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Review Article

A review on magneto rheological fluids and their applications

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ABSTRACT

The present work covers various advancements made in synthesis, characterization and applications of magneto rheological (MR) fluids. It also focuses upon the challenges associated with synthesis of MR fluids, appropriate measures to address the challenges associated with synthesis of MR fluids. Research gaps in the area of MR fluids preparation, characterization are identified and suitable conclusions are drawn based on the body of literature reviewed. From the review of vast literature on MR fluids, the following observations were made. High magnetic saturation, low sedimentation, high shear yield strength, high permeability are some of the desirable characteristics for selection of MR fluids for vast majority of applications. From the literature, carbonyl iron particles are found to be one of the efficient and cost effective MR fluid particles with high magnetic saturation. From recent studies, multi walled Nano tube based anti-sedimentation agents have resulted in high suspension and low sedimentation of MR particles. From some of the latest scientific studies, MR fluids made out of ionic liquids and silicon oils [17] have found to show superior shear yield strength compared to other carrier fluids like mineral oil, synthetic oils. MR fluid with carbonyl iron particle of size 4 μm, suspended in carrier fluid made out of synthetic or mineral oils is found to cater the needs of many applications.

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Certain class of fluids when subjected to magnetic or electric fields, show considerable changes in their deformation behavior and flow characteristics. Magneto rheological (MR) fluids are smart materials which show fast reversible change and undergo transition from liquid to solid state and vice-versa under the presence of external magnetic fields. Their rapid phase change characteristic is one of the contributing factors for their wide range of applications. MR fluid consists of micron sized magnetic particles suspended in non-magnetic fluid medium. Ferrous particles, have high saturation magnetization, and are the most common materials that are used as magnetic particles [2]. Typical magneto-rheological fluid consists of 3 parts: soft magnetic particles, the carrier fluids and additives [3]. Soft magnetic particles mainly include iron oxide, nickel, cobalt etc.. Among them, iron cobalt alloy has the highest magnetic saturation and its magnetic saturation can reach 2.4T. However, it is expensive. The most

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widely used materials is pure iron and carbonyl iron powder. Their magnetic saturation is approximately 2.1T. The carrier liquid is a medium for suspending soft magnetic particles. Synthetic oil, Mineral oil and water etc can be used as carrier liquid. Additives are used to improve stability and dispersing rate of ferrous particles in MR fluid. They are used to minimize sedimentation of the particles. Various dispersant and anti-sedimentation additive agents like alcohols, stearic glycerol monooleate, hydrophilic silicone oligomer, organometallic silicon copolymer, ultrafine amorphous silica are used. During recent times, multi walled nano tubes are coated on carbonyl iron particles to improve the sedimentation stability of MR fluid particles [4]. Particles coated with MWNT have shown superior sedimentation resistance compared to other conventional anti-sedimentation agents. The carbonyl iron particles concentration in MR fluid could range from 20% to 40% by volume, and the size of the particles is usually between 3 and 5 μm with a mean size of around 4.25 μm. Too low size may result in the magneto rheological fluids not developing high yield stress. Very large size of particles will result in erosion and friction. Recent studies have shown that the replacement of micron sized nano particles by a mix of nano and micro sized particles in M.R fluids resulted in better suspension and strong chain formation in response to external magnetic field [5]. This translated to better magnetic and rheological properties. However, yield strength dropped in comparison to micron sized M.R particle suspended fluids. The schematic of strong chain like structure formation is shown in figure1. Research has shown that, the shape of the carbonyl iron particles has a considerable influence on the wear of the vessel or container carrying the fluid. Spherical shaped particles are known to have less wear effect on the walls of the vessel inside which the MR fluid passes. On the other hand, fiber shaped particles showed high yield strength and low viscosity compared to spherical particles [6,7]. Varying one of the components of MR fluids influences the properties of MR fluids [8]. However, there are certain challenges associated with synthesis of MR fluids [1]. A perfect set of combinations of these three constituents of MR fluid is essential to yield desirable properties required for various applications. Table1 shows the general properties of MR fluids.

SYNTHESIS OF MR FLUIDS

The preparation of MR fluids comprises of two stages: The solid phase stage and the liquid phase. The solid phase consists of ferrous or carbonyl iron particles coated with various additives such as guar gum in a certain proportion such that the volume to mass ratio of particles increases. The liquid phase consists of a carrier fluid, to which additives are added in certain proportion so as to increase the concentration of the carrier fluid. The solid phase is then mixed with the liquid phase using a stirrer for a considerable duration.

The final mixture is then left unperturbed to observe the characteristics of the magnetic particles that are suspended in the fluid. Addition of additives and surfactants reduces the problem of sedimentation to a large extent. The function and purpose of some of the commonly used additives is illustrated in Table 2.

