Chapter 3
Magneto-Rheological Fluid Technology

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Abstract Increasingly, Magneto-rheological (MR) fluid technology has been successfully employed in various applications across various fields. This technology has received significant attention due to its adaptability in the operation of semi-active control systems requiring small power sources. It can potentially deliver highly reliable mechanical operations, managed by a magnetic field as the external operating power. To summarize current magneto-rheological technology, MR fluid can be described as a controllable material that is included in the group of smart materials that have the unique ability to change yield stress. This property can be used in MR devices to generate and control force. The aim of this chapter is to review recent research into MR fluid technology by describing the important factors affecting MR devices design, such as MR fluid properties, operational modes, magnetic materials, and magnetic circuits.

3.1 Introduction

Developments in science and technology have generated a new family of materials call smart materials. These kinds of materials have remarkably improved the design of devices by joining mechanical and electronics effect. Intelligent materials have the ability to change their shape, size, or state from liquid to solid, are

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Table 3.1 Main properties of MR fluids [8]

Property	Typical value
Yield stress	50–100 kPa
Magnetic field strength	$\approx$250 kA/m
Viscosity	0.1–1.0 Pa-s
Operation temperatures range	−40–150 °C
Response time	Milliseconds
Density	3–4 g/cm^3
Power supply	2–25 V @1-2 A

controlled by external power and can be used in many applications [1]. Their properties can be dramatically altered and controlled by means of external influences such as temperature, and electric or magnetic fields. Individual types of smart material have a property that can be significantly altered, such as conductivity, volume, or viscosity. This property that can be changed influences the type of applications for which the smart material can be used. There are different types of smart materials such as piezoelectric materials (PZT), electro-rheological fluids (ERF), and magneto-rheological fluids (MRF) [2]. This chapter focuses on MR fluid material. MR fluid can be included in two general subjects areas: in the scientific area of conventional Magnetism, and also in the engineering area of Rheology. The relationship between MR fluids and a magnetic field is that the magnetic field can change the rheological properties of an MR Fluid [3]. MR fluids are suspensions of micron-sized magnetizable soft particles suspended in a carrier fluid such as silicon oil, mineral oil, or hydrocarbon oil. The carrier liquid acts as a dispersant medium and ensures the homogeneity of the particles in the fluid. Important characteristics of the magnetic dynamically diffused particles are particle shape, size, density, saturation magnetization, particles suspension and distribution [4, 5]. Therefore, a variety of additives are added to MR fluids such as those that affect the polarization of the particles, and those that stabilize the particles suspension in the MR fluid and stabilize the MR fluid structure by prevented gravitational settling and reduction of friction between particles [6, 7]. These additives are used in order to keep the particles suspension in the fluid stable. Table 3.1 shows the main properties of MR fluids.

A common problem in MR fluids technology applications is the inclination of the active magnetic particles to settle down, which disturbs the homogeneity of the MR fluid and could influence its properties. This is important in MR fluids technology because the magnetic particles can be denser than the liquid, and they can settle under gravity to form a hard "cake", which makes them difficult to redistribute.

This chapter presents a state-of-the-art review on MR fluid technology, and focuses on the following:

- MR fluid technology, in particular MR fluid modes as well as models.
- Magnetism and magnetic materials, in particular the fundamentals of electromagnetism and types of magnetic materials.
- MR fluid technology, in particular the effect of different additive techniques.

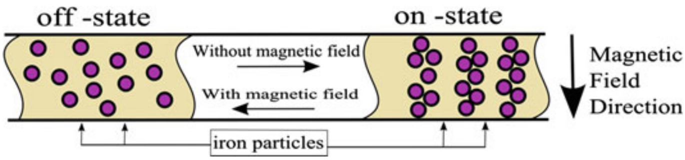


Fig. 3.1 Illustrate off-state and on-state

3.2 Magneto-Rheological Fluid

The MR fluid effect was discovered in the 1940s by Jacob Rabinow at the US National Bureau of Standards. In 1948, Rabinow applied MR fluids as a new material to clutch technology [9]. MR fluids contain magnetizable particles, non-magnetizable suspending fluids, and additives. The most popular materials used as particles are carbonyl iron, or iron powder, because they have a high level of saturation magnetization [10]. An MR fluid is a fluid that exhibits rheological behaviour. Rheology is the study of flow and deformation that responds to an applied magnetic field and has the ability to change reversibly from a free flowing linear viscous fluid to a semi-solid state. The behaviour of MR fluid can be described by elastic and plastic deformation. When a magnetic field is not present, an MR fluid behaves like a Newtonian liquid. This state is called off-state as shown in Fig. 3.1. It accepts low viscosity as shown in Fig. 3.2, and is characterized by Newton's law:

$$\tau = \eta \dot{\gamma} \tag{3.1}$$

where τ is shear stress (units: N/m^2), η is dynamic viscosity (units: Pa. s), and $\dot{\gamma}$ is shear rate (units: 1/s). Water and oil examples of Newtonian fluid. The dynamic viscosity in newtonian fluid has a constant value.

