Magneto-Rheological Fluid Technology

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ABSTRACT:

Magneto-rheological Fluid (MRF) can transform its colloidal structure in presence of magnetic field and regain original form with simplicity. This has led it to be referred as Smart Fluids. Yield stress can be increased in proportion to magnetic field and it behaves as Newtonian Fluid in normal state and Bingham fluid in magnetic field. Easy controllability and simplicity in designing has caused significant advancement in application of MRF technology in industries. MRF operates in three modes, namely valve mode, shear mode and squeeze mode. Several applications using valve and shear mode are already in the market. This paper presents design criteria for applications using shear and valve mode. The paper provides the solution in use of MRF technology in applications where motion is controlled by changing viscosity of the fluid. MRF proves to be the next choice of technology for various applications.

Keywords: magneto-rheological fluid, controllability, parameter analysis.

1. HISTORY AND SCOPE

Magneto-rheological fluid (MRF) belongs to the category of "Smart Materials" whose physical and chemical properties can be varied in a controlled manner. The essential characteristic of MRF is that they can alter state from normal Newtonian fluid to stiff semi-solid under the influence of magnetic field [Simon *et al.*, 2001]. Rabinov Jacob discovered MRF effect in 1940s at US National Bureau of Standards. During that period, Wislow was working on electro-rheological fluid (ERF) technology. In earlier times, ERF was being researched more than MRF. Magneto-rheological effect depends on magnetic field while electro-rheological effect depends on electro-static field. In terms of operation, MRF and ERF have some similarities as both require an external stimulus to trigger transition. With respect to power requirement, MRF works between 2 and 24 V and some amperes while ERF requires thousands of volts and some milli-amperes [Olabi and Grunwald, 2007]. Table 1 provides an outline of ERF and MRF features. All these advantages of MRF technology have created major interest for introducing MRF products in recent years.

Table 1. ERF versus MRF [Olabi and Grunwald, 2007].

Representative Feature	***ERF***	***MRF***
Operational Temperature	-25 ℃ up to +125 ℃	-40 ℃ up to +150 ℃
Maximum yield stress	2-5 kPa	50-100 kPa
Response time	Some millisecond	Some millisecond
Energy Density	0.001 $\mathrm{J/cm^3}$	0.1 $\mathrm{J/cm^3}$
Power supply	2-5 kV @ 1-10 mA	2-24V @ 1-2 A
Operational field	~4 kV/mm	~250 kA/m
Stability	Poor for most impurities	Good for most impurities

In the beginning, automotive industries were facing some challenges in application based on MRF due to its non-predictive behavior, such as sedimentation, abrasion and in-use thickening [Carlson, 2001]. Research in the field of non-predictive behavior of MRF has been made in several universities across the world and companies in Europe, USA and Japan in recent few years. Currently, applications based on MRF such as dampers, clutches, brakes have revolutionized the market.

Current paper describes the working principle behind magneto-rheological fluid and its components. It also states three operational modes through which MRF applications can be implemented in real world. Design factors required for operation of valve and shear mode has been analyzed. Controllability and lifetime of MRF has been discussed.

2. INTRODUCTION

Magneto-rheological fluids are formed by suspending finely polarized ferromagnetic particles in viscous or viscoelastic carrier fluid. In normal state, MR fluid behaves as a Newtonian fluid for which dynamic viscosity is constant. Under the influence of magnetic field, particles align in the direction of applied field and form chain like structure as shown in figure 1.

