MR- FLUID TECHNOLOGY & ITS APPLICATION FOR DESIGNING HYDRAULIC VALVE

Akshay Thakur*

Akshay Baste**

Abstract-

Magneto Rheological (MR) fluids, which can rapidly be changed from a liquid state to a solid state and vice versa by a magnetic field, have the potential to revolutionize several industrial sectors. The key issue is to enhance their yield shear stress. 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 technology, its working modes and its field of applications.

***Key Words*—Controlled fluid, Metal particles, MRF,Rheological fluid, Smart fluid, MRF Applications, MR directional controllable valve.**

* Lear Corporation

** MET's Institute of Engineering

1. INTRODUCTION

MRFT stand for Magneto-rheological fluid technology. The essential components of MRFT are MR fluid and a magnetic field to control the viscous property of the fluid. The basic principle of MRFT is that very small suspended particles having magnetizing properties are introduced in the base fluid. When a magnetic fluid is applied to this fluid, these particles form a chain aligned in the direction of the field which creates a resistance to the fluid flow. Resulting, an increase in the fluid viscosity takes place. Thus in the presence of magnetic field the MR fluid converts into a semi solid with an increase in its yield strength. This work phenomenon takes only milliseconds to occur [2]. MR fluids thus act similar to Bingham fluids used in many engineering applications. In the absence of magnetic field, the MR fluid behaves like newtanion fluids. As a result MRF development is ongoing continuously. Approximately sixty years ago, in the 1940s, Jacob Rabinov discovered the MRF effect at the US National bureau of Standards. At the same time W. Wislow was working on a competitive technology called Electro- Rheological Fluid (ERF). Since the time when both technologies were discovered in the 1940s, more research work has been carried out on ERF than on MRF. There are some similarities between the two different technologies regarding the required power, but in the case of ERF, thousands of volts and some milli-amperes are required, and in the case of MRF, normally between 2 and 24 volts and some amperes are required. The electro-rheological (ER) effect depends on an electrostatic field and the magneto rheological (MR) effect depends on a magnetic field. MRF products have between 20 and 50 times higher control effect than the equivalent ERF products. Also with MRF technology today there is better stability with regard to contaminants. All these MRF technology advantages have created a very high level of interest to introduce products based on MRF technology during the most recent couple of years. Table 1 gives an overview of the ER and MR key features [1]. Over approximately the most recent five years more MRF publications than ERF publications have been presented in the public domain. At the beginning of the development work on MRF, non-predictable behavior, such as in-use thickening, sedimentation and abrasion [2,3] were described. This created some challenges for the industrialization of the first application based on MRF, especially for an automotive application. During the most recent few years the stability, sedimentation and abrasive behavior have been studies in several universities and companies in the USA (Lord Inc.), in Europe (DEA, BASF, Bayer) and in Japan

(Bridgestone Inc., Sigma Inc.) Recently MRF applications such as dampers, clutches, active bearings have already come to the market or are close to the start of serial production.

Table 1.Comparison of MRF and ERF

Representative Feature	**MRF**	**ERF**
Max. Yield Stress	50-100kPa	2-5kPa
Power Supply	2-24V @ 1-2 A	2-5kV @ 1-10 mA
Response time	0.02sec	0.06sec
Operational Field	~250 kA/m	~4kV/mm
Energy density	$0.1 J/cm^3$	$0.001 J/cm^3$
Stability	Good for most impurities	Poor for most impurities
Operational temperature	-40°C up to +150°C	-25°C up to +125°C

2. 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 [3]:

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 [4]. 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 [1]. 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.) [3-6]

C. Additives

It is necessary to add certain additives to MR fluid for controlling its properties. These additives include stabilizers and surfactants [7]. 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 behavior. 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.

3. PROPERTIES OF MR FLUIDS

More recently MR fluids have gained considerably more attention than their electric analogue electro rheological (ER) fluids which were discovered by WINSLOW in 1948 [9, 10].One of the advantages of MR fluids is the higher yield stress value than ER fluids. The reason for having higher yield stress for MR fluids is the higher magneto static energy density, of MR fluids compared to electrostatic energy density, of ER fluids. Low voltage power supplies for MR fluids and relative temperature stability between –40°C and +150 °C make them more attractive materials than ER fluids. Ferro fluids do not exhibit yield stress, but show an increase in the viscosity. The viscosity under an applied magnetic field increases almost twice as much as the viscosity when there is no magnetic field applied. Since Ferro fluids are synthesized by colloidal magnetic particles, these fluids are more stable than MR fluids based on non-colloidal magnetic particles.