When MR fluid behaves like a Newtonian fluid, the most important property is the viscosity as shown by Newton's law. The viscosity changes with temperature. Because of this, temperature would normally be considered as an uncontrollable feature. There are two ways of expressing the viscosity-dynamic and kinematic viscosity. Dynamic viscosity is defined by:

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{3.2}$$

Kinematic viscosity is express as:

$$v = \frac{\eta}{\rho} \tag{3.3}$$

where ρ is density (units: kg/m^3)

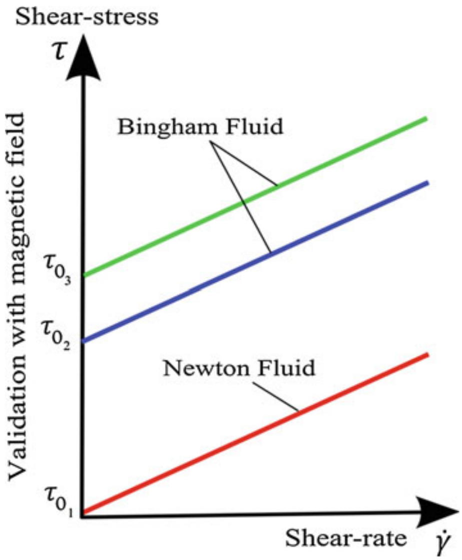


Fig. 3.2 Shear stress versus speed for Newton and Bingham model of MRF

Figure 3.2 represents the relationship between shear stress and shear rate for a Newtonian and a Bingham fluid. The Bingham plastic model is used to describe the rheological characteristics of an MR fluid [8]. The Bingham plastic model can maintain a certain quantity of yield stress without having the corresponding shear rate as shown in Fig. 3.2.

The MR fluids deform with a shear rate unitell shear stress goes beyond the highest yield stress of MR fluid material [11, 12]. The maximum yield stress can be applied without causing continuous movement of the magnetizable particles. The yield stress can be controlled, increasing, or decreasing through the strength of the magnetic field applied to MR fluid, the fluid under an applied external magnetic field shows a characteristic of the Bingham plastic model [13] and is called on-state as shown in Fig. 3.1. If the stress has reached its maximum value, the chains are going to break and the fluid will flow even if the magnetic field is still in effect on the MR fluid [14]. The maximum value of yield stress can be controlled through the value of the magnetic field applied to the MR fluid [8] as:

$$\tau = \tau_y H + \eta \dot{\gamma} \tag{3.4}$$

where τ_y is yield stress at zero shear rates (units: N/m^2), H *is* the magnetic field intensity (unit: A/m).

In a magnetic field each metal particle of the MR fluid becomes a dipole and their ferromagnetic properties attract the neighbouring particles to make chains that are called the MR fluid structure [12]. Since they aligned in this manner, the particles are restrained from moving away from their respective “fluxes” lines, and act as a barrier opposing any external force [15].

3.2.1 Shear Yield Stress

There are two ways of expressing the yield stress, the dynamic and the static yield stress. The dynamic yield stress of an MR fluid is usually described as the zero-rate intercept determined through a linear regression curve fitted to the flow data as shown in Fig. 3.2. The static yield stress identifies to the shear stress essential to zero flow of shear-rate. The shear yield stress [16] can be calculated from Eq. (3.3):

$$\tau_y = F_y/\pi r^2 \tag{3.5}$$

where, τy is shear yield stress, r is radius of the pipe where the MR fluid under magnetic flied effect (units: m), Fy is the press force (units: N).

3.3 MR Fluid Modes

MR fluid devices can be operated in several modes depending on the function and the type of deformation employed. Usually they are designed to operate either in Valve mode, Shear mode, or Squeeze mode [8, 17].

3.3.1 Valve Mode

In valve mode, as shown in Fig. 3.3, the MR fluid flow is located between two static plates forming an orifice. The force generating through the MR fluid is created by a pressure drop. The magnetic field, which is applied perpendicular to the direction of the flow, is used to change the viscosity of the MR fluid in order to control the flow. This pressure drop is fundamentally in a device, which resists an output force attacking the device. The pressure drop developed in a valve mode device can be created by two independent viscous components, i.e.: $\Delta P\eta$ as the pure rheological component, and ΔP_{mr} as the magneto-rheological component that is dependent on the magnetic field [18]. The pressure value drop can be expressed as:

$$\Delta P = \Delta P_\eta + \Delta P_{mr} = \frac{\eta}{\tau^2}\left[\frac{12}{f^2}\right]\left[\frac{\Delta P_{mr}}{\Delta P_\eta}\right]Q_{\cdot mr} \tag{3.6}$$

where η (units: Pa-s) is the dynamic viscosity, τ_{mr} (unites: N/m^2) is the yield stress variable in response to an applied magnetic field, Q (unites: m^3-s) is the volumetric flow rate of the MR fluid, while L, g, and w (unite: m) are the length, fluid gap, and the width of the flow orifice as shown in Fig. 3.3 [19, 20]. f (no unit) is an empirical factor that is indentified experimentally. This is dependent on the ratio of the pressure drop relating to the magneto-rheological response factor, and the pressure drop relating to the natural viscosity state of the fluid. The value of