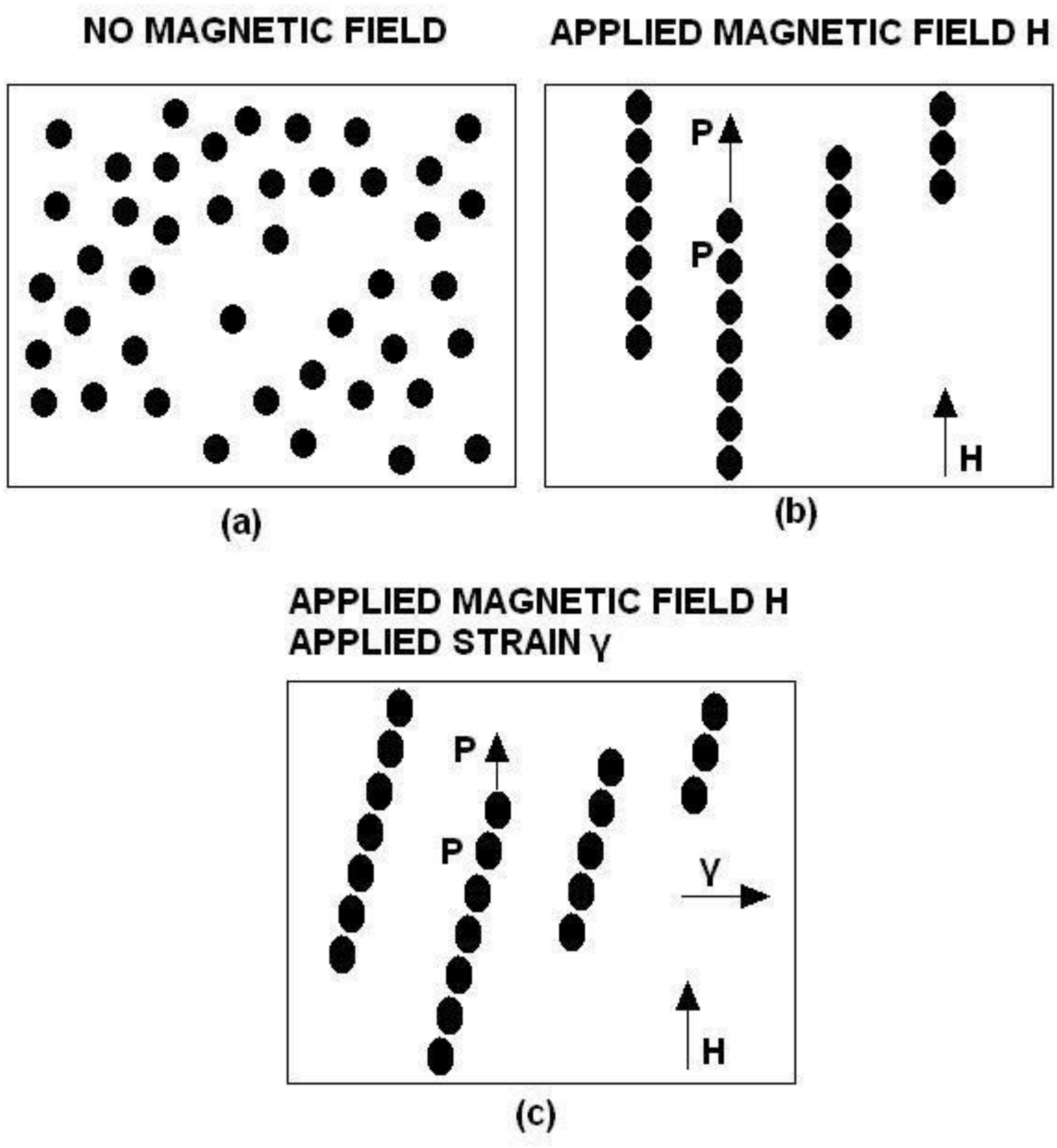

Figure 1. The MR effect: (a) particles flowing in absence of magnetic field; (b) the behavior of particles in presence of magnetic field. (c) schematic behavior of microstructure under application of shear strain [Simon *et al.*, 2001].

This columnar structure increases its resistance dramatically under the application of shear strain as depicted in figure 2. This feature has caused influence in design of various new products based on MRF such as semi-active dampers, clutches, brakes and robotic control systems.