3.1. Magnetic materials for MR fluids

In MR fluids, materials with lowest coercively and highest saturation magnetization are preferred, because as soon as the field is taken off, the MR fluid should come to its demagnetized state in milliseconds. Due to its low coercively and high saturation magnetization, high purity carbonyl iron powder appears to be the main magnetic phase of most practical MR fluid compositions. Iron powders made by the CVD decomposition of iron pent carbonyl (Fe (CO) $_5$) are preferred as opposed to for example, those prepared using the electrolytic or spray atomization process. This is because carbonyl iron is chemically pure and the particles are micro-scale and spherical in nature in order to eliminate the shape anisotropy. The micro-scale particles are necessary since they have many magnetic domains. The high level of chemical purity (> 99.7%) means less domain pinning defects. The spherical shape helps minimize magnetic shape anisotropy. The impurities that cause magnetic hardness in metals also cause mechanical hardness, due to resistance to dislocation motion, and make the iron particles mechanically harder. In MR fluid based devices, it is preferred to have non-abrasive particles. This is another reason why spherical, high purity iron powders are more appropriate for applications as a dispersed phase in MR fluids. Thus, carbonyl iron is chosen because of its high saturation magnetization (2.1 T, at room temperature) [30] and magnetic softness. Among other soft magnetic materials, Fe-Co alloys (composition w (Fe) = 50%) have a saturation magnetization of 2.43 T [36]. Although some researchers reported an enhanced yield stress for Fe-Co based fluid, the settling problem of the fluid will be aggravated due to the higher bulk density (8.1 gr/cc) than that of Fe (7.8 gr/cc). Also the cost of these alloys makes them undesirable for MR fluids. CARLSON and WEISS reported that as well as iron-cobalt alloys, iron-nickel alloys in ratio ranging from 90:10 to 99:1 showed a significant increase in the yield stress of MR fluids . MR fluids have been prepared based on ferromagnetic materials such as manganese-zinc ferrite and nickel zinc ferrite of an average size of 2 µm. The saturation magnetization of ceramic ferrites is relatively low (0.4~0.6 T) and therefore the yield stresses also tend to be smaller.

3.2. Properties of commercial MR fluids

Magnetic, rheological, tribological and settling properties of four commercial MR fluids are discussed. The basic composition of these four fluids commercially available is given in

Commercial MR fluid	**Percent iron by volume**	**Carrier fluid**	**Density / -1 g mL**
MRX-126PD	26	Hydrocarbon oil	2.66
MRX-140ND	40	Hydrocarbon oil	3.64
MRX-242AS	42	Water	3.84
MRX-336AG	36	Silicone oil	3.47

Table*. *2 Basic composition and density of four commercial MR fluids

The rheological properties of controllable fluids depend on concentration and density of particles, particle size and shape distribution, and properties of the carrier fluid, additional additives, applied field, temperature, and other factors. The interdependency of all these factors is very complex, yet is important in establishing methodologies to optimize the performance of these fluids for particular applications. Both linear models and models accounting for nonlinear magnetic effects such as particle saturation predicted quadratic behavior at very low flux densities.

3.3. Stability of MR fluids

The stability and redispersibility of MR fluids have been one of the most important issues of these materials. Stable MR fluids are considered to exhibit no or very little amount of particle settling. For dilute systems, the dependence of the sedimentation velocity of a spherical particle can be obtained

FromStoke's law $v = \frac{2R_s^2}{9}\frac{(\Delta\rho)g}{\eta}.$

Rs is the particle radius, Δρis the difference in density of the magnetic phase and carrier liquid, η is the viscosity of the carrier liquid and g is the gravitational acceleration (9.8 m/s2). Since, less viscous liquids will aggravate the settling of the particles in an MR fluid, Rankin and co-workers formulated a suspension with viscoplastic continuous phase (e.g., grease) to prevent sedimentation. When the yield stress of the viscoplastic medium is bigger than the critical yield stress that was defined for each particulate material and particle radius, the particles are suspended. Although, for most of the applications the figure of merit for MR fluids is to keep the off state viscosity as small as possible, for applications such as control of seismic vibrations, paste-like MR fluids can be more appropriate since the gravitational settling over an extended period can be prevented.