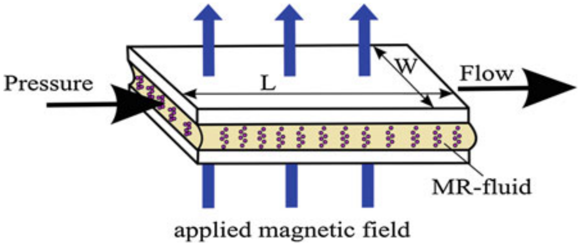


Fig. 3.3 Valve mode with an applied magnetic fluid

constant *f* ranges between 2 and 3 depending on the value of the $\Delta P_{mr}/\Delta P_{\eta}$ ratio for the device. If the $\Delta P_{mr}/\Delta P_{\eta}$ ratio is equal or less than 1, the value of *f* is likely to be 2, and for a $\Delta P_{mr}/\Delta P_{\eta}$ ratio equal or larger than 100 the value of *f* is likely to be 3. An MR fluid device designed to operate in valve mode can be described by Eq. (3.6) [8]. This equation can be considered in terms of volume, and can be rewritten in terms of the minimum volume, *V* (unit: m^3), of an active fluid:

$$V = L.w.g = \frac{\eta}{\tau^2}\left[\frac{12}{f^2}\right]\left[\frac{\Delta P_{mr}}{\Delta P_{\eta}}\right]Q.\Delta P_{mr} \tag{3.7}$$

Equation (3.7) stands for the minimum volume of an activated fluid required to reach the MR effect at a given flow rate *Q,* for a given pressure drop. The valve mode as an operational mode is used in many applications, particular in dampers. They have been studied and developed for commercial applications [18].

3.3.2 Shear Mode

Shear mode can also be referred to as direct shear mode, and is shown in Fig. 3.4. In shear mode the MR fluid flows is located between two surfaces moving in relation to each other, with the magnetic field flowing perpendicularly to the direction of motion of these surfaces. The magnetic field is used to change the viscosity of the MR fluid in order to control the flow and to generating force between the two surfaces [14]. Shear mode can generate force from two independent viscous components, $\Delta P\eta$ as the pure rheological component, and ΔP_{mr} as the magneto-rheological component that is dependent on the magnetic field, similar to valve mode [8]. The total force in shear mode can be expressed as:

$$F = F_{\eta} + F_{mr} = \left[\frac{\eta.S.A}{g}\right] + \tau_{mr}.A \tag{3.8}$$

where *S* is the relative speed of the two surfaces, η is the dynamic viscosity, *g* is gap size of the flow channel, τ_{mr} is the yield stress developed in response to an applied magnetic field, and *A* is the surfaces area of the activated fluid and can be define as shown in Fig. 3.4. The surfaces area can be expressed as:

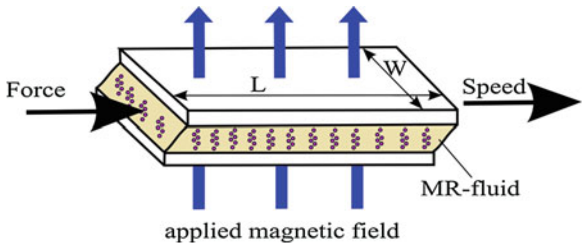


Fig. 3.4 Shear mode with an applied magnetic fluid

$$A = L.w \tag{3.9}$$

where L and w, are the length and width of the flow channel as shown in Fig. 3.4. Equation (3.8) can be used for the design of MRF applications that operate in shear mode. The $\Delta F_{mr}/\Delta F\eta$ ratio indicates the range of force adjustability inherent in the MR fluid device in shear mode [8]. A larger ratio indicates that the device is capable of considerable changes of force from off-state to on-state, as shown in Fig. 3.1. By rewriting Eq. (3.8), the minimum volume, V, of activated fluid can be calculated as

$$V = L.w.g = \frac{\eta}{\tau^2}\left[\frac{F_{mr}}{F_\eta}\right]F_{mr}.S \tag{3.10}$$

3.3.3 Squeeze Mode

Squeeze mode is shown in Fig. 3.5, and operates when a force is applied to the plates in the same direction as the magnetic field to reduce or expand the distance between the parallel plates, causing a squeeze flow. The magnetic field flowing perpendicularly to the direction of MR fluid motion is used to change the viscosity of the MR fluid in order to control the flow and to generating force. In this mode the acting force is in line with the magnetic flux lines and the particle chains [18, 21]. MR fluid devices in squeeze mode usually have little or no flow of MR fluid depend on the devices structure. In squeeze mode, the force is dependent on the mechanical properties of the carbonyl iron particles chains, rather than the viscosity changes of the MR fluid. This mode has been used in the control of small amplitude vibration isolators' application [22]. Larger displacement applications designed to operate in squeeze mode have yet to be investigated, and there may be some novel device designs that are currently being explored to develop this type of squeeze mode operation. Few squeeze mode studies were found investigating squeeze mode operation that is capable of producing compression and tensile stresses at same time. This would create more force compared to valve and shear operational modes [8, 21].