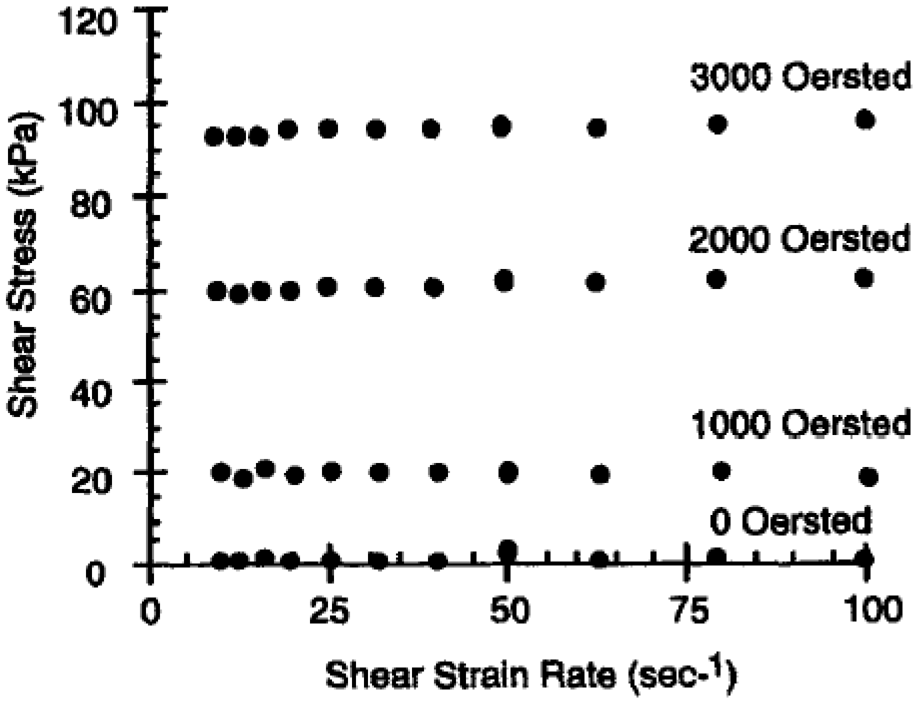

Figure 2. Shear strain rates versus shear stresses in the post-yield regime, for various values of the magnetic field intensity [Simon *et al.*, 2001].

2.1 MAGNETORHEOLOGICAL FLUID COMPONENTS

MR fluids can be described as fluids with rheological behavior which in turn depends on magnetic field strength. Rheology is the study of deformation in fluid flow. Rheological property such as viscosity varies in accordance to physical properties, namely shear stress, chemical formulation and temperature. These properties are fixed by environment for a particular situation and as a result it cannot be controlled easily. Control of viscosity in MR fluid can be possible intelligently using magnetic field and the change is reversible. MR effect can be explained as the difference in rheological properties in the absence and presence of magnetic field.

Magneto-rheological fluids consist of three basic components, namely base fluid, metal particles and additives. The basic fluid serves as carrier and combines lubrication and damping features. High MR effect can be achieved by having small fluid viscosity which is equivalently independent of temperature. In normal state, MR fluid shows characteristics of base fluid. Carrier fluid can be mineral oils, hydrocarbon oils or silicon oils. In off-state, fluid viscosity will be higher if concentrations of metal particles are high and the fluid will appear as thicker. In many cases, the dynamic viscosity η_d at ambient temperature is approximately 100 mPa [Wong et al., 2001]. In on-state, metal particles arrange itself in the direction of magnetic field and therefore restrict the motion of fluid by changing its rheological behaviour. MR effect is created by chain like structure which resists the flow. The metal powder in MR fluid can be up to amount of 50 % by volume [Carlson, 2004]. Size of metal particles is µ-metres and can vary upon manufacturing processes. In on-state, larger particles and high concentration will generate high torque but results in higher viscosity in off-condition. The particle size depends on achievement of purpose in several applications. In controlling MR effect, permeability is an important factor.

Additives include surfactants and stabilizers. Poor lubrication in MRF can lead to friction and wear [Hu et al., 2012]. Materials having high viscosity such as grease benefits in improving settling stability [Natural bureau of standards, 1948]. Ferrous naphthanate can be useful as dispersants [Wislow, 1959]. Additives are necessary in controlling viscosity, friction, settling rate of particles and to avoid thickening after defined number of cycles [Olabi and Grunwald, 2007].

Rheological behavior of MR fluid is defined by all three components. Variation in properties of single component will affect the rheological properties in off-condition and magneto-rheological properties in on-condition. A trade-off in combination of all three components is necessary in order to achieve optimized formulation [Olabi and Grunwald, 2007].

Ferro-fluids have some similarity with MR fluids. They both contain base fluid, iron particle and additives. The major variation lies in the size, quality and quantity of particles. Ferro-fluids have much smaller particles and it remains in liquid state in presence of high magnetic field [Olabi and Grunwald, 2007]. The primary effect in ferro-fluid is to attract and guide the fluid in accordance with magnetic field and viscosity dependency is a secondary effect. The difference can be described more accurately by energy factor λ. Energy factor is defined with respect to magnetic polarization energy and Brownian thermal energy as:

$$\lambda = \frac{\mu_o . P_{mag}^2 . V}{(12.k.T)} \quad (1)$$

where P_{mag} is polarization, *V* ((m^3) is volume of particle, *T (K)* is temperature and k is Boltzmann constant. When the value energy factor is greater than one, fluid shows MR functionality in magnetic field as magnetization energy has higher value than thermal energy. In contrast, where thermal energy is higher, particles would be just guided by the magnetic field according to flux density. Table 2 depicts the overview of features for MRF and ferro-fluids.

Table 2. Ferro-fluid versus MRF [Olabi and Grunwald, 2007].