3.4. Effect of temperature on MR fluids

When a magnetic field is applied across MR fluids, a yield stress is developed, and their rheological properties can then be categorized into two distinct regimes: pre-yield and post yield. The research basically concerns about the viscoelastic behavior of MR fluids in the pre-yield region. Oscillatory tests were carried out to determine the complex shear modulus properties of MR fluids between the temperature range of -20°C and +50°C. The test results show that the storage modulus and loss modulus increased in value as the excitation frequency was increased from 5Hz to 50Hz. The complex modulus was also found to be influenced by changes in temperature; the higher the temperature, the lower the complex modulus. This is consistent with the behaviour of viscoelastic polymers. The sets of temperature-dependent and frequency-dependent data were subsequently condensed using the method of reduced variables into master curves of complex modulus, which effectively extended the frequency coverage of the data at the reference temperature.

4. 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.

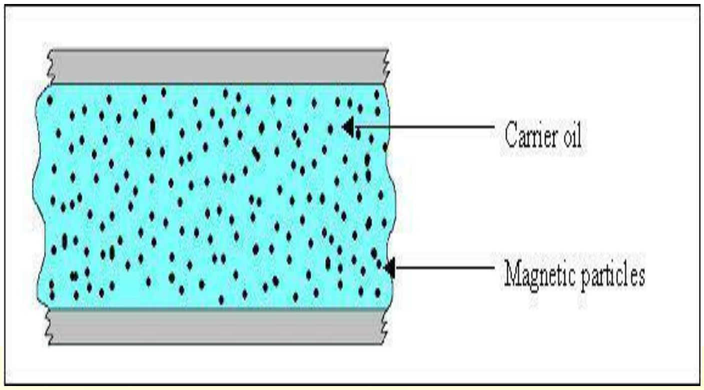
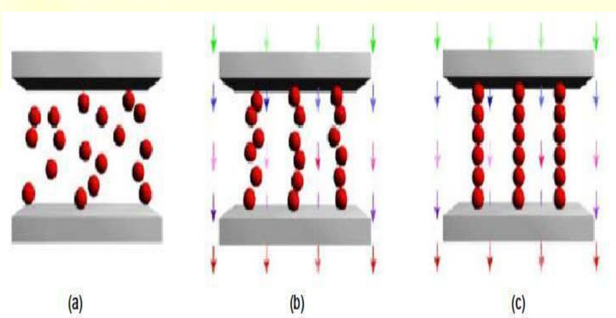


Fig. 1 Principle of MRF Technology

In absence of magnetic field, these metal particles align themselves along the direction of flow (figure 2(a)) however when a magnetic field is applied each metal particles becomes a dipole aligning itself along the direction of magnetic field (Figure 2(a) and (b)). 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. [3-4]



of metal particles. Behavior of the MR fluid in the presence of magnetic field varies according to different magnetic intensities. As we increase the intensity of the magnetic field, the shear stress increases continuously. With the increment in shear stress, the fluid starts to behave like semi solid.

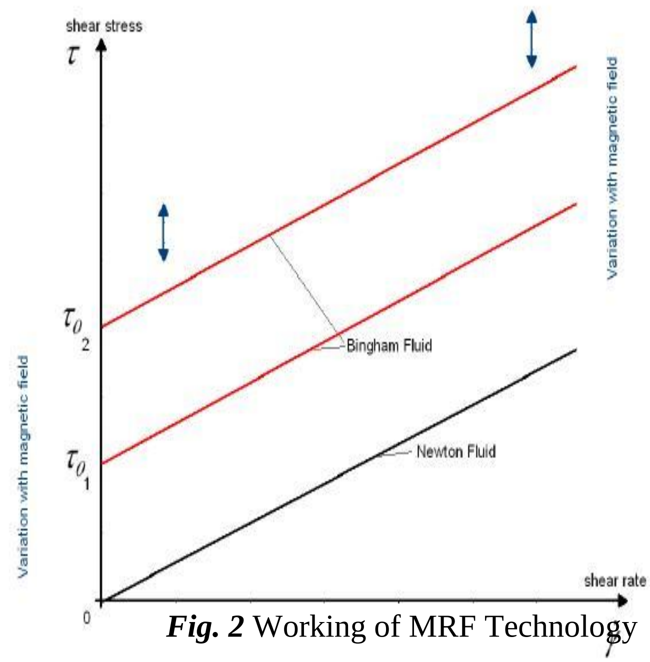


Fig. 2 Working of MRF Technology

6. RHEOLOGY OF THE MR FLUID

Rheology is the study of the deformation and the flow of the liquid. Basically three factors viscosity, shear stress and rate of strain are considered in the study of flow and deformation. In most of the fluid applications viscosity is an important property. In case of general fluids, viscosity changes with change in other physical properties such as shear stress, temperature etc. In most applications these physical properties cannot be controlled as they are governed by the working environment and hence the viscosity also cannot be controlled. In the absence of magnetic field the MR fluid behaves like a newtanion fluid (Fig.3) and has nearly the same characteristics as the carrier or base fluid .when a magnetic field is applied the MR fluid behaves like a Bingham fluid showing resistance to flow even at zero shear rates. The yield stress i.e. the maximum shear stress which can be applied without continuous movement is a function of the strength of the magnetic field. Thus MR fluid is controlled resistive fluid. The yield strength also depends on the magnetization characteristics of the metal particles which in term depends on the concentration and nature