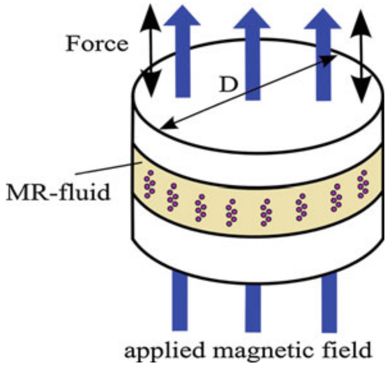


Fig. 3.5 Squeeze mode

3.4 MR Fluid Modeling

One of the challenging aspects in developing devices to achieve high performances is the development of models that can accurately describe their unique characteristics. Models of MR fluids play an important role in the development of MR fluid devices. A wide variety of nonlinear models have been used to characterize MR fluids. Three kinds of models were established for MR devices. These are the Bingham plastic model [17], the bi-viscous model [23], and Herschel-Bulkley model [24] for MR fluid applications.

3.4.1 Bingham-Plastic Model

The Bingham plastic model is normally used to describe MR fluid flow behaviour, particularly in damper design [25]. The MR fluid material can absorb a certain level of shear stress without any change in viscous behaviour in the Bingham plastic model. The MR fluid begins to flow when the generating stress level is higher than the yield shear stress [26] as illustrated in Fig. 3.6. The MR fluid flows in the case of a post-yield of viscosity. The yield stress is a function of magnetic field, and can be increased if the magnetic field is increased. The Bingham plastic model of the stress–strain constitutive relationship can be expressed as [17]:

$$\tau = \begin{cases} \tau_y + \eta\dot{\gamma} & \tau > \tau_y \\ 0 & \tau \leq \tau_y \end{cases} \tag{3.11}$$

3.4.2 Bi-viscous Model

The Bi-viscous Model has two viscosities. The first viscosity is called the pre-yield viscosity, $\eta_{pr.}$ The second viscosity is called the post-yield viscosity, $\eta_{po.}$ Also, there are two yield stresses. The first yield stress is called the dynamic yield stress,

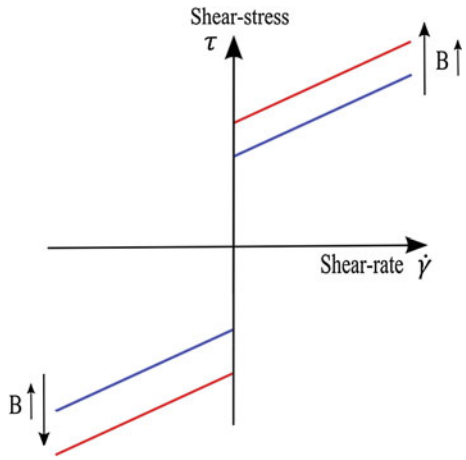


Fig. 3.6 Bingham plastic model of MR fluid

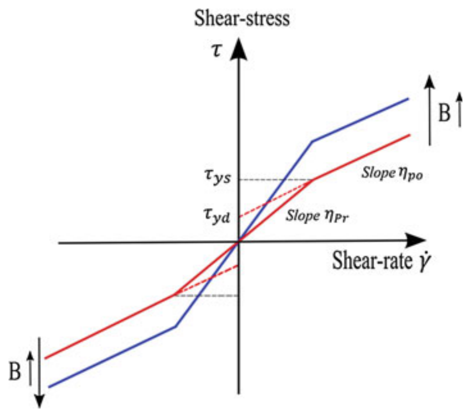


Fig. 3.7 Bivicovs model of MR fluid

τ_{yd}. The second yield stress is called static yield stress, τ_{ys} [27]. The bi-viscous model is demonstrated in Fig. 3.7. The shear stress equation is expressed as:

$$\tau = \begin{cases} \pm\tau_{yd}(B) + \eta_{po}\dot{\gamma} & \tau > \tau_{ys} \\ \eta_{Pr}\dot{\gamma} & \tau \leq \tau_{ys} \end{cases} \tag{3.12}$$

3.4.3 Herschel-Bulkley Model

The Herschel-Bulkley model is similar to the Bingham plastic model [28]. However, Herschel-Bulkley's post yield property of material exists in two states as illustrated in Fig. 3.8. The first state is shear thickening, (m > 1), and the second state is shear thinning, (m < 1) [29]. Herschel-Bulkley can be expressed as:

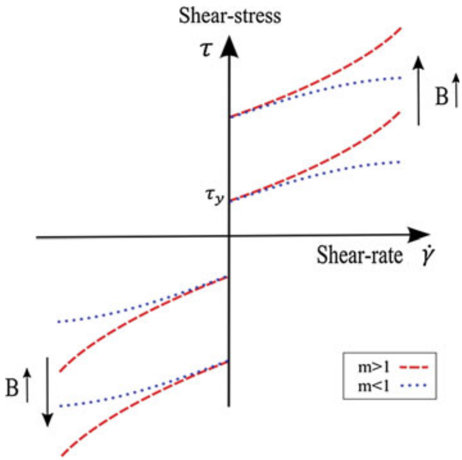


Fig. 3.8 Herschel-Bulkley model of MR fluid

$$\tau = \pm \tau_y(B) + \eta(\eta)^{\frac{1}{m}}. \quad (3.13)$$

3.5 Types of Magnetic Materials

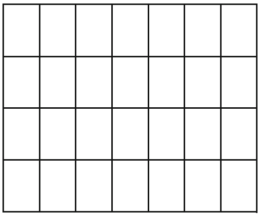
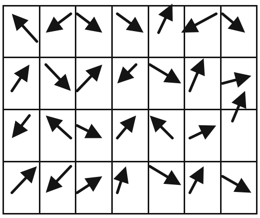
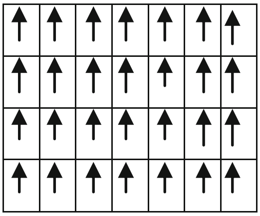
Magnetic materials can be classified as diamagnetic materials, paramagnetic materials, and ferromagnetic materials. The classification criterion of magnetic materials is based on the variation between the external applied magnetic field, *H*, and the internal induced magnetic flux density, *B* [30]. In general, the magnetic materials' characteristics can be obtaining from a graph of the magnetization curve of magnetic flux density *B*, versus magnetic field strength *H*. This is called the *BH* curve, and the slope of the curve is the magnetic permeability of the material.

The behaviour of diamagnetic materials, paramagnetic materials, and ferromagnetic materials under the influence of a magnetic field is illustrated in Table 3.2 for each class of magnetic materials, with the magnetic behaviour, magnetic susceptibility, and examples of the materials.

The rheological effect of a magneto-rheological fluid is mainly attributed to the carbonyl iron particles. Iron is a type of ferromagnetic material, so MR fluids properties can be controlled and managed like any other material with ferromagnetic properties [8, 21].

Ferromagnetic materials under the influence of a magnetic field show that this influence is concentrated inside the materials. That creates strong attractions between the ferromagnetic material and the magnetic field, which acts in all magnetic field directions, and the magnetic permeability and the magnetic susceptibility are very large. The magnetization curve of the material reaches saturations when the magnetic field reaches a certain value, as illustrating in Fig. 3.9 showing the behaviour of ferromagnetic materials under a magnetic field.

Table 3.2 Different of magnetic behaviour

Type of magnetism	Magnetic behaviour	Magnetic susceptibility	Examples
Diamagnetic		Small and negative	Capper, silver, gold, and alumina
Paramagnetic		Small and positive	Aluminum, titanium and alloys of copper
Ferromagnetic		Very large and positive, function of applied field, microstructure dependent	Iron, nickel and cobalt

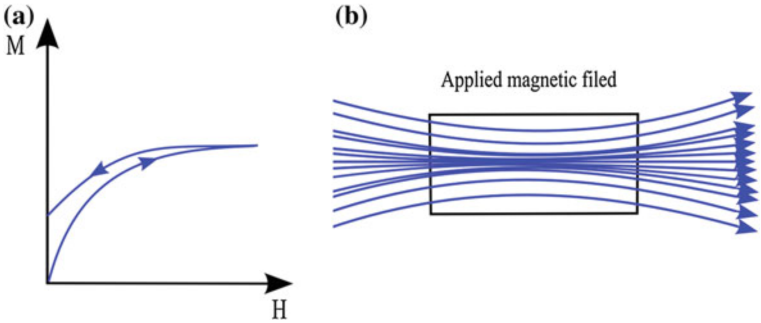


Fig. 3.9 Ferromagnetic materials behaviour under magnetic field. **a** Magnetization curve for ferromagnetic materials. **b** The schematic diagram about the field difference between the external and internal of the ferromagnetic material under magnetic field

