ISSN (ONLINE): 2321-3051
INTERNATIONAL JOURNAL OF RESEARCH IN AERONAUTICAL AND MECHANICAL ENGINEERING

# Review - MR Fluid and Its Application

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## Abstract

Magneto rheological (MR) fluids offer solutions to many engineering challenges. Magneto rheological fluid (MRF) is a smart fluid whose properties can be controlled with the help of metal particles and magnetic field. These fluids have the ability to transmit force in a controlled manner with the help of magnetic field, thus improving their performance especially in areas where controlled fluid motion is required. Some applications of magneto rheological fluid technology are in dampers, brakes, journal bearings, pneumatic artificial muscles, optics finishing, fluid clutches, aerospace etc. where we give electrical inputs and get the mechanical output comparatively faster and in a controlled manner. This is a review paper covering the principles of MR fluid working modes and its field of applications.

***Keywords:*** Magneto rheological (MR); bearings; pneumatic artificial muscles; dampers; brakes.

## 1. INTRODUCTION

Magneto rheology is a branch of rheology that deals with the flow and deformation of the materials under an applied magnetic field. They are manufactured by suspending ferromagnetic particles in a carrier fluid. The latter is typically some kind of oil. MR fluids exhibit a change in rheological properties when being exposed to a magnetic field (this is known as the on-state). Rheology is defined as the study of the deformation and flow of matter (typically materials such as rubber, molten plastics, magneto-rheological fluids, blood, paint, etc) under the influence of an applied stress. The rheological properties of a liquid are the dominant features that can be quantified to characterise its behaviour. The properties that can be affected are elasticity, plasticity and viscosity. In the on-state, ferromagnetic particles are magnetically induced and aggregate to form chain-like or column-like structures parallel to the applied field. Due to this, MR fluids have the ability to reversibly change from viscous liquids to semi-solids in milliseconds when being exposed to a magnetic field. This feature enables a rapid response interface between electronic controls and mechanical systems, making MRF technologies attractive for many applications (e.g. dampers).

A typical MR fluid contains between 20 – 40 % by volume (50 % is maximum) of suspended particles. Normally, soft iron particles are used (e.g. carbonyl iron), since they provide a good trade-off between cost and fluid strength (i.e. large saturation magnetisation). Other particles that are used include powder iron or

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iron/cobalt alloys. The particle size is in the µ-meter range and varies according to different manufacturing processes. The particle size is varied in order to achieve different purposes (e.g. torque vs. viscosity). The particles are suspended in a carrier liquid, e.g. a mineral oil, synthetic oil, water or glycol. In addition, a variety of other additives (like those found in lubricants) are commonly added to the fluid. This is done in order to reduce gravitational settling, enhance particle suspension and lubricity, modify viscosity and reduce wear. Lord Corporation is the world's leading provider of MR fluids. Table 1.1 gives an overview of some other MR Key features.

Table No.1.1 – MRF Key Features [1]

| **Representative feature** | **Typical MR fluid** |
|---|---|
| Maximum yield stress | 50-100kPa |
| Power supply | 2-24 V at 1-2 A |
| Response time | Some millisecond |
| Operational field | Up to 250 kA/m |
| Energy density | 0.1 J/cm$^3$ |
| Stability | Good for most impurities |
| Operational temperature | -40C up to +150 C |

## 2. Literature survey

### 2.1 History:

MR and ER fluids both have histories that date from 1940s. Jacob Rabinow at US National Bureau of Standards (now the National Institute of Standards and Technology) was responsible for initial discovery and early development of MR fluids. He applied for his MR fluid patent in 1947. MR fluids made by Rabinow for the use in clutches were not dissimilar to many of those made today and exhibited comparable yield strength. Rainbow's pioneering work led to a brief period of interest in MR fluids in the 1950s and early 1960s. However by the late 1960s interest in MR fluid had wanted and growing interest in ER fluid began to emerge.