Fig.3 Rheology of MRF Fluid

7. MRF MODES AND THEIR APPLICATIONS

According to the type of fluid flow, there are following three modes of MRF operation:

A. Valve mode

B. Shear mode

C. Squeeze mode

A. Valve Mode:

The valve mode as an operational mode is used in dampers, shock absorbers and is shown schematically in Figure 5.In this mode of MRF operation, fluid flow through the two fixed surfaces and magnetic field is applied perpendicular to the direction of flow the resistance of the fluid can be controlled by controlling the intensity of magnetic field. This mode of MRF technology is used in various types of dampers and shock absorbers and has vast application in automobile industry. The pressure drop in this mode is the summation of pressure developed due to fluid viscosity ΔP_v and pressure developed due to the magnetic field. ΔP_m.

$$\Sigma P = \Delta P_v + \Delta P_m$$

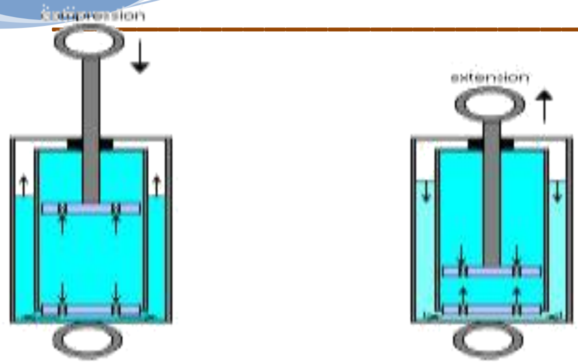
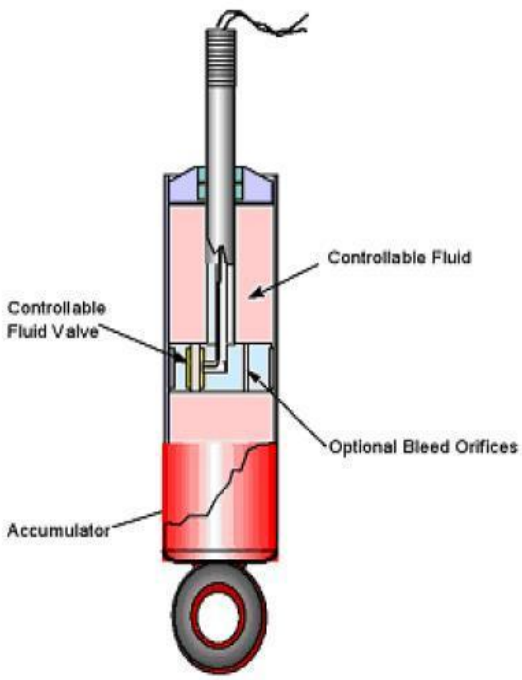


Fig.4. Conventional damper

In conventional dampers, fluid flows from the inner Cylinder to outer cylinder through the foot valves. In outer cylinder there is air and fluid. As piston moves down, the fluid level in outer cylinder increases and free air behaves as a compressed medium and produces damping effect. When the piston expands, direction of flow gets reverse.



non magnetized condition, fluid can move through the orifice but when suspension is required, the coil is energized and current starts to flow through the coils, and develops a magnetic field. Due to the effect of this magnetic field, fluid in the orifice behaves like a semi solid and offers resistance to the fluid flow. Thus the fluid in the chamber starts to behave like a shock absorbing medium. These types of dampers are used for seat vibration control in vehicles. This technology is quicker, effective and requires less maintenance. In general it has been shown that for different velocities damping force produce by the MR damper is larger than force developed by the conventional dampers and amplitude of force can be enhanced by increasing the voltage in between the coils of MR dampers. 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,7 such as the Seville STS and Escalade EXT [8, 9]. 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 50th 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. Figure 6-7 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 [9].