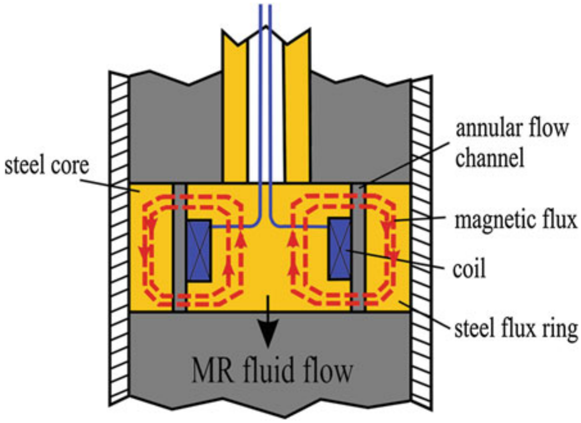


Fig. 3.10 Magnetic circuit design for MR device

3.6 Magnetic Circuit

Magnetic circuit plays an important role in MR device design, in order to generate sufficient force and improve MR device performance. Certain structural characteristics are important, such as the path of the magnetic flux lines in the fluid resistance space, geometry of flow area, selection of the materials in magnetic circuit structure, and effective surface area of the magnetic field in the device [31].

Figure 3.10 shows a typical Magnetic circuit design for MR device. The Magnetic circuit design usually contains a magnetic flux lines board, a magnetic core, an electromagnetic coil, and an MR fluid flow channel located between the outside of the magnetic core and the inside of the magnetic board [32]. The magnetic circuit design guides and focuses the magnetic flux lines through the active surface magnetic area of the MR device to control the viscosity of MR fluid, and in turn, the dynamic yield stress of the MR Fluid is changed by the magnetic field intensity generated by the electromagnetic coil. As a result, the force of MR device is activated and aligned with the MR fluid motion, which is under the control of the magnetic field intensity value. Without the magnetic field, the MR device force is solely due to the viscosity of the MR Fluid itself [33]. Good magnetic circuit design has a small cross section of steel to keep the magnetic field in the steel very low, and also minimizes the total amount of steel in the magnetic circuit design and in the MR device. It is usually composed of low carbon steel, as it has a high magnetic permeability and saturation boundary. This gives an opportunity to guide magnetic flux line into the MR device's magnetic area.

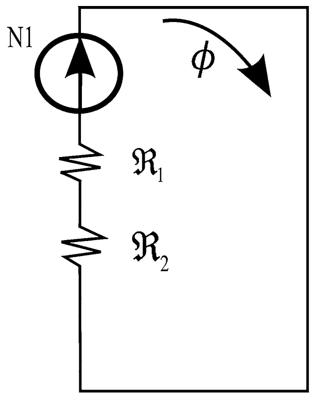


Fig. 3.11 Reluctances in the magnetic circuit

3.6.1 Electromagnetic Circuit Design Calculation

The mathematical calculations of the magnetic flux lines ϕ in a magnetic circuit is based on the Eq. (3.14) and is similarity to Ohm's law [34]:

$$\phi = \frac{F}{\sum \Re} \tag{3.14}$$

where F is a magnetic movement force in the circuit, and $\sum \Re$ is the summation of the magnetic reluctance of each material used as part of magnetic circuit. The electromagnetic circuit is usually designed with a low reluctance flux conduit by using steel to guide and to focus the magnetic flux density into the MR Fluid of the cylinder of the MR device. Therefore, any magnetic circuit design for an MR device has two reluctances as shown in Fig. 3.11, where $\Re_1$ is the reluctance of the steel and $\Re_2$ is the reluctance of the MR fluid.

Equation (3.15) can be used to calculate the reluctance in each material utilized in the magnetic circuit:

$$\Re = \frac{l}{\mu A} \tag{3.15}$$

where l is the length of magnetic path for each material used in the magnetic circuit, A is the cross-sectional area of the flux path for each material used in the magnetic circuit, and μ is the permeability of each material used in the magnetic circuit.

The permeability μ, of each material can be found out through BH curve and calculated by Eq. (3.16) for each material of the magnetic circuit.

$$\mu = \frac{B}{H} \tag{3.16}$$

The saturation point is shown in the BH curve for each material of the MR damper design.

3.7 Magneto-Rheological Fluid Properties

The most important properties of MR fluids are the particle density and size. These play an important role in the capability of the MR fluid. Jolly and Carlson [19] studied the magnetic properties of MR fluids, and their theoretical model results indicate that these fluctuates significantly depending on the particle density loading in the MR Fluid. The study examined three different samples with iron loadings, 10, 20, and 30 % by volume. The magnetic induction increased with field strength until the saturation boundary of the fluid was reached. Also, their results indicated that when the iron particles loading by volume was increased, the inherent induction of the magnetic flux density also increased due to the permeability being high due to the high volume [35]. The intrinsic induction or the polarization density of an MR fluid at complete saturation was equal to $\varphi \times J_s$ Tesla, where φ is the percentage volume of the particles in the fluid (unitless), and J_s is the saturation polarization of the particles' material (Tesla). For instance, with an MR fluid containing 40 % iron and J_s equal 2.1 Tesla, it is expected to become saturated at about $0.40 \times 2.1 = 0.84$ Tesla.