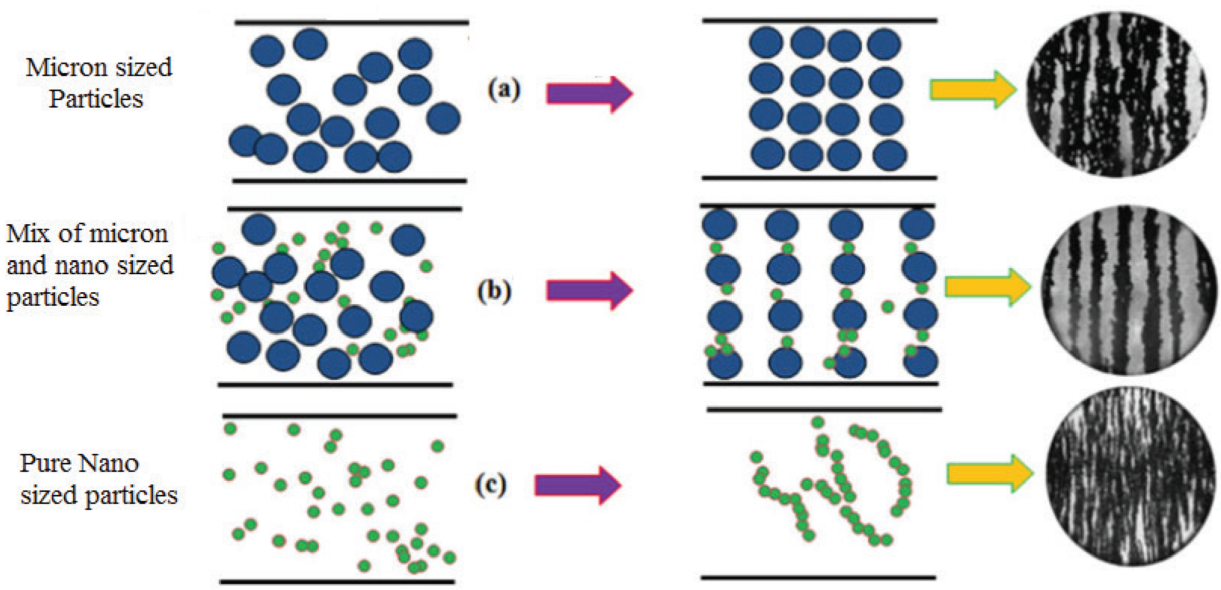

Figure 1. Size of Magnetic particles on magnetic and rheological properties.

Table 1. General Properties MR fluids and their range

Property	Typical value
Operating Temperature	(-50) to (150) ^{0}c
Viscosity	0.2 -0.3 Pa-s (at room temp)
Magnetic Field Intensity	150-250 kA/m
Density	3-4 g/cm^3
Reaction Time	Few milliseconds
Yield Strength	50-100 kPa
Voltage	2-25 V
Intensity of Current	1-2 A
Specific gravity	3-4

particles in the form of chains.. These chains stick together forming large links. This results in carrier fluid flowing freely without carrying the particles along with it[12]. Squeeze mode compression of fluid results in the separation of MR particles in radially perpendicular directions to the applied compressive force. Study indicated that when the fluid is under compressive forces, the fluid gets separated from its solid particle phase and thus changes the particle chain structure as well. This results in built-up of pressure on account of resistance offered to compressive forces [13]. Oxidation results in corrosion or rusting of iron particles used in MR fluids. This adversely affects the functionality of MR fluids. Magnetizing capability of carbonyl iron particles of the MR fluid decreases drastically due to their exposure to atmosphere and high temperature. Studies showed thickening of MR fluids when exposed to oxidation over long period of time. A study was carried out to examine the effect of MR fluid synthesized with corroded iron particles on MR devices [14]. A significant drop in performance was observed. MR fluids displayed significant changes in viscosity with changes in temperature beyond their operating temperature range of – 20 °C to 150 °C. It was observed that the viscosity of MR fluid varied uncontrollably in a rampant manner. Researchers proposed a relation between viscosity and temperature of MR fluids [15]. It was observed that the shear stress which remained unaffected in the optimal temperature range showed random variations 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. Studies illustrated the effect of

Table 2. Additives used in MR fluid synthesis

SNO	ADDITIVE	PURPOSE
1	Guar gum	Guar gum is coated on iron particles to reduce density and sedimentation
2	Polyvinyl butyral	Polyvinyl butyral is coated on iron particles to reduce density and improve anti-corrosion strength.
3	Tetramethylammonium hydroxide	Tetra methyl ammonium hydroxide is a surfactant coated on iron particles to reduce agglomeration of particles
4	Olefin polymer emulsifier	Olefin improves sedimentation time and increases stability of MR fluid.
5	Grease	Grease reduces sedimentation of MR fluid particles
6	Lecithin	Lecithin reduces the settling time of MR fluid particles
7	Oleic acid	Oleic acid is an additive which reduces friction and wear of MR fluid particles
8	iron oleate	Dispersants used to disperse the magnetic particles in the carrier fluid
9	Stearic acid	Stearic acid is used to increase density and improve sedimentation, stability of MR fluid particles
10	Cholesteryl chloroformate	Cholesteryl chloroformate enhances the thermal stability , reduces sedimentation and improves stability of MR fluid