Fig.5. MRF Damper

MR dampers are slightly different from the conventional dampers .They don't have valves in the piston as piston of conventional dampers.MR damper shown in the figure 5 is used in the suspension of highway vehicles [8]. In this type of damper there is an annular orifice passage, through which MR fluid can be transmitted from one chamber to another. In

Fig.6.Base C5 Corvette and 50th anniversary Corvette with Magnetic Selective Ride Control suspension

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 Motion Master™ 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 10 semi-active damper over conventional passive dampers in secondary or seat suspensions [9-10]. Agricultural off-highway vehicles also stand to benefit from the superior vibration isolation available with the Motion Master™ system. Sears Seating has partnered with Lord Corporation to develop a Motion Master™ system tailored for agricultural and off-highway equipment [10]. School transportation officials have also taken advantage of the Motion Master™ system. In fact, in an effort to reduce worker compensation claims, school transportation officials in many states have adopted the Motion Master™ Ride Management System for use in buses. When retrofitted with the Motion

Master™ Ride Management System drivers report less fatigue and reduced back and leg discomfort.

B.Shear Mode:

The direct shear mode is used in brakes and clutches and is shown schematically in Fig.8 Shear mode of MRF technology is used in various types of brakes and clutches of the vehicles. In this mode, the total shear force developed is a summation of the force developed due to the viscosity of the fluid (Fv) and the force developed due to the magnetic field (Fm).

$$\Sigma F = Fv + Fm$$

A conventional braking system has certain disadvantages such as high energy consumption, bulky, problem with leakage in hydraulic line, brake noise due to metal-with metal friction, brake pad need to be replaced periodically, response delay due to pressure build up, require auxiliary components such as hydraulic pump, fluid transfer, brake valve & fluid reservoir.

MRF braking system functioning has been shown. There is an outer stationary cylinder and an inner rotating cylinder and the space between these two cylinders is filled with MR fluid. In the absence of magnetic field, the rotating cylinder rotates freely. But when the solenoid coils are energized then a magnetic field is generated to an extent that the MR fluid starts behaving as a semi solid and offers resistive torque to the rotating cylinder.

This phenomenon takes milliseconds to occur after the energising of the solenoid coils. Braking torque can be controlled by varying the intensity of the external magnetic fluid. This technology has following advantages over conventional braking system:

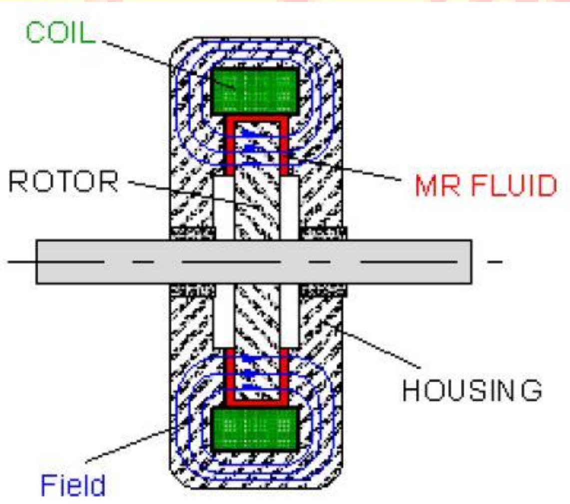


Fig.7Construction of MR-brakes

1. Low power requirements (only several amperes)

2. Simple design and construction

3. Hydraulic free: no hydraulic line & need less space requirement

4. No metal-with-metal friction

5. No brake pad needed

6. Easy to control (potential to be used for brake-by wire (BBW) system)

7. Fast response (0.02 second)

A.MRF Clutches

Since MRFs have the inherent property of changing their yield stress depending on the applied magnetic field, devices designed using MRFs may be controlled easily by varying the current through the electromagnetic coil placed in the device. MRF clutches exist primarily in two different configurations: 'Disc-shaped' and 'Cylindrical' or 'Bell-shaped' clutches. The disc-shaped clutch shown in Figure 8 consists of two 'discs', one connected to the input shaft and the other to the output shaft of the clutch. The MRF fills the small gap between the two discs. The coil is placed in the housing as shown in the figure. As the magnetic field in the gap is increased by increasing the current through the coil, the MRF in the gap gets activated. This results in more torque being transmitted from the input shaft to the output shaft. The cylindrical clutch has a configuration similar. Here, the input shaft is connected to the outer cylinder. The output shaft is connected to a rotary piston.