In 1974, William started work on magnetorheological (MR) fluids, which are suspensions of micron-size ferromagnetic particles, such as iron, in fluids such as oil or water. The viscosity of the fluid increases in the presence of a magnetic field. The stronger the field, the stiffer the fluid becomes. The ability of either kind of fluid to transmit force can be controlled by the strength of the applied magnetic field. Initial interest was in using "smart" MR fluids for mechanical applications such as vibrational damping and actuators. The main challenge was to create stable MR fluid suspensions, rather than thick, paste-like mixtures of solids and liquids which were characteristic of the state of the art. William Kordonski and two or three people working with him developed a stable MR fluid and built the first magnetorheometer to measure mechanical properties of MR fluids in a magnetic field. [2]

Magneto-Rheological application and development started in early 80's.i.e.in the year 1991-1996.Its System engineering was established in 1996. After that, in 1997, world's first commercial MR products commonly known as MR rotary brake came into being. In 1998, Motion Master Seat Suspension system was put forth before the world. Commercial scale up began in 1999which showed a new direction to this system launching of the First GM Car popularly known as Cadillac Seville in the year 2002 was commercialized with Lord MRF , containing damper by Delphi. By 2006, it sold about 50000 steer-by-wire tactile feedback Devices .The Annual MRF volume grew by hundreds of tons. By the same year, it developed Integrated Cab Suspension which means air spring, MR damper, electronics. Currently, Lord Corporation is the leading producer of MR fluids and devices.

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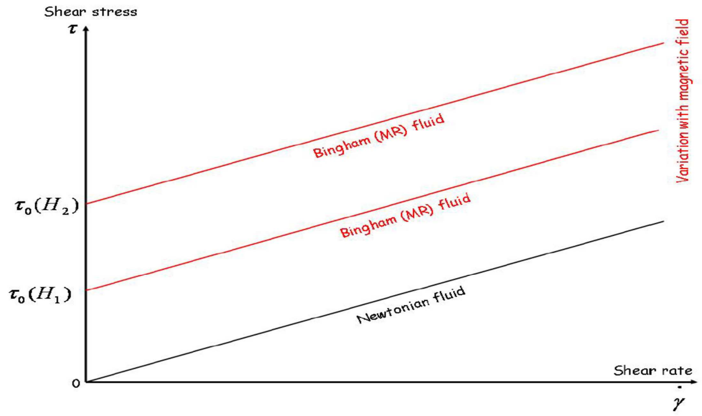
**2.2 Rheological Background**

As discussed in section 1, an MR fluid is a fluid with rheological behavior that depends on the strength of a magnetic field. Also, an MR fluid can reversibly change from liquid to semi-solid. Normally, the viscosity of a fluid changes with physical properties, such as chemical composition, shear stress and temperature. Unfortunately, these features are not easily controlled in most applications. They are most likely fixed by the operational environment in each setting. As an example, the variation of a fluid's viscosity with temperature is reversible, but this does not allow the viscosity to be controlled easily.
The dynamic viscosity (η) of a liquid is defined in equation below [3]

$$\eta = \frac{\tau}{\Upsilon} \qquad (2.1)$$

Here, $\eta$ is the dynamic viscosity [Pa s], $\tau$ is the shear stress [N/mm$^2$] and $\Upsilon$ is the shear rate [s$^{-1}$]. For a Newtonian fluid (like water), the viscosity does not change if the shear rate changes. This means that it is a linear relationship between the shear stress and the shear rate for such a fluid.

It is recognised that a simple Bingham visco-plasticity model is well suitable for describing the rheological behaviour of an MR fluid. A Bingham fluid is defined as an incompressible visco-plastic yield stress fluid. It is characterised by the fact that when the stress is below the yield stress, the strain rate is zero, and the fluid moves as a rigid solid (Graph 2.1). When the stress is above the yield stress, the strain rate is in linear relationship with the stress, and consequently, the fluid flows in a viscous manner. As shown in the below, a typical relationship between shear stress and shear rate for a Bingham fluid is given. Graph 2.1 also compares the behaviour of a Newtonian fluid with a Bingham fluid. If a magnetic field is not present, an MR fluid behaves like a Newtonian fluid. Otherwise, the MR fluid behaves like a Bingham fluid. When a magnetic field is present, there is some resistance to flow at zero shear rate. The force causes therefore a plastic deformation, but no continuous movement.