CHALLENGES ASSOCIATED WITH SYNTHESIS OF MR FLUIDS

Synthesis of MR fluids comes with its own set of challenges. The following are some of the commonly encountered problems during synthesis of MR fluids. A. Formation of hard flake or hard cake like structure. B. Clumping effect C. Fluid particle separation D. Oxidation E. Temperature and F. Erosion. Agglomeration of carbonyl iron particles during magnetization results in the formation of a hard flake or cake like structure. This defect remains prominent even when the magnetic field is put off resulting in a non-homogenous mixture. The application of various types of surfactants greatly enhances the settling time of the MR particles and makes re-dispersion possible [9-11]. Oleic acid and tetra methyl ammonium hydroxide are generally used as surfactants to eliminate agglomeration issue in iron carbonyl particles. Clumping effect comes into picture as a consequence of very high magnetic field operating over a long period of time resulting in entrapment of solid phase temperature on performance of MR fluids using Bingham plastic model [16]. Friction between solid phase particles of MR fluid causes erosion. A series of studies showed significant changes in the structure of carbonyl iron particles due to friction and shock. Irreversible thickening of MR fluid suspension happens because of erosion which ultimately leads to degradation in the performance of magneto rheological fluids [17]. They also erode the container walls in which they flow. Spherical-shaped carbonyl iron particles reduce the problem of erosion to a significant extent. The shear yield strength of MR fluids can be improved by preparing the MR fluid with carrier fluids made of ionic liquids and silicone oils [18].

MEASURES TO MINIMIZE SOME CHALLENGES ASSOCIATED IN SYNTHESIS OF MR FLUIDS

Recent advancements in preparation of MR fluids have shown that, of late MR fluids are being prepared using a carrier fluid made out of combination of silicon oil, honey and organic oils. In addition to this, natural oils like sunflower and cotton seed oils are also used. The MR fluid synthesized using the above blended carrier fluid showed significant improvement in anti-sedimentation characteristics and shear viscosity compared to conventional MR fluids. In use thickening is the major problem associated with MR fluids which limits their use over longer periods of time in various applications like brakes, dampers..etc. Recent developments have shown that MR fluid comprising of hydrophobic organic clay has shown very less in-use thickening and anti-sedimentation characteristics compared to conventional MR fluids. This MR-fluid showed satisfactory results in wide range of applications from brakes, clutches, dampers..etc to composite structures.

CHARACTERIZATION OF MR FLUIDS

The MR fluid characterization for evaluation of rheological properties is very vital for their applications in various fields. Bingham Plastic (BP), Casson's fluid (CF) and Herschel-Bulkley (HB) model are the most popularly used models for characterization of MR fluids. The common assumption under all these models is that the fluid flow initiates only after a threshold value of yield stress is reached during shearing mechanism. However, the post-yield behavior of these models is different [19]. Bingham Plastic model is a two parameter model. It is the simplest model and widely used in characterization of MR fluids. Bingham Plastic model assumes that the fluid sample behaves like a rigid body in the pre-yield region. In the post-yield region flow curve shows a linear behavior, where shear stress is proportional to the shear rate[20]. The mathematical expression describing shear flow behavior according to Bingham model is shown by equation 1.

$$\tau = \tau_o(H) + \eta\gamma \qquad (1)$$

Where τ is the shear stress due to applied field, τ_o is the shear yield strength, H is the magnetic field strength, γ is the shear rate and η is the plastic flow velocity. In certain cases, the post yield behavior becomes nonlinear i.e post yield viscosity of fluid sample either decreases or increases. For this kind of behavior, Herschel-Bulkley fluid model can be used [21]. This model relates non-linearly, the shear stress due to applied magnetic field and shear rate in the MR fluid. The constitutive relation is described by equation 2.

$$\tau = \tau_o(H) + k\gamma^n \qquad (2)$$

Where k is the consistency factor and n is the power law exponent or flow index. Also, the fluid flow model proposed by Casson is a two-parameter nonlinear model like that of HB model [22, 23]. It is also used to predict the pre and post yield characteristics of the MR fluid. In the literature, the Bingham Plastic (BP) model was shown to be the best model for MR fluids. However, it does not represent the flow behavior for the MR finishing fluid realistically because of the presence of non-magnetic abrasive particles in the fluid. Recent studies have shown that the experimental data fits best with the HB model which describes the flow behavior of the MR finishing fluid. Various properties of MR fluids such as viscosity are estimated. The schematic view of Saybolt viscometer is shown in figure 2. It is used to measure viscosity of the prepared MR fluid [24]. The fluid is filled into the Saybolt apparatus and the time required to fill 60 ml of fluid is measured through an orifice provided for the equipment. kinematic viscosity value is obtained from the apparatus which is then converted into dynamic viscosity. The other properties of MR fluid such as flux density are measured using Gauss meter as shown by line diagram in Figure 3.

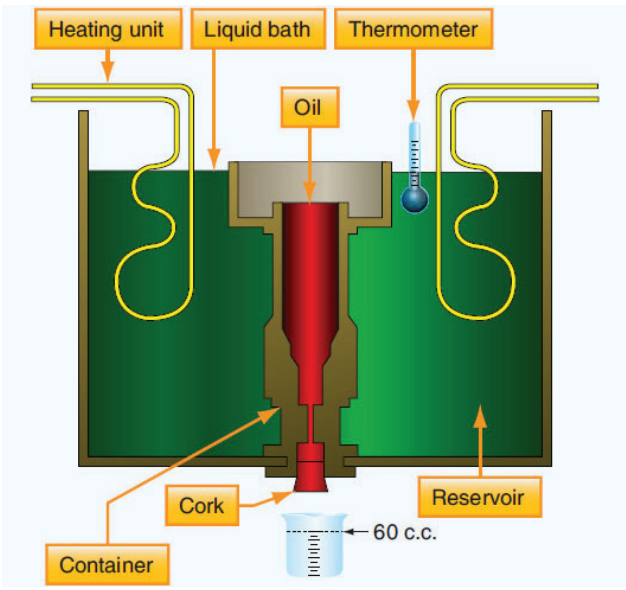

Figure 2. Schematic view of measurement of MR fluid Viscosity using saybolt viscometer.