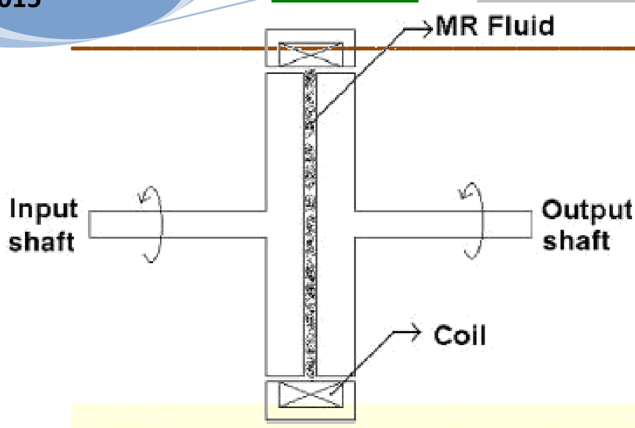


Fig.8.Construction of MR Clutch

The MRF is held in a small annular gap between the outer cylinder (input) and the rotary piston (output). The coil is housed in the piston. As the MRF is excited using the electromagnetic coil, the torque transmitted across the clutch increases. Compared to the disc-shaped device, the cylindrical clutch is preferred due to the complexities in the practical design of the disc-shaped clutch and also due to the exaggerated effect of centrifuging in disc-shaped clutches compared to their cylindrical counterparts.

7. MR Directional Control Valve

Directional control valve has complex construction, such as moving spool to control the direction of actuator and desired speed. Magneto-rheological (MR) fluid is one of controllable fluids. Utilizing the MR fluid properties, direct interface can be realized between magnetic field and fluid power without the need for moving parts like spool in directional control valves.. The valve worked proportionally to control the direction and speed of hydraulic actuator. The MR directional valve can replace many types of the spool directional control valve for controlling hydraulic actuator.

7.1Design of MR directional valve and its working

Hydraulic valves have complex construction and moving parts, thus the characteristics and life of hydraulic proportional directional control valves are affected greatly by moving parts as shown in Fig.9.

Using the rheological property of MR fluid, the new type of MR flow directional hydraulic control valve can be designed with the absence of moving parts.

MR directional valve design is compact and easily installed in hydraulic systems along with the other hydraulic components. It consists of the following main parts: four single MR valve bodies, three insert partitions two covers and. Single MR Valve was designed by Salloom and Samad

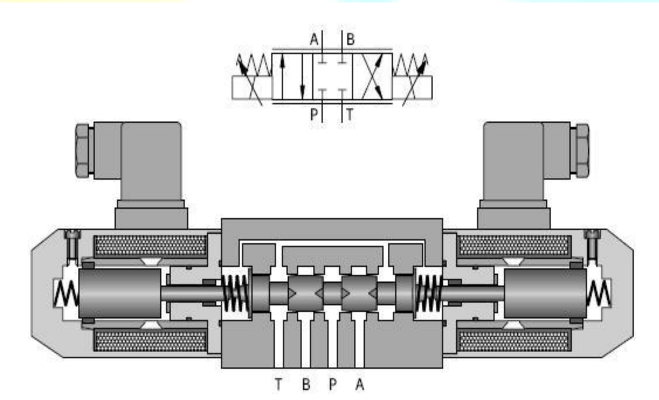


Fig. 9. Hydraulic (4/3) directional control valve.

The construction of single MR valve is shown in Fig.12.Four single MR valves (elements) is equips inside the valve body which were arranged one after another to make the desire configuration type as shown in Fig. 10. The input/ output ports were threaded by 1/8 Inch BSP thread, so that standard pipe fittings can be connected easily to them. The terminals of the coil can be easily fed to the hole available in the body. Four single MR valves (elements) is equips inside the valve body which were arranged one after another to make the desire configuration type as shown in Fig. 10. The input/ output ports were threaded by 1/8 Inch BSP thread, so that standard pipe fittings can be connected easily to them. The terminals of the coil can be easily fed to the hole available in the body.

Designs that take advantage of controllable fluids are potentially simpler and more reliable than conventional electromechanical devices. In addition, the MR fluid is one of the most efficient means to interface mechanical components along with electronic controls, offering fast speed switching and continuous variable control [11].Some researchers did connect a set of MR valves in order to make it more useful. Yoo and Wereley [12], Yoo et al. [13] and Shaju et al. [14] have arranged a set of four MR valves implemented as Wheatstone bridge hydraulic power circuits to drive a hydraulic actuator using a gear pump as hydraulic power source.

The performance of hydraulic system with MR valve is dependent on output load and driving current to MR valve.Recently, the MR directional control valve was designed with absence of moving parts using the rheological property of MR fluid. The compact new design has been developed by Salloom and Samad [15]. They have proposed combining a set of single MR valves thus becoming a compact unit in order to simplify the design and manufacturability. They have presented the construction and the principle of work of MR directional control valve. The following content presents the possibility configurations of the newly designed MR directional control valve.

