led to innovative mechanical designs and fluid flow paths and can only be short-term solution. MR elastomers need further research for characterization and accurate modeling as well as repeatability in manufacturing process to be predictable in applications before they can be an alternative to the more versatile MRF.

Clearly, the exact mechanism of changes in rheological properties, damping force, changes in ON-state and OFF-state viscosity and also the response to shear rate need a detailed research with the use of such devices and the fluid variables over a longer period of use to ensure reliable operation.

Techniques of controlling mechanical vibration by varying damping capability of rheological fluids through active mechanism will help to minimize mechanical vibration problem in varying conditions such as in real-time operations.

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