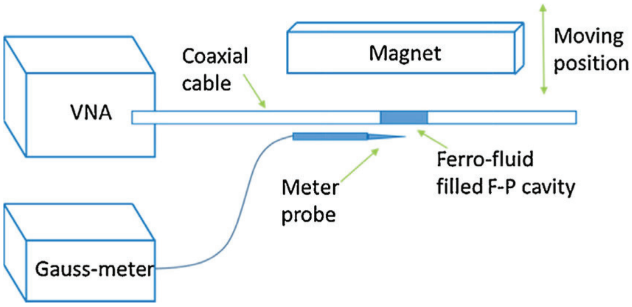

Figure 3. Gauss-meter setup to Measure flux density of MR fluid.

while measuring, some amount of MR fluid is taken randomly in beaker. A wire wound damper piston is immersed into the MR fluid. Current with an incremental step size of 0.2 Amp is passed through the damper coil. To alter the current in the circuit, a rheo-stat is used . Due to the flow of current in the coil, ferrous particles in the fluid get magnetized. Flux density of oil is checked using a probe of Gauss meter. The probe is immersed into the fluid and current is increased in the steps. The sedimentation ratio is calculated from the sample kept in the glass test tube shown in Figure 4. After every 5 hour time interval, the change at the boundary of fluid is observed. The observations are continued and sedimentation ratio is calculated based on the volume of clear and turbid parts of the boundary. A parallel plate Rheometer shown in Figure 5 is used to determine yield stress, shear rates and viscosity.

Figure 4. Glass jars to measure sedimentation in MR.

Figure 5. Rheometer to measure shear strength of MR fluids.

A scanning electron microscope is used for morphological studies of MR fluid samples [25]. A vibrating sample magnetometer as shown in figure 6 is used to determine properties such as magnetic saturation, permeability, coercivity and retentivity of the samples.

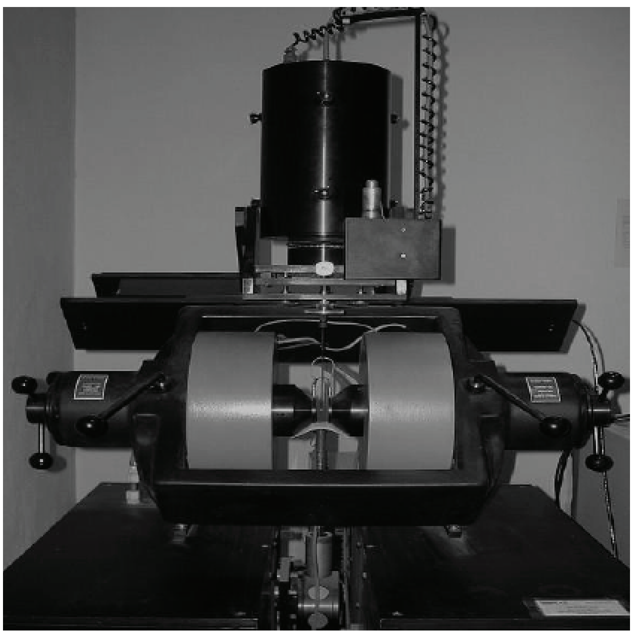

Figure 6. Vibrating sample magnetometer (Measures properties of MR samples).

Yan Yang et al. [26] proposed a constitutive relations relating shear strength of MR fluid and magnetic field based on experimental data from LORD corporation. Equation (3) shows the relation between shear stress and magnetic field of MR fluid. Where τ is the shear stress, B is the magnetic field strength, γ is the shear rate whose value is 10 s^{-1} and σ_s is the static yield strength.

$$\tau = 45.64 \exp(O.19B) + (0.192\gamma + 0.26\sigma_s)B \qquad (3)$$

On the basis of various operational modes of MR fluids like flow mode, shear mode, pinch mode, squeeze mode, various engineering and medical applications like artificial knee, dampers, brakes, clutches..etc were developed. During the recent times, there has been significant improvements in state of art MR fluid based device technology [27]. The schematic of various modes of operation of MR fluids is shown in Figure 7.

APPLICATIONS OF MR FLUIDS

Flow mode or valve mode of operation of MR fluids is used in dampers and shock absorbers. Shear mode of operation is useful in clutch and brake applications. Squeeze mode is useful in various pneumatic and mechanical controllers

MR FLUID BASED SMART PROSTHETIC KNEE

In the design of prosthetic knee for people with amputations, the role of MR dampers is widely appreciated. They are used in prosthetic knee to absorb shock forces from the ground and make the user experience more realistic style of walking. A small volume of MR fluid is circulated inside the damper for this purpose. Developments have paved way for prosthetic MR fluids compatible to almost all situations. Researchers designed the HIP or High Intelligence Prosthesis which is prosthesis above the knee. A group of sensors attached to the joint decides the knee angle, axial force, turning moment and swing velocity instantaneously. The Lord Corporation undertook the commercialization of MR damper for prosthetic knee. The CAD model of the MR damper based prosthesis knee is shown in figure 8.The assembly of prosthetic knee houses the battery, sensors, damper and the control unit [28].