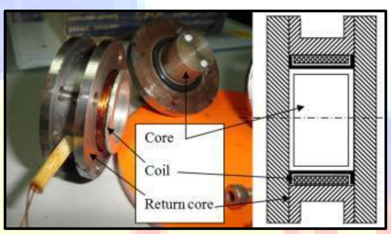


Fig. 10The construction of single MR valve.

Referring to Fig. 11, the general configuration MR directional valve consists of four adjacent single MR valves a, b, c, d. In the null position (closed configuration), coil of all single valves are energized with maximum current. In extended position of MR directional valve, the coils of two single MR valves (a and c) are energized with maximum current, while the coils of two other single MR valves (b and d) are set at low current (0- maximum designed current). Under this condition, the flow of MR fluid pass through port P to port A and returns through port B to port T, hence, moving the actuator extended. In retracted position of valve, the coils of two other single MR valves (b and d) are energized with maximum current, while the coils of two single MR valves (a andc) are set at low current (0-maximum designed current). Under this condition, the flow of MR fluid pass through port P to port B and returns through port A to port T, hence, moving the actuator retracted. The coils of MR directional valve can be connected with particular electrical circuit using many ways. These connections give different types of operation to the MR directional valve [17].

The new type MR flow-directional hydraulic control valve can be designed with absence of moving parts. The construction and working principle of the new type valve will be introduced. Next work, the new type valve will be used to replace a three position four-way (4/3) directional control valve with various center positions. Using an arrangement similar to the Wheatstone bridge circuit concept, the hydraulic system will be shown in Fig. 11 and Fig. 12. The speed and position control for hydraulic actuator will be studied, by using the proposed flow-directional hydraulic control valve.

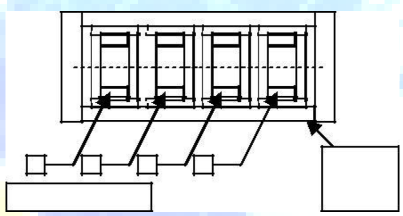


*Fig. 11.*Basic drawing of MR directional control valve.

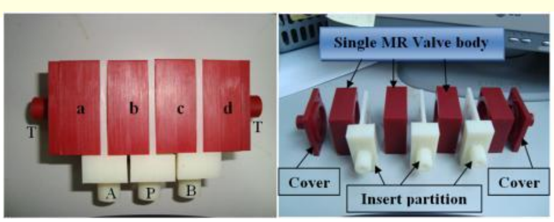


*Fig. 12.*The construction of MR directional control valve.

7.2 The Experiment

An experiment to test 4/3 MR valve has been performed. In fact, the purpose of the test is to confirm the functional principle of work. Arrangement and setup of the overall hydraulic control circuit for valve test is shown in Fig. 13. The experimental rig includes hydraulic cylinder, MR fluid tank, MR valve, DC power supply, particular electric circuit, and all necessary instruments such as pressure gauge. The variable current is achieved using the rheostat connected in series with the valve's coil.

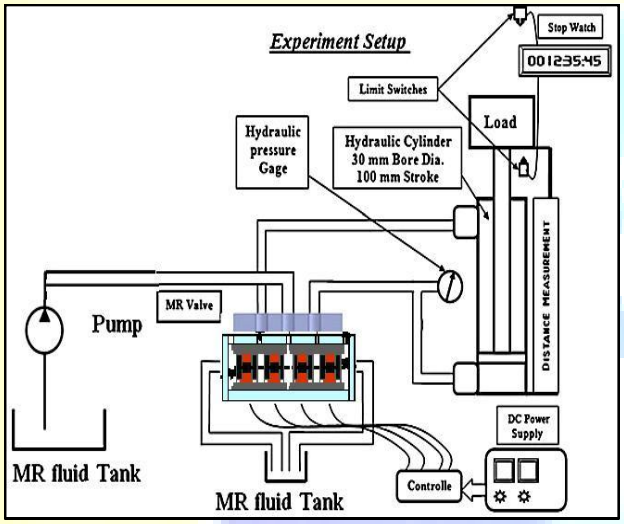


Fig. 13.Hydraulic control circuit for valve test.

The experiment test shows the working principle of the valve and how to change the direction using the proposed electrical circuit. The valve can be used to replace a four way three position (4/3) directional control valve. The experiment test was done according to the procedure explained by Salloom and Samad [18].

8.Result and Discussion

As a result, there are eight configurations, fully closed, only pressure port closed, only return port closed, only port A closed, only port B closed and fully open, (see Table 3). The flow of the MR fluid depends on which type of configuration chosen. Fully closed configuration is when all ports of MR directional valve are closed, while fully open configuration is when all ports of MR directional valve are opened. Other configuration one port is closed, while three other ports are open. The valve can be operated not only as an ON-OFF directional control valve, but also as a proportional directional control valve. Thus, the valve can also be utilized to control the speed of hydraulic actuator.