Graph 2.1 – Shear Stress vs. Shear Rate for Newtonian and Bingham (MR) Fluid [4]

The maximum stress that can be applied without causing continuous movement is called the yield stress. For an MR fluid, the yield stress can be controlled by varying the magnetic field. The total shear stress ($\tau$) is defined in equation below. [5]

$$\tau = \tau_0(H) + \eta \times \Upsilon^0 \qquad (2.2)$$

Here, $\tau_0$(H) [Pa s] is the yield stress caused by the applied magnetic field, where H[A/m] is the magnetic field strength. The magnetic field required to impose the control depends especially on the quality and quantity of the metal powder. The strength of an MR fluid depends on the square of the saturation magnetisation of the suspended particles. Generally, saturation magnetisation is a measure of the maximum amount of field that can be generated by a material. It depends on the strength of the dipole moments of the atoms that make up the material and how densely they are packed together. This means that in order to have a strong MR fluid, particle with large saturation magnetisation must be chosen.

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## 3. MR fluid components

Magneto rheological (MR) fluids are basically non colloidal suspensions of micro sized magnetisable particles in an inert base fluid along with some additives.
Thus there are basically three components in an MR fluid:
A. Base fluid,
B. Metal particles and
C. Stabilizing additives.

### A. Base fluid

The base fluid is an inert or non-magnetic carrier fluid in which the metal particles are suspended. The base fluid should have natural lubrication and damping features. For better implementation of MRF technology the base fluid should have a low viscosity and it should not vary with temperature. This is necessary so that MRF effect i.e. variation of viscosity due to magnetic field becomes dominant as compared to the natural viscosity variation. Due to the presence of suspended particles base fluid becomes thicker. Commonly used base fluids are hydrocarbon oils, mineral oils and Silicon oils.

### B. Metal particles

For proper utilization of this technology we need such type of particles which can magnetized easily and quickly therefore we use metal particles. Metal particles used in the MR- technology are very small. Size of the particle is approximate of the order of 1μm to 7μm. Commonly used metal particles are carbonyl iron, powder iron and iron cobalt alloys. Metal particles of these materials have the property to achieve high magnetic saturation due to which they are able to form a strong magnetizing chain. The concentration of magnetic particles in base fluid can go up to 50% (approx.)

### C. Additives

It is necessary to add certain additives to MR fluid for controlling its properties. These additives include stabilizers and surfactants. Surfactants serve to decrease the rate of settling of the metal particles. While the functions of additives are to control the viscosity of the fluid, maintain friction between the metal particles and to reduce the rate of thickening of the fluid due to long term use of the fluid thus additives also increase the life of the MR fluid. Commonly used additives are ferrous oleate and lithium stearate. All the three components of an MR fluid define its magneto rheological behaviour. Changing any one component will result in change in the Rheological and magneto rheological properties of the MR fluid. An optimum combination of all the three components is necessary to achieve the desirable properties of an MR fluid. [6]

### 3.1 Working Principle of MR Fluid Technology

The MR fluid is a smart fluid whose properties can be controlled in the presence of magnetic field. In the absence of magnetic field, the rheological properties of the MR fluid are similar to that of base fluid except that it is slightly thicker due to the presence of metal particles.

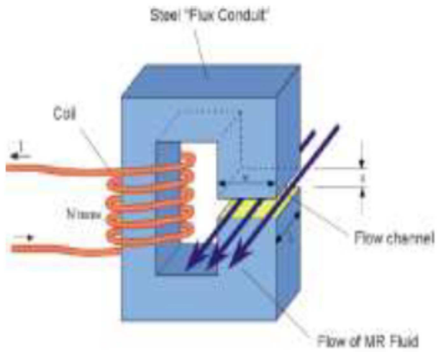


Figure 3.1 Principle of MRF Technology [7]

In the absence of magnetic field, these metal particles align themselves along the direction of flow however when a magnetic field is applied each metal particles becomes a dipole aligning itself along the direction of magnetic field. Thus a chain like structure is formed along the line of magnetic flux which offers mechanical resistance to the flow resulting in an increase in the viscosity of fluid .This mechanical resistance created due to the chain column imparts yield strength to the fluid, making it stiff like a semi-solid. This stiffness and hence the yield strength depends on the strength of the magnetic field and also the quality and quantity of metal particles.