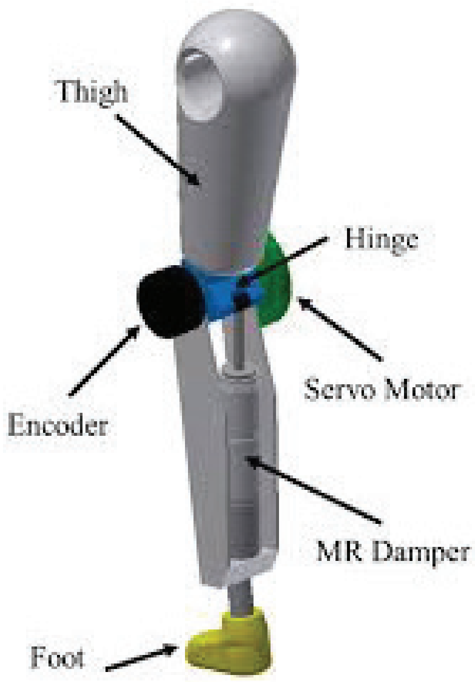

Figure 8. Intelligent Prosthesis with MR damper (Prosthetic Knee).

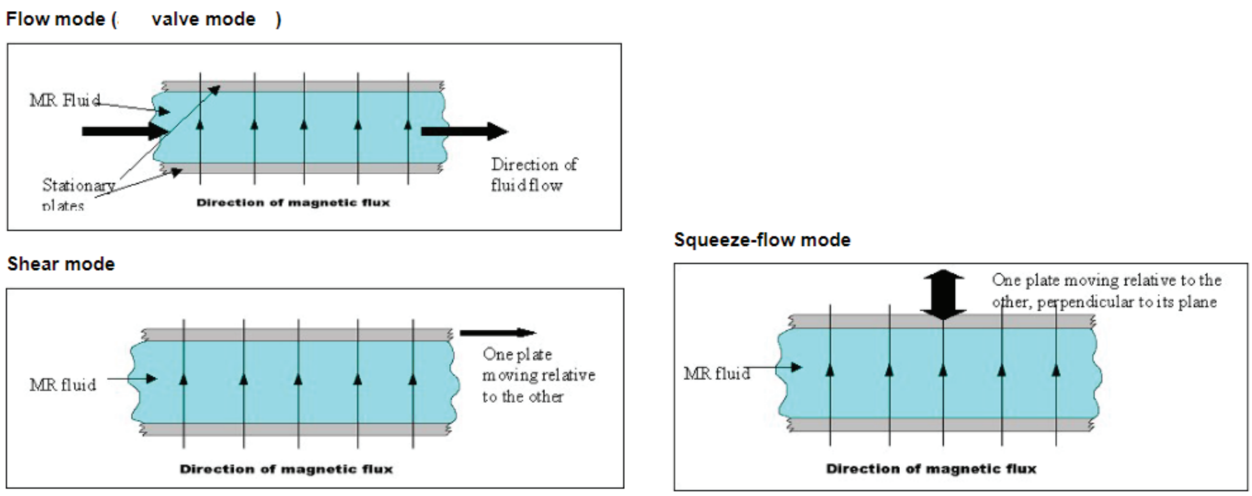

Figure 7. Modes of operation of MR fluids.

MR FLUID DAMPER FOR WASHING MACHINE

In Figure 9, the line diagram of working of MR damper installed household washing machine is shown. The damper helps in controlling the vibrations induced during the working of washing machine. The focus is on the spin tub dynamics at low speeds of rotation and about the drum resonance frequency. This work instead mainly focuses on the vibration induced at high spin velocity. Many civil engineering structures like suspension bridges are now days equipped with smart MR fluid dampers [29]. The control of viscosity of MR fluid through magnetic field and regulation of flow of MR fluid paved way for its applications in suspension systems and torque transfer devices [30]. These semi-active control devices are frequently used to control wind induced vibrations [31]. Research is focused on enhancing the performance of isolated structures like bridges against earth quakes. Advancements in shock absorber technology resulted in automobile suspension systems being equipped with (MR) fluid dampers due to their mechanical simplicity, useful dynamic range, low power consumption, and robustness [32]. Ride quality of the vehicle is found to improve considerably with the use of MR dampers. Even though, the MR damper suspension systems are in use in automobile industry for quite some time, the use of MR shock absorbers for motor cycles has gained popularity during recent times [33].