Regarding experimental results of MR directional valve operation with actuator can be discussed the following: when the valve is used as ON-OFF, it can change the directions of moving actuator but with maximum break pressure 12 bar that is limited by high current (e.g. 1.5A) . When the valve is used as proportional control, it can change direction and speed of actuator using different level of current (0.08 to 0.5A) for break pressure 12.7 bar.

Configurations	**Coil operation (1= Null, 2= Extended and 3= Retract)**
	1. Coils **a,b,c** and **d** ON at max.current 2. Coils **b** and **d** ON at max.current**a** and **c** OFF (no current) 3. Coils **a** and **c** ON max.current**b** and **d** OFF (no current)
	1. Coils **b** and **c** ON at max.current**a** and **d** OFF (no current) 2. Coils **b** and **d** ON at max.current**a** and **c** OFF (no current) 3. Coils **a** and **c** ON at max.current**b** and **d** OFF (no current)
	1. Coils **a** and **d** ON max.current**b** and **c** OFF (no current) 2. Coils **b** and **d** ON at max.current**a** and **c** OFF (no current) 3. Coils **a** and **c** ON at max.current**b** and **d** OFF (no current)

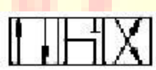
	1. Coils **c** and **d** ON at max.current**a** and **b** OFF (no current) 2. Coils **b** and **d** ON at max.current**a** and **c** OFF (no current) 3. Coils **a** and **c** ON at max.current**b** and **d** OFF (no current)
	1. Coils **a** and **b** ON max.current**c** and **d** OFF (no current) 2. Coils **b** and **d** ON at max.current**a** and **c** OFF (no current) 3. Coils **a** and **c** ON at max.current**b** and **d** OFF (no current)
	1. Coils **a,b,c** and **d** OFF (no current) 2. Coils **b** and **d** ON at max.current**a** and **c** OFF (no current) 3. Coils **a** and **c** ON at max.current**b** and **d** OFF (no current)
  	1. Coils **b,c,d** ON at max.current and **a** OFF (no current) 2. Coils **b** and **d** ON at max.current**a** and **c** OFF (no current) 3. Coils **a** and **c** ON at max.current**b** and **d** OFF (no current)
   	1. Coils **a,b,c** ON at max.current and **d** OFF (no current) 2.Coils **b** and **d** ON at max.current**a** and **c** OFF (no current) 3.Coils **a** and **c** ON at max.current**b** and **d** OFF (no current

Table 3: Configurations for MR directional valve (on-off operation)

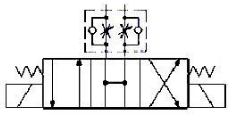
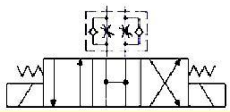
Configurations	Coil operation
 	1. Coils a,b,c and d OFF (no current)....null 2. Coils a and c ON at max.current, d at control current and b OFF (no current) ....retract with meter out 3. Coils b and d ON at max.current, a at control current and c OFF (no current) ....extended with meter out
	1. Coils a,b,c and d OFF (no current) ....null 2. Coils a and c ON at max.current, b at control current and d OFF (no current) ....retract with meter in 3. Coils b and d ON at max.current, c at control current and a OFF (no current) ....extended with meter in

Table 4: Configurations for MR directional valve (proportional operation)

The possible operating types of MR proportional directional valve are shown in Table 4. This can be done easily using different connection between valve's coils with particular electric circuit, whereas hydraulic control valves need to change the spool which is not easy and should be done in the factory.

9. Future Scope for MR directional Valve

In the present work, the construction and principle of work for a proposed MR directional valve was introduced. The valve will be used to replace a four-way three position (4/3) directional control valve, using four elements arrangement similar to the Wheatstone bridge circuit concept. The proposed design of MR directional valve enables its configurations and types of operation to be changed easily. This change can be done only by reconnecting the coils with particular electrical circuit. On the other hand, traditional directional control valve which has three positions is limited to only three different configurations unless its spool is changed.

Furthermore, MR directional valve can be used as proportional directional control valve, as well as ON-OFF valve, while in traditional valve, the designs of proportional and ON-OFF valve are different. The flow rate induced by the MR directional valve decreases when the increase in the current. The MR directional valve can be operated with variable flow rate Q by changing the value of the current. It is found that current is inversely proportional to the flow rate.

10. CONCLUSION

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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