The MR effect is reversible. When the magnetic field is removed the fluid returns to its original condition. The MR fluids with their controllable properties are found to be useful in the implementation of smart fluid concept. Where the fluid motion is controlled by varying its viscosity with the help of magnetization .The simpleness of MR fluid technology, the controllability and the quick response of the rheological properties makes it a smart fluid with application areas where fluid motion is controlled by varying the viscosity. [8, 9]

### 3.2 MR Fluid Operational Modes

All devices that use MR fluids can be classified as operating in one of the three modes demonstrated in Figure 3.2. As shown in the figure, valve mode involves fluid flowing as a result of a pressure gradient between two stationary plates. Devices that utilise this mode include servo-vales, dampers, shock absorbers and actuators. The pressure drop, ΔP, in an MR fluid device utilising the valve mode principle can be represented by the following equation: [10]

$$\Delta P = \Delta P_{\eta} + \Delta P_{\tau} = \frac{12\times\eta\times Q\times L}{g^3\times W} + \frac{c\times\tau_0(H)\times L}{g} \qquad (3.1)$$

Here, ΔP [Pa] is the pressure drop that is a sum of a viscous component, $\Delta P_{\eta}$ [Pa], and a field dependent induced yield stress component, $\Delta P_{\tau}$ [Pa]. Q [$m^3/s$] is the flow rate of MR fluid, whereas L [m], g [m] and w [m] represent respectively length, fluid gap and width of the flow orifice between the fixed magnetic poles. 'c' is a dimensionless constant that varies between 2 and 3, depending on the ratio between the viscous component and the yield stress component. Equation (3.1) can be used for the design of MRF applications in valve mode, e.g. the minimum volume of active fluid can be established. $\tau_0(H)$ is the yield stress, defined in equation (2.2), and η is the dynamic viscosity (see equation (2.1)).

Shear mode involves fluid between two plates that moves relative to one another, and is particular useful in clutches and brakes. Squeeze mode involves fluid between two plates moving in the direction perpendicular to their planes. This mode is not that well understood as the other modes, and few applications exist. One exception is use in some small-amplitude vibration dampers. In all the three cases mentioned above, the magnetic field is perpendicular to the planes of the plates in order to restrict the fluid in the direction parallel to the plates.

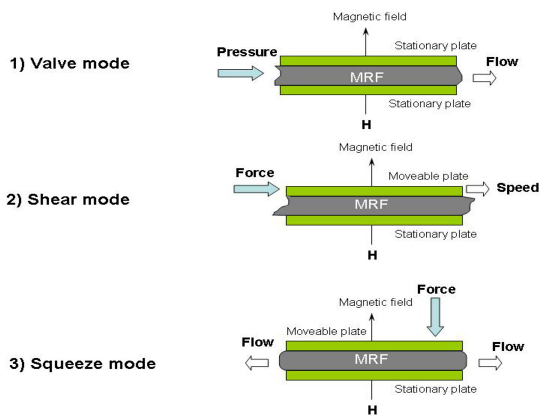


Figure 3.2 – MR Fluid Operational Modes [1]

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## 4. Applications

Following are the various application MR fluids.

### 4.1 Brakes and clutches

MR fluid-based brakes and clutches generally work in the shear mode but may also work in the flow mode. The MR fluid rotary brake made by Lord Corp. is a controllable rotary resistance element that is compact, smooth acting and low power consuming. An MR fluid brake that has been used for cycling and stair-climber types of aerobic exercise machine is shown in Fig. 4.1 The brake is 92 mm in diameter and provides a maximum dissipative torque of 7 N m for speeds of up to 1000 r/min. The maximum mechanical energy dissipated is 700 W, while the maximum required electrical power supply is 10W (0.8 A at 12 V). They are used in conjunction with velocity feedback where the torque is controlled in real time such that the user is forced to maintain a desired target speed profile. Their simplicity and ease of control make them a very cost-effective choice for a wide variety of applications ranging from controllable exercise equipment to precision active tension control.