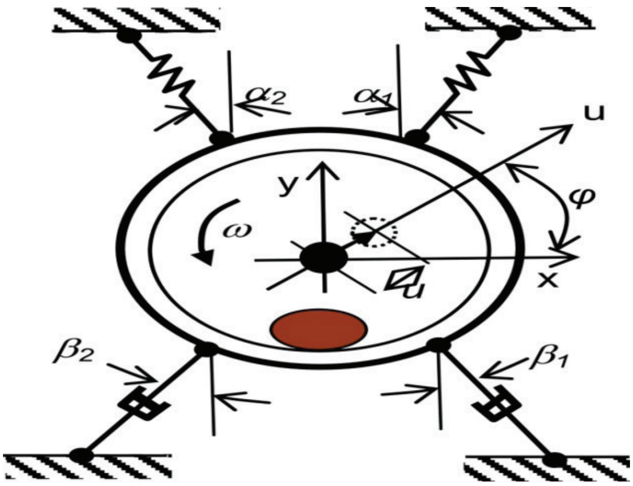

Figure 9. MR Fluid damper based washing machine line view.

MR FLUID BRAKES

A feasibility study is under progress to study the reliability and efficiency of MR fluid brakes in order to replace the conventional braking systems for heavy vehicles. The shear stress of MR fluid actuates the necessary braking torque which is in turn controlled by the application of magnetic field [34]. Empirical study of MR fluid brakes for high speed applications was conducted and the results were found to be satisfactory [35]. Schematic diagram showing working of M.R fluid brake is shown in Figure 10.

MR FLUID VIBRATION MOUNTS

Vibration isolation and damping are essential in many machine tools. The efficiency of a vibration mount is estimated in terms of the reaction time it takes to damp the vibrations and the magnitude of vibrations it controls. Due to quick response time offered by MR fluid based vibration mounts and wide operating range compared to conventional mounts, they have wide spread applications in recent times [36]. The damping carried out by perturbation of MR

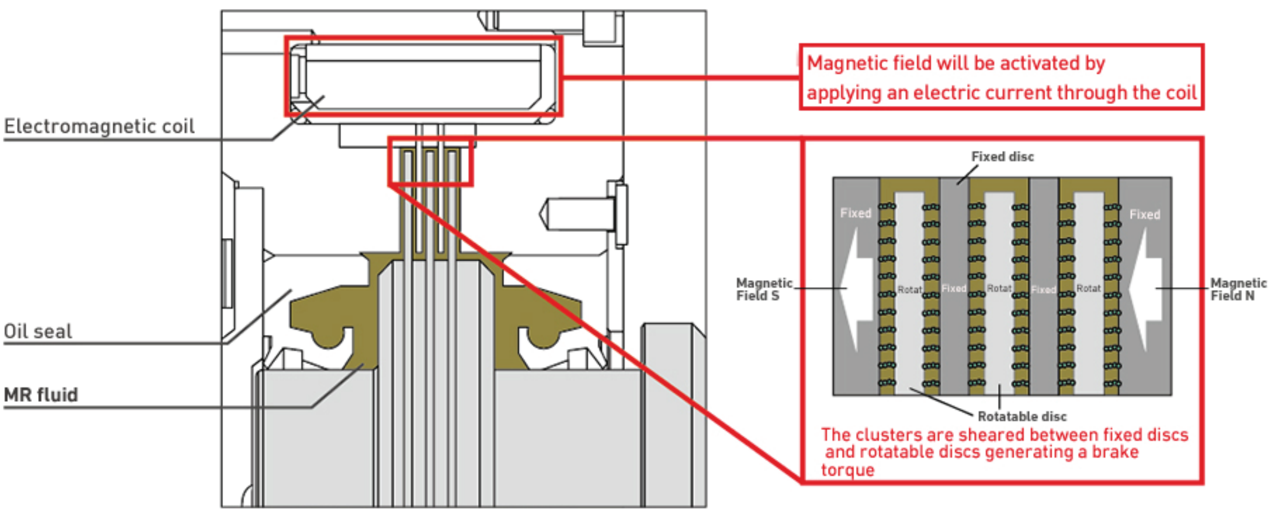

Figure 10. Schematic view of working of M.R fluid brake.

fluid flowing through the chamber valves [37,38]. Squeeze mode vibration mounts are found

to be suitable for small displacements and low amplitude vibration damping [39].

MR FLUID MICRO-MACHINING

Conventional grinding induces surface cracks, residual stresses and causes work hardening of machined surfaces. Heat treatment is necessary to minimize the residual stresses in such cases. MR fluid based polishing or micro machining aims at reducing these residual stresses. However, the material removal rate achieved using MR fluids is relatively low compared to conventional grinding [40]. Figure 11 shows the schematic view of micro finishing operation using M.R fluid.

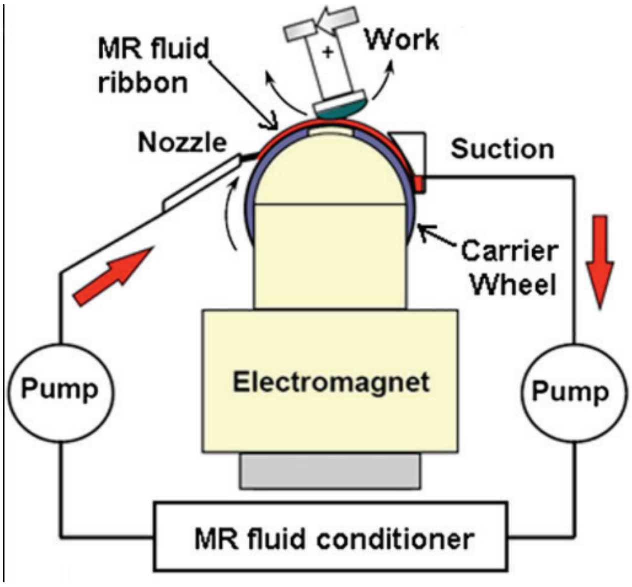

Figure 11. Schematic view of M.R fluid based micro finishing operation.