Representative feature	***Ferro-fluid***	***MRF***
Particle material	Iron oxide	Carbonyl iron
Particle size	Some nm	Some µm
Fraction by volume	Up to 10 %	Up to 50 %
Maximum yield stress	10 kPa	100 kPa
Energy factor λ	< 1	> 1
Functionality	Controllable liquid flow	Controllable shear stress
Stability	Good	Medium

2.2 RHEOLOGICAL BEHAVIOR OF MR FLUIDS

Rheology deals with the science of deformation in flow, which is either elastic or plastic. In a conventional application such as damper or hydraulic pump, viscosity proves to be an important property. Viscosity is expressed as dynamic or kinematic viscosity.

Dynamic viscosity is expressed as:

$$\eta = \frac{\tau}{\gamma^{o}} \tag{2}$$

where η (*Pa/s*), γ^{o} = shear rate (*1/s*), τ = shear stress (N/mm^2).

Kinematic Viscosity is expressed as:

$$\nu = \frac{\eta}{\rho} \tag{3}$$

where ν (m^2/s , $10^4\ Stokes, 10^6\ cSt$), ρ = density (kg/m^3), η (*Pa/s*).

Viscosity depends on temperature and temperature is considered generally as an uncontrollable feature which can be determined by approximation for a conventional fluid such as mineral oil or silicon oil:

$$\eta(T) = A.e^{\left(\frac{b}{(T+273)}\right)} \tag{4}$$

where factors A and b are determined practically [Olabi and Grunwald, 2007].

Newtonian Fluid shows linear relationship between shear rate and shear stress, as a result dynamic viscosity remains constant. Figure 3 shows relationship between shear rate and stress and also relationship between shear stress and dynamic viscosity for various fluids.

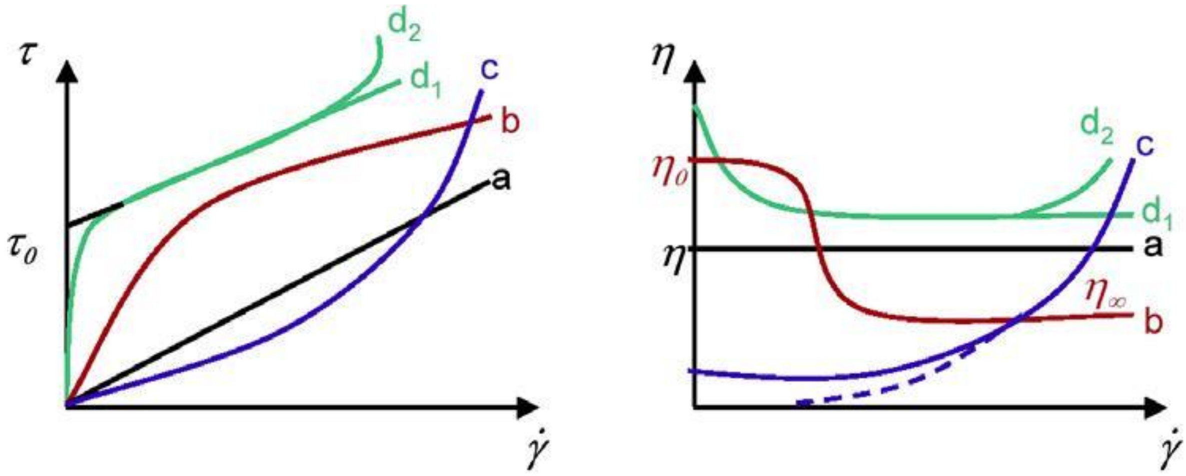

Figure 3. Different type of fluids [Olabi and Grunwald, 2007].

Curve (a) represents Newtonian fluid having linear relationship between shear rate and shear stress. In case of curve (b) shear stress dependency reduces with shear rate while in curve (c) it increases. Curve (d) describes the behavior of MR fluids in presence of magnetic field while in normal state it shows similar behavior as a carrier fluid.