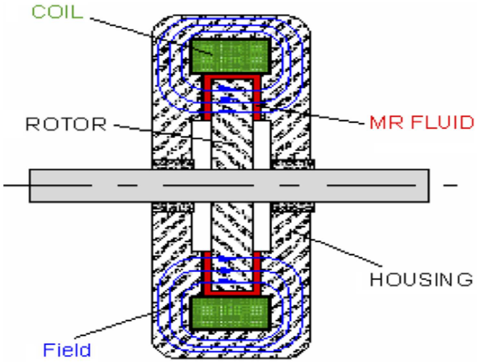


Figure 4.1: MR Fluid Rotary Brake [4]

Carlson and Catanzarite applied for a patent on MR fluid devices and a process of controlling force in MR fluid-based exercise equipment. With few constructive changes, the rotary brake can be transformed into a disc clutch. At high speeds of rotation the particles of MR fluid in the disc clutch would be thrown to the edge of the disc but a cylindrical clutch can be used to overcome the problem. In recent years more patents on clutches have appeared. These clutches can be controlled by electromagnets or by permanent magnets. Because their transmission torque is relatively low, MR fluid clutches may be used in the controllable transfer of auxiliary power, such as the controllable power transfer in automobiles between the engine and supplementary equipment (generator, ventilator). Lee *et al.* analysed the torque transmission characteristics of an MR fluid clutch by considering the complex shape of the clutch, magnetic flux field and corresponding distribution of MR fluid viscosity. The results showed that the analysis agreed quite well with the experiments. Hence, the analysis method may be used for a precise design of an MR fluid clutch.[11]

### 4.2 MR dampers

MR dampers have been most widely used for commercial applications among MR devices. An MR damper is capable of responding quickly while providing large dynamic forces. An additional advantage is that, unlike hydraulic dampers, MR dampers do not require mechanical valves to restrict flow. Such a device has instead an electromagnetic coil incorporated into the piston while the reservoir is filled with an MR fluid. A magnetic field is developed in the angular orifice (see Figure 4.2) when a suitable current is applied. As a consequence, a yield stress is developed in the fluid as it passes through the flux path. This leads to an apparent increase in fluid viscosity.

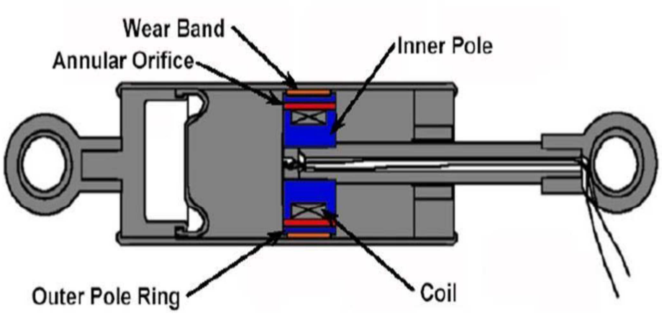
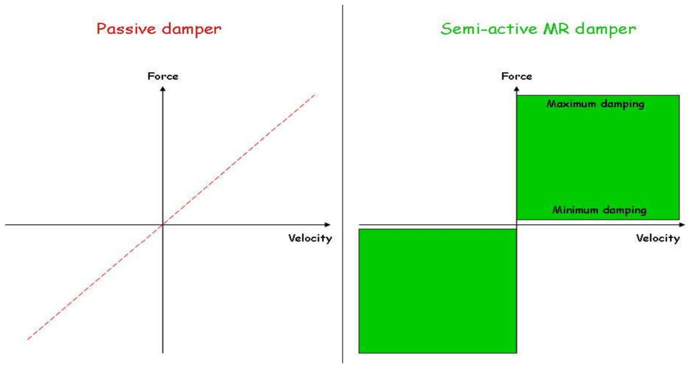



Figure 4.2 – Schematic Drawing of an MR Fluid Damper [5]

MR fluid dampers are considered as semi-active damping elements due to their ability to offer controllable damping force, and with minimal power requirements. The benefit of using an MR fluid damper over a conventional passive damper is related to the force generated by the damper.

As seen in Graph 4.1, a linear viscous damper will generate a force proportional to the velocity. However, an MR damper is capable of generating a continuously variable force (within its range).