MR FLUID SEALS

Vacuum based equipment demand air tight and leak proof sealing. Designing a leak proof air tight system is no small task even till date [41,42]. MR fluid based sealing can be regarded as breakthrough technology for sealing upto pressures of 3300 kPa [43,44]. Researchers suggested a one-step seal for a rotary shaft [44]. At a rotational speed of 1000 rpm, the MR seal system with two different sizes of gaps (1–1.7, 0.06–0.5 mm) was tested. The main advantages associated with MR sealing system are its ease of operation, low maintenance and good sealing capacity. Studies on MR fluid seals show that different intensities of the magnetic fields are required for different shaft rotational speeds [45]. External source of power actuates the MR fluid seal and its performance is not efficient during shaft rotation. The simple operation and ease of maintenance of MR fluid seal outweighs its limitations. Research showed that critical pressure is proportional to the square of applied magnetic field strength. Studies show that size and volume of MR fluid influences the magnitude of burst pressure of the seal [46]. Figure 12 shows a flow diagram representing the working of MR fluid seal. The red colored region indicates the effective sealed area.

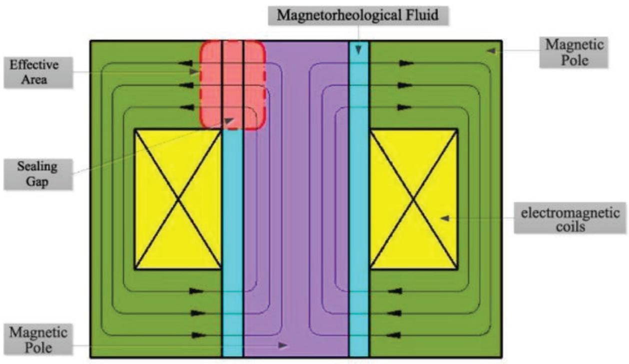

Figure 12. Schematic view of MR fluid seal.

MR VALVES AND ORIFICES IN HYDRAULIC CIRCUITS

Douglas E ivers et al. [47] developed a two way valve assembly that can be used in MR fluid dampers and MR fluid mounts. The assembly consists of a valve body and a magnetic circuit, controllable flow passage and magnetic flux generator based on designed magnetic circuit. The change in magnetic flux changes the rheological properties of MR fluid passing through the controlled passages. This ensures that high pressure differential is created for flow through one of the passages and low pressure differential for flow through other passage.

MR FLUID BASED CLUTCHES

Research showed that, M.R fluid based clutches have considerably low probability of slippage compared to conventional hard disk clutches. This characteristic of M.R fluid clutches enables them to be used for heavy torque transmission applications. Rabinow's investigations and contributions lead to the design and development of first MR fluid based clutch was for torque transmission and control [48]. Further investigations by Lampe were focused upon different clutch designs and problems associated with their functionality and performance [49,50]. Design of high torque transmission clutch which was later successfully implemented in the power train of heavy duty vehicles was first proposed by Kieburg et al. [51]. Kikuchi et al. [52], designed and developed a compact MR clutch which is capable of transmitting high torque. The high torque transmission capacity in M.R fluid clutches is achieved by taking 50% volume fraction of iron particles suspended in silicone oil. Also, a magnetic flux density of 700 mT is considered during design and manufacture of the clutch. This enables the M.R fluid clutch to reach a shear yield strength of 70Kpa necessary for high torque transmission. The schematic diagram of high torque transmission M.R fluid clutch is shown in Figure 13.

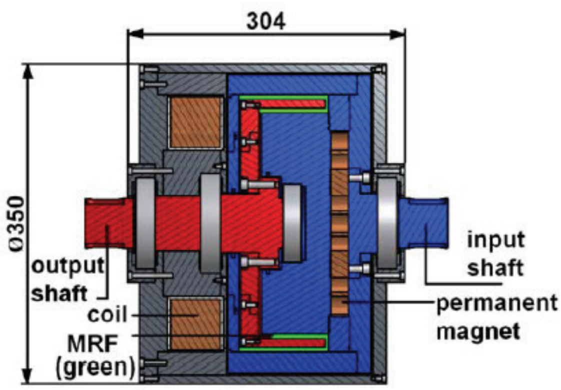

Figure 13. Schematic view of high torque transmission M.R fluid clutch.

OTHER MEDICAL APPLICATIONS OF M.R FLUIDS APART FROM PROSTHETIC LEG

Adam coon et al. [53] made significant contributions to study the effect of patients skin properties on accuracy of tonometric (cardio-vascular) blood measurements through a skin tunable MR apparatus. G.A flores et al. [54] applied a novel principle for cancer treatment through M.R fluids. The approach is to block the blood supply to the tumor and prevent its further growth.

RECENT ADVANCEMENTS IN MR APPLICATIONS

Composite structures employed in civil, structural and aerospace applications are subjected to vibrations resulting in catastrophic failure. To damp or suppress the vibrations, recently, MR fluid based vibration control systems have been developed and are put into use. Recent studies show that when magnetic field in the range 0-1600 gauss is applied to MR fluid embedded composite structures, the natural frequency of the structure increased and the amplitude of vibrations reduced considerably [55]. Recent advancements in MR fluid applications include development of Energy harvesting MR fluid damper system [56]. Cho in 2005 developed an electromagnetic induction device attached to MR fluid damper to generate energy. This device can develop electrical energy from mechanical vibration energy and this in turn is supplied to MR damper coil. Another recent advancement in MR fluid applications is energy harvesting through induction coil. Wang and Bai introduced a method of generating energy through induction coil in MR dampers. This model uses integrated relative displacement sensor technology and activates MR damper through induction. Figure 14 shows the schematic view of Energy harvesting M.R damper developed by Cho and his team.

RESULTS AND DISCUSSIONS

Research on MR fluids carried out during the last two to three decades showed significant advancements in preparation and applications of MR fluids. Size of carbonyl iron particles showed to impact the properties of the MR particles like wet ability and sedimentation resistance. Too low size resulted in low wet ability, while large size resulted in high sedimentation. The optimum size is found to be [3 to 5 μm] . The size and shape of MR particles also influenced the shear yield strength, friction and wear induced on container vessel. Flake shaped M.R particles resulted in low shear yield strength and high wear and friction on container vessel. On the other hand, spherical particles of

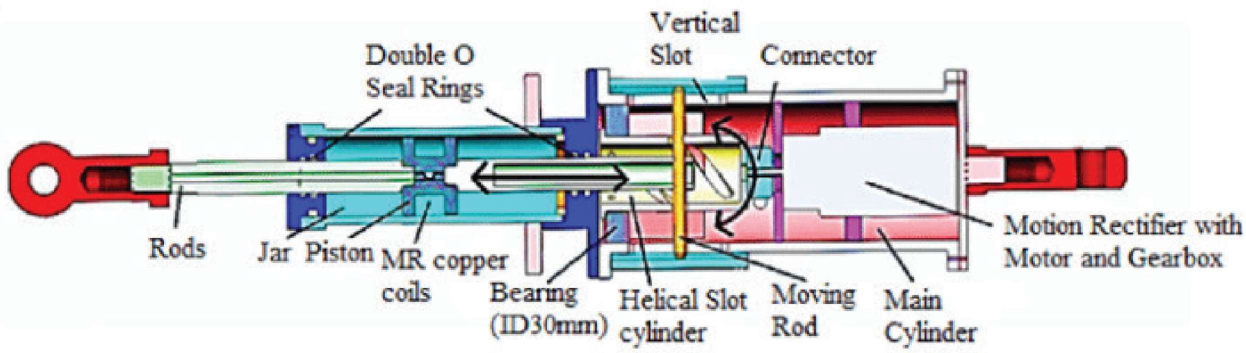

Figure 14. Energy harvesting MR damper schematic view.

the size [3 to 5 μm] yielded significantly better results. The shear mode characteristic of M.R fluid is responsible for its application in M.R braking systems. Selection of M.R particles with high shearing yield strength ensures high braking torque. The squeeze mode characteristic of M.R fluids is responsible for its applications in wide varieties of vibration dampers. Higher the damping, higher is the requirement for M.R fluid with high compressibility characteristics. Energy harvesting / regeneration characteristics of M.R fluid particles can be attributed to the inherent magnetic properties of these particles and electromagnetic induction devices used in the applications.

RESEARCH GAPS

The study of recent literature shows significant improvements in synthesis, characterization and applications of magneto rheological fluids. However not much attention is focused and no significant contributions are available on the long term reliability of MR fluid dampers, vibration mounts and devices used in medical applications. Even till date, the nonlinear behavior of MR fluid dampers are not fully investigated to ensure the designs are reliable under various operating conditions. Many commercially available MR fluid dampers come with good characteristics such as high shear yield strength, short response time and continuous control. However, most coils depend on single coil embedded in a piston slot. Not much attention is focused on development of MR fluid dampers with dynamically adjustable damping range and good heat dissipation characteristics.

CONCLUSION

MR fluid made of hydrophobic organic clay is found to have good anti-sedimentation and minimum in-use thickening characteristics compared to conventional MR fluids. A mix of nano and micro sized MR particles showed better magnetic responses compared to pure micro sized particle based MR fluids. However, their shear yield strength is low.

Carbonyl iron particles of 4μm size and 30% volume fraction yielded best results.MR fluids made out of carrier fluids blended with silicon oils, organic oils, honey and natural oils like cotton seed oil showed better anti-sedimentation characteristics and high shear viscosity compared to conventional MR fluids.

High Shear yield strength, High retentivity, high permeability are some of the desirable characteristics of M.R fluids which make them suitable for wide range of applications.

Operational modes of M.R fluid are the governing aspects for selection of M.R fluid for a specific application. Eg: Shear mode- Brake application, Squeeze mode- Damper application.

From this study it is observed that, reliability issues of MR fluid devices like brakes, clutches , dampers..etc are not fully addressed till date despite of many advancements made.

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