Bingham model demonstrates the rheological properties of MR fluids. MR fluid behaves as Newtonian fluid in absence of magnetic field and under the application of magnetic field, it shows characteristics of a Bingham fluids. MR fluids shows resistance at zero shear rates and the force leads to plastic deformation with no continuous movement. Maximum stress that can be applied in this condition is yield stress which is a function of magnetic field strength (H) in case of MR fluids. The yield stress can be increased or decreased with respect to magnetic field strength for MR fluids and it can be formulated as:

$$\tau = \tau\,(H) + \eta.\gamma^{o} \tag{5}$$

In presence of magnetic field, a metal particle of MR fluid acts as a dipole and as a result particles forms a chain like structure with neighboring particles in accordance with magnetic flux paths. This chain offers resistance to the fluid flow due to increment in viscosity of the fluid. Mechanical resistance can be monitored by varying strength of magnetic field which results in transformation of MR fluid from liquid state to semi-solid state. Control depends on formulation of fluid with respect to quality and concentration of metal particles. MR effect is reversible and original condition can be re-established on removal of magnetic field. Yield stress relies on the magnetization properties of the particles which can be represented as flux density B (*Tesla*) and it changes with strength of magnetic field H (A/m). MR fluids with carbonyl iron particles can operate with yield stress of 100 kPa. For a predictable behavior the equipment should have linear operation with respect to B = f(H) curve along with small hysteresis effect [Olabi and Grunwald, 2007].

MRF operation is possible in three different modes, namely valve mode, shear mode and squeeze mode. Figure 4 shows the basic principle of these modes.

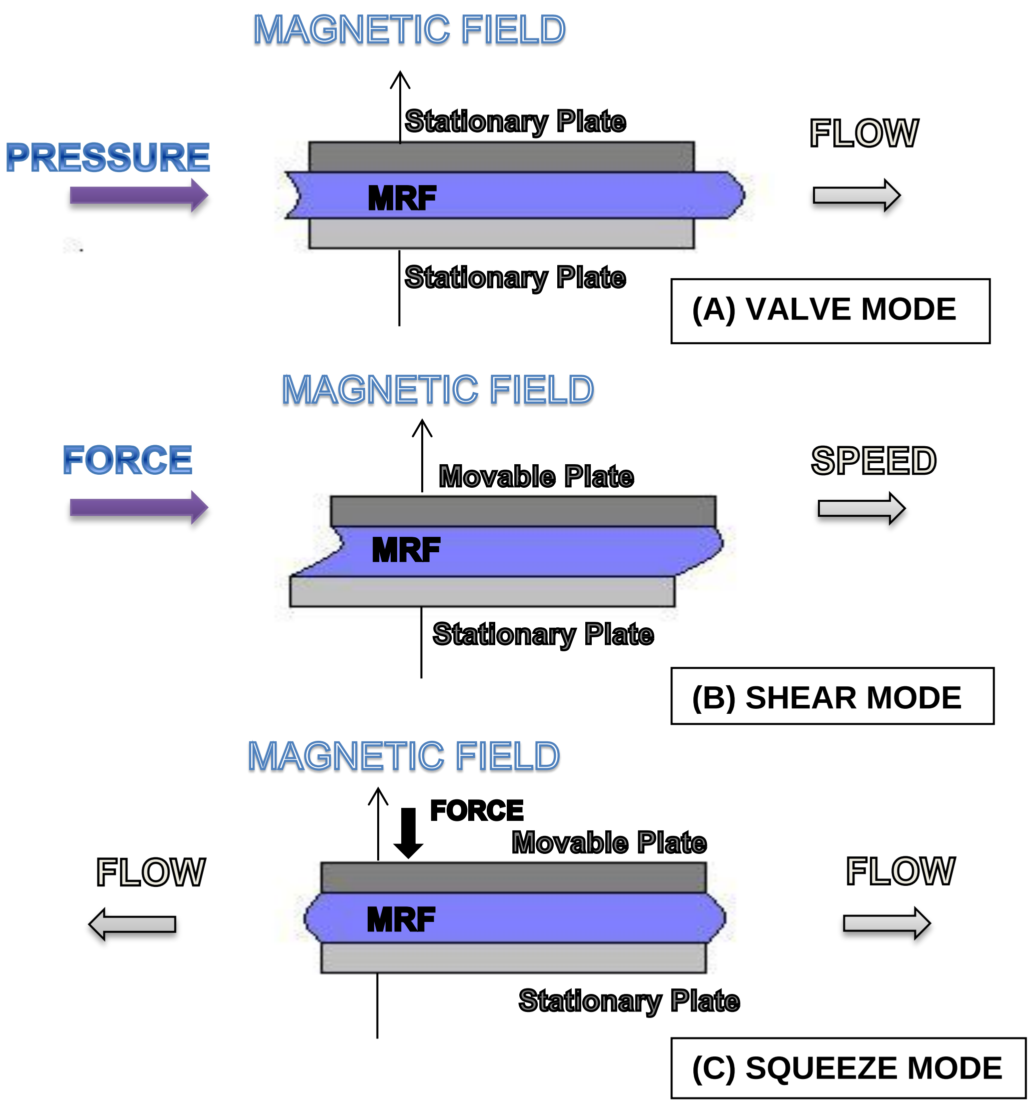

Figure 4. MR fluids operational mode.