Graph 4.1 – Passive Damper Characteristics vs. Semi-active MR Damper Characteristics

Currently, three main categories of MR dampers exist, including the mono tube, the twin tube and the double-ended MR damper.

**4.3 MR devices in automotive applications**

The automotive industry in particular has taken advantage of MR fluid dampers as real time semi-active damping elements. First introduced by Crosby and Karnopp semi-active systems have since been considered for vehicle primary suspensions. Semi-active suspensions have been shown to offer valuable benefits for vehicle primary suspensions. Moreover, semi-active suspension systems which use MR fluid dampers have developed into a technology that is currently being implemented. As early as 2002, Cadillac has offered an MR semi-active suspension in its premium vehicles, such as the Seville STS and Escalade EXT. Currently, Cadillac offers a Magnetic Ride Control suspension on the 2004 STS and the 2004 SRX. Other GM brands are offering similar advanced suspensions. With the release of the $50^{th}$ anniversary Corvette, Chevrolet offered a Magnetic Selective Ride Control system. The same suspension has carried over into the sixth generation Corvette. Advantages of this suspension include real-time control and the ability of the suspension to adapt to changing road and driving conditions. Picture 4.1 illustrates the performance benefits of the Magnetic Selective Ride Control system. A 60 mph pass over the Ride and Handling Loop at the Milford Proving Grounds demonstrates the superior control of the MR suspension.


Picture 4.1–Base C5 Corvette and 50th Anniversary Corvette with Magnetic Selective Ride Control Suspension [13]

Vehicle secondary suspensions are also good candidates for MR dampers. One of the most commercially successful MR devices to date is the Rheonetic RD-1005-3 MR damper that is manufactured by Lord Corporation. Much of the success attributed to the Rheonetic RD-1005-3 MR damper is its use in semi-active seat suspension systems for large on and off road vehicles. This particular damper is used in a seat suspension system available from Lord Corporation called the MotionMaster™ Ride Management System, which consists of the damper and a control unit. This system, which is intended as a retrofit to existing hydraulic truck seat dampers, as well as for use by the original equipment manufacturer, has been very well received by the industry. There have been a number of studies which demonstrate the advantages of a semi-active damper over conventional passive dampers in secondary or seat suspensions. Agricultural off-highway vehicles also stand to benefit from the superior vibration isolation available with the MotionMaster™ system. Sears Seating has partnered with Lord Corporation to develop a MotionMaster™ system tailored for agricultural and off-highway equipment. School transportation officials have also taken advantage of the MotionMaster™ system. In fact, in an effort to reduce worker compensation claims, school transportation officials in many states have adopted the MotionMaster™ Ride Management System for use in buses. When retrofitted with the MotionMaster™ Ride Management System drivers report less fatigue and reduced back and leg discomfort.

**4.4 Others application:**

Microprocessors, sensor technologies and increasing electronic content and processing speeds have created real-time control possibilities of smart systems used MR devices, Positional and velocity control of pneumatic actuator systems, MR sponge dampers for washing machines, Magnetorheological fluid polishing tools, Very large MR fluid dampers for seismic damage mitigation in civil engineering structures, large MR fluid dampers to control wind-induced vibrations in cable-stayed bridges

## 5. CONCLUSIONS

Magneto rheological fluid technology has a wide scope in the coming era. This technology is very useful in those places where controlled fluid with varying viscosity is required. The main features of MRF technology are fast response, simple interface between electrical input and mechanical output and intelligent controllability. This technology is simple and involves less moving parts. Hence MRF based products require less maintenance and have comparatively longer life. The main drawback of MRF technology is that the MR fluid becomes thick after prolonged use and needs to be replaced, also due to presence of high density metal particles, the weight of MRF products is high.

At present automobile industries are using this technology. Some other fields where this technology can be used are in aerospace and medical field. There is a vast scope for research in MRF technology .MRF systems need to be made more sensitive, possibly by introducing the uses of sensors and feedback system i.e. closed loop systems. The life span of MRF devices in terms of the total energy dissipated from the equipment need to be increased. An improved MRF technology would make it the smart technology of future.

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