Chiriac and Stoian [36] identified a relationship between particle size and yield stress. This relationship could explain the greater magneto-static interaction between larger magnetic particles. Increasing the particles' dimension contributes towards improving the MR fluid yield stress in a magnetic field [36]. The conclusion of that study was that greater yield stress corresponds to bigger particles size.

MR Fluids usual utilize micrometer scale carbonyl iron particles as solids, with contents by weight of up to (80 %), with a high yield stress domain range of (50–100 kPa). The higher the solids contents by weight, the higher the yield stress, which can be attributed to the higher magnetic field density at saturation.

However, the problem of high density and large particles size becomes apparent in the absence of a magnetic field or without constant motion of the particles in MR fluid. Over time suspended micro-particles slowly sediment, due to gravitational forces acting on the particles that have a higher density compared to the carrier fluid, and have a larger particle size. This problem leads to the particles suspension becoming no longer effective because the particles collect in lumps on the bottom of the device container. High density and large particles size leads to the difficulty of keeping the particles in a state of suspension.

3.8 Additives

Additives are used as a solution for alleviating sedimentation of particles and keeping particles in suspension. There are two additive techniques using synthesized particles and syntheoil carrier fluid. The synthesized particle method involves mixing micro-particles with nano-particles in the MR fluid [37].

Nano-particles in MR fluid result in thermodynamic forces which tend to neutralize gravitational forces, thereby delaying the onset of the sedimentation

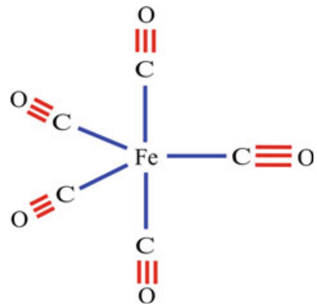


Fig. 3.12 Construction of pentacarbonyl

problem. Sedimentation rate, R, can be determined by placing MR fluid in a vertical cylindrical container at room temperature [37]:

$$R = \Delta h / h \tag{3.17}$$

where $\triangle h$ is the length of the turbid fluid and h is the whole length of the fluid.

3.8.1 Synthesized Particles Additives

Carbonyl iron nano-particles additive is synthesized and then added to the MR fluid to improve sedimentation stability. There are different synthesized particles suspensions in MR fluid, such as pentacarbonyl [38] mixed with kerosene [37].

3.8.1.1 Pentacarbonyl Compound

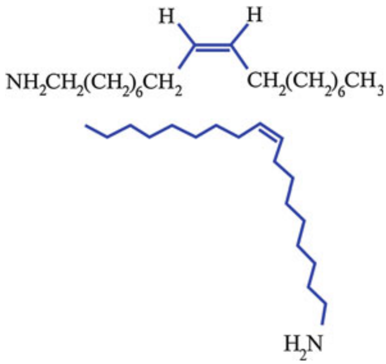
Pentacarbonyl is a compound with the formula $Fe(CO)_5$ and its formulation is shown in Fig. 3.12. This compound is synthesized from iron metal heated in the presence of carbon monoxide (CO), at a pressure of greater than 50 bars, and at temperatures in the range of 100–200 °C. The highly volatile organo-metallic compound, iron pentacarbonyl, $Fe(CO)_5$ is formed by the reaction:

$$\mathrm{Fe} + 5\mathrm{CO} \rightarrow \mathrm{Fe(CO)}_5$$

3.8.1.2 Oleylamine

The oleylamine is an amine of the fatty acid, oleic acid, and its formulation is shown in Fig. 3.13. It is a reagent in the chemical synthesis of nano-particles, and functions as coordinating agent to stabilize the surface of the particles. Most commercially available oleylamine is technical grade, with only 70 % clarity. The oleylamine is formed by the reaction:

Fig. 3.13 Construction of oleylamine



3.8.1.3 Synthesis of Carbonyl Iron Nano-Particles

Carbonyl iron can be synthesized for use as magnetic nano-sized particle additives, as follows. Oleylamine (Tokyo Chemical, Japan) and kerosine (Yakuri Pure Chemical, Japan) are mixed in a 3-neck flask and heated about 150 °C. Then pentacarbonyl (Aldrich, USA) is added to the flask while stirring vigorously. After 3 h, the mixture is cooled to 20 °C. The magnetic particles are precipitated by adding ethanol to the flask. The supernatant is removed by centrifugation. For dispersion stability, the mixture is resuspended in hexane with oleylamine. After resuspension in hexane, the mixture is dried in a vacuum oven [37, 39].