3. OPERATIONAL MODES AND APPLICATIONS OF MR FLUIDS

Magneto-rheological fluid is categorized into three modes of operation based on rheological stress and fluid flow: valve (or pressure driven) mode, direct shear mode and squeeze mode.

3.1 VALVE MODE

The valve mode is used in operation of devices such as dampers, valves and shock absorbers. It is suitable for application in car suspension as it provides larger displacement and damping force [Kasemi et al., 2011]. Fluid flow in this mode is depicted in Figure 5.

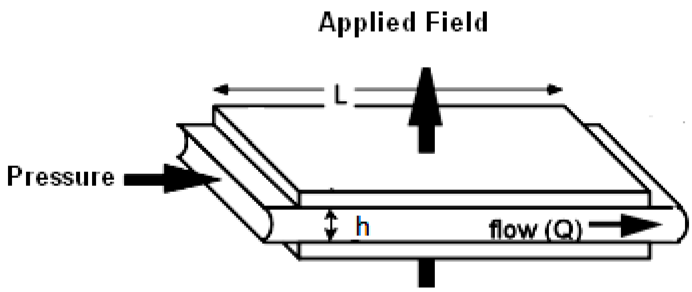

Figure 5. Valve (or pressure) mode [Kasemi et al., 2011].

In case of damper, the pressure drop is the summation of rheological component ΔP_r and magnetic field dependent component ΔP_{mr} . The following approximation is used to determine the value of this pressure drop:

$$\Delta P = \Delta P_r + \Delta P_{mr} = \frac{[\,12.\ \eta\ .\ Q\ .\ L\,]}{[\,g^3\ .\ h]} + \frac{[\,f\ .\ \tau_{mr}\ .\ L\,]}{g} \quad (6)$$

In rheological component ΔP_r of the equation, *Q* ($m^3\ s$) is rate of flow, η (*Pa s*) is dynamic viscosity*, L (m)* is geometrical length, *g (m)* is the gap size of the flow channel and *h (m)* is width. The former part of equation has been justified theoretically and the latter magnetic field dependent part has been solved empirically. In magnetic field dependent component ΔP_{mr}, τ_{mr} (N/mm^2) is yield stress, f (no units) is an empirical factor; *L (m)* and *g (m)* are same as in viscous component. Pressure drop due to magneto-rheological component ΔP_{mr} is the difference of observed pressure drop ΔP and pressure drop due to rheological component ΔP_r. ΔP_{mr} depends on generation of yield stress in magnetic field and geometrical factors stated above. Several other factors also influence this pressure drop and are denoted by empirical factor f. It is dependent on rheological pressure drop and observed pressure drop.

In case of

$$\frac{\Delta P_{mr}}{\Delta P_r} < 1 \qquad (7)$$

factor f takes the value 2 and when

$$\frac{\Delta P_{mr}}{\Delta P_r} \sim 100 \qquad (8)$$

factor f takes the value 3 [Olabi and Grunwald, 2007].

The minimum fluid volume required to achieve MR effect for a known flow rate Q with desired pressure drop can be expressed as:

$$V = L \, . \, h \, . \, g \qquad (9)$$

Magneto-rheological damper with valve mode can be designed from equation (6). Figure 6 describes the features of rheonetic linear damper used as secondary suspension element in vehicles [Carlson, 1995]. This serves as a damping control unit. In addition, it is MRF's first application in automotive industries. A magnetic coil is impinged into the piston and generation of magnetic field in turn causes the resistance in motion of flow due to MR effect. Dampers using valve modes are introduced in automotive industries since 2002 by GM/Delphi.

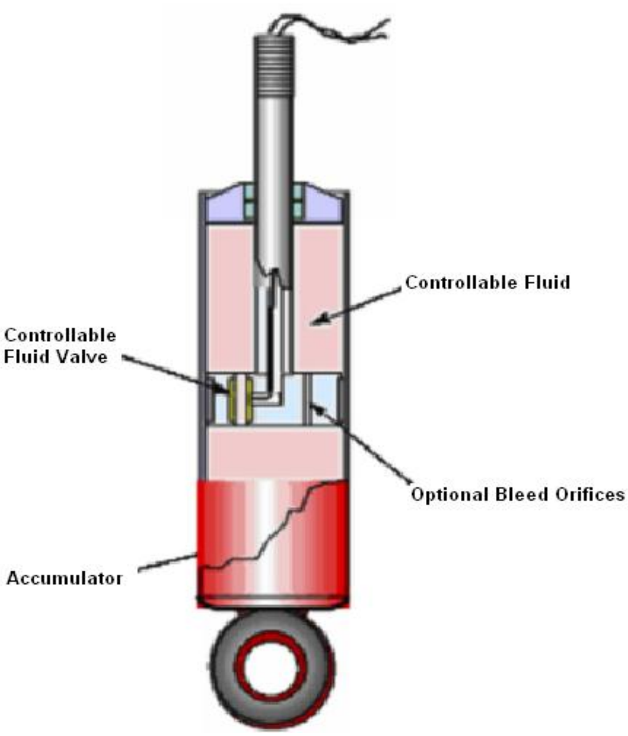

Figure 6. Functional Principle of MRF Damper [Olabi and Grunwald, 2007].

Additional functionality can be achieved by MRF applications while keeping its simplicity. Other applications adopting valve mode are vibration dampers, dampers of knee prosthesis in medical sector, seismic dampers in civil sector, prop-shaft mounts and active engine mounts.

3.2 DIRECT SHEAR MODE

Direct shear mode has relatively movable poles which translate or rotate perpendicular to the field as shown in Figure 7. Devices that operate in this mode are brakes, dampers with small displacement, clutches and locking devices [Kasemi et al., 2011].

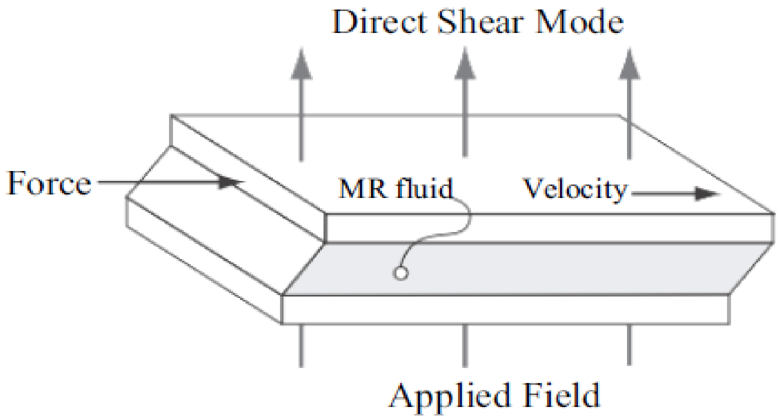

Figure 7. Direct Shear Mode [Kasemi et al., 2011].

In shear mode, total force is the sum of viscous (rheological) component F_r and magnetic field dependent component F_{mr}, which can be defined as:

$$F = F_r + F_{mr} = \frac{[\eta \, . \, S \, . \, A]}{g} + \tau_{mr} \, . A \quad (10)$$

In equation (10), S (m/s) is the relative speed, η (*Pa s*) is dynamic viscosity, *L (m)* is length, *w (m)* is width, *g(m)* is the gap size and $A = L \, . w$ is the working interface area for rheological component. In magnetic field dependent component, τ_{mr} (N/mm^2) is yield stress and *A* is same in both components.

The minimum volume of fluid required to achieve MR effect [$\frac{F_{mr}}{F_r}$] at a known speed *S* with desired torque is defined as:

$$V = L \, . w \, . g \quad (11)$$

Brakes using direct shear mode contains few parts such as shaft, sealing devices, interface disc, bearings, housing with coil and MRF. MRF brake is used currently as a controllable resistive element in aerobic exercise equipment. Simplicity and smooth controllability serves to be a cost effective solution for this equipment [Carlson 1995]. Figure 8 shows some MRF features in relation to brake.

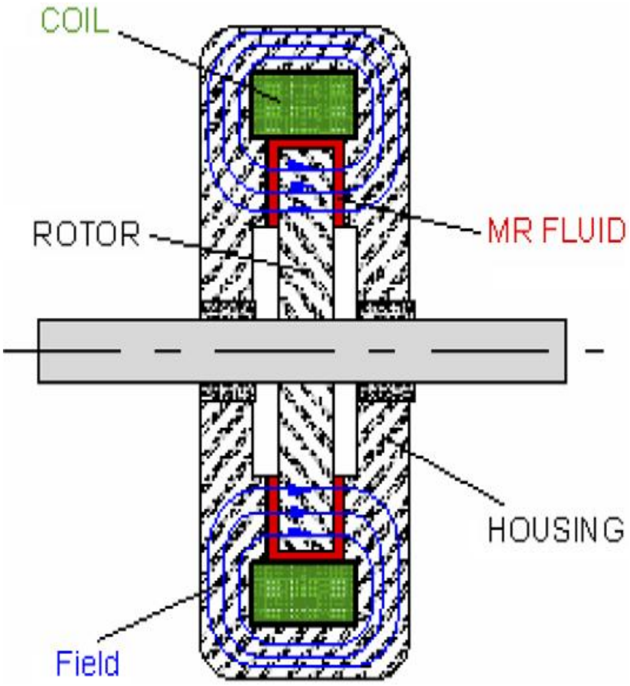

Figure 8. Functional principles of MRF brake [Olabi and Grunwald, 2007].

3.3 SQUEEZE MODE

In squeeze mode, the poles move top and down relatively in the direction of magnetic field as shown in figure 9. Devices that operate in this mode include dampers used in high –force and low-motion applications.

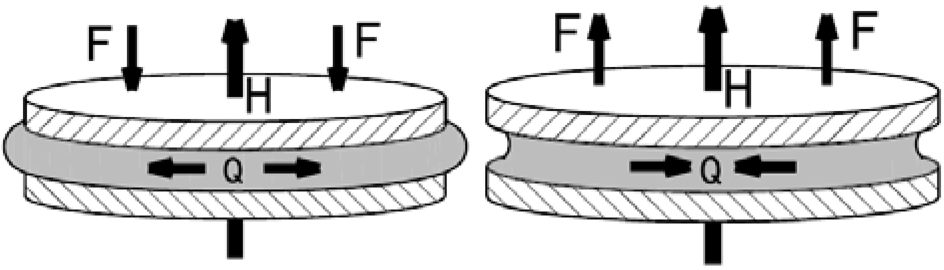

Figure 9. Squeeze mode [Kasemi et al., 2011].

Squeeze mode offers the possibility of producing very large forces for small motions that can be controlled by MR effect [Carlson 1999]. Yield stress achieved in this mode can be ten times higher than valve mode or shear mode. High capability of this mode has been confirmed theoretically and experimentally by Zhang [2004]. Strong MRF effect with additional benefits described in this paper would definitely create a new horizon for MRF technology. It could attract many industries as a next generation technology.

4. RESULTS AND DISCUSSION

The criterion which makes good MRF is ‘non-settling’ and ‘high yield strength’. MRF dampers and rotary brakes serve as highly efficient mixing devices [Carlson, 2001]. Homogenous state of MRF can be quickly achieved by normal movement of the device as it quickly stirs the stratified MRF. The environment to which MRF is exposed in MR devices is quite different in actual service than in a laboratory. Also manufacturing process in commercialization of MRF is quite different than in a laboratory.

Valve (or pressure) mode and direct shear mode have been reviewed in detail. Squeeze mode have not been researched thoroughly. Applications using first-two modes are already used in automotive industries. Initial problem of thickening of MR fluids has been found in early phase of research. If MRF is subjected to high shear rate and shear stress, it would develop thickening over a long period. MRF provides very good performance but semi-active control would be difficult to achieve due to in-use-thickening after 600,000 on-state cycles. This causes unacceptability of MRF damper in world-wide use.

Better quality MR fluids shows reasonable thickening after more than 10 million cycles (Lifetime) [Carlson, 2001]. Parameters like temperature, operation time and shear rate causes deterioration in MR fluid. The total dissipated energy that can be regulated by MRF unit is expressed as:

Lifetime Dissipated Energy (LDE) = $= \frac{1}{V} . \int_0^{Lifetime} P \,.\, dt$ (12)

In above equation, $V\ (m^3)$ is total volume of MRF fluid and P (W) is the mechanical power transformed into thermal energy in MRF unit [Olabi and Grunwald, 2007]. LDE can be defined as the ratio of total mechanical energy dissipated in form of thermal energy to the unit volume of MRF until the life period of device [Carlson 2001]. If the limit of LDE is exceeded, MR fluid would become thick to a certain extent where its effect is no longer prevalent.

The next step in development of MRF technology would be using principle of MR effect into the devices of conventional application. In recent years, observing researches carried out in field of MRF, it signifies to be a promising technology for future development. Distinctive features such as fast response, simplicity, and better controllability makes this technology suitable for various applications. Yield stress that can be achieved in shear or valve mode are being challenged by some applications and as a result different mode needs to be considered for achieving