3.8.1.4 Synthesized Effecting

Ngatu and Wereley [40], studied the MR fluid density effect on sedimentation and yield stress by mixing micro-particles and nano-particles. The results indicated that mixing reduces sedimentation and improved particles suspensions in MR fluids with a small reduction in yield stress. The study examined four different samples with solids contents loadings by weight of 50, 60, 70, and 80 %. Table 3.3 shows the approximate sedimentation velocities for all the MR fluid samples. For instance, for 70 wt% particles load in MR fluid, the sedimentation rate dropped from 0.07 to 0.006 m/s with partial substitution of 10 wt% of the total micro-particles with nano-particles. Table 3.4 shows the yield stress for the MR fluids. There was a significant decrease in yield stress as wt% of the nano-particles increased. Therefore, results from the two tests show that sedimentation can be mitigated with a relatively small yield stress penalty by substituting 10 wt% of the total micro-particles with nano-particles at higher iron particles loading of 70 and 80 wt%.

Table 3.3 Sedimentation velocities for all the MR fluids samples

Synthesized particles size composition	Iron particles loading by %wt			
	50	60	70	80
	Sedimentation rate (μ m/s)			
100 % micron particles size	10	8	0.07	0.03
90 % micron mixing with 10 % nano particles size	0.02	0.01	0.007	0.003
85 % micron mixing with 15 % nano particles size	0.006	0.005	0.006	–

Table 3.4 The yield stress for all the MR fluids samples

Synthesized particles size composition	Iron particles loading by %wt			
	50	60	70	80
	Yield stress (KPa)			
100 % micron particles size	15	20	35	55
90 % micron mixing with 10 % nano particles size	11	17	26	47
85 % micron mixing with 15 % nano particles size	5	13	24	–

3.8.2 Synthetic Oil

Some researchers have tested various additive techniques. Materials were added to the formulation of the MR carrier fluid, in order to improve the stability of MR fluid, and reduce sedimentation of particles. There are three types of carrier fluids usually used in MR fluid composition, silicone oil (Oks 1,050), synthetic oil (Oks 352), and mineral oil (Oks 600), and these are mixed with carbonyl iron particles. In order to reduce sedimentation, Arsil 1,100, Arabic gum, and Aerosil 200 and 972 are materials added to stabilize the MR fluid.

3.8.2.1 Synthetic Oil Effect

In a study carried out by Turczyn and Kciuk [41] of the sedimentation of the carbonyl iron particles, additional components were added to the fluid of between 1 and 2 % of the carbonyl iron particles content. Depending on the carrier medium, different stabilizers, such as Aerosil 200 and 972 (Degussa AG) and Arsil 1,100 (Rudniki S.A.), were used for silicone and mineral oil, and Arabic gum (Sigma-Aldrich GmbH) was chosen for synthetic oil suspensions.

These additives have a most important effect on the magneto-rheological properties of the MR fluid. They stabilise the MR fluid, and create a more homogeneous suspension of iron particles in the carrier fluid. This improves the MR fluid technology as it results in faster response times to changes in magnetic field at lower magnetic field value [6].

Turczyn and Kciuk's study showed that the properties of such substances are very important. In case of Arsil 1,100 the sedimentation rate was higher, which can be explained by the state of the silica surface and its modification [42] and it can be consider as ordinary stabilizer. However the Aerosil 972 showed a lower sedimentation rate, decreasing below 60 % after 35 h in the case of low viscosity mineral oil OKS 600 (only 7.3 mPa·s) containing 20 % of iron carbonyl particles [41].

3.8.3 Others Technique

Finally, various researchers have introduced other techniques, such as polymer coating the magnetic particles, in order to overcome sedimentation problems. Coating of polymeric shells onto the surface of iron carbonyl particles to reduce the density mismatch has been reported to be a complex process in practice because of various factors affecting the coating thickness such as temperature, molar ratio among reactive agents, and reaction time [43, 44]. For this reason, introduction of additives into iron carbonyl suspensions has been reported as the more usual method employed as it can prevent the physical contact of the magnetic particles, thus preventing hard baking [45].

3.9 Conclusion

MR fluid technology has been widely investigated, is employed in many applications, and has rapidly entered the marketplace. This chapter has clarified the reasons for the extensive use of MR fluid material technology. The studies discussed above evaluated the parameters at the centre of MR fluid technology such as, MR fluid properties, operational modes, magnetic circuit, and additives. These parameters can been summarised as follows:

Knowledge of MR fluids can be gained through understanding MR fluid modes and models. These modes and models describe motion in a fluid that changes viscosity, and can provide solutions based on MR fluid technology. This knowledge can be used to design and develop MR device functionality.

The fundamentals of electromagnetism and types of magnetic materials should be understood, leading to electromagnetic coils that can generate a magnetic field of sufficient strength so that the saturation boundary of the MR fluid is reached. These coils can also control levels of yield stress by generating different values of magnetic field strength.

MR fluid properties of a material is dependent on particles size and density, and these parameters are used to increase yield stress by increasing the magneto-static force between the particles and the permeability of iron particles in the MR fluid

There are two additive techniques, these are synthesized particles and syntheoil carrier fluid. They have been investigated and are used to improve MR fluid properties and to reduce the particle sedimentation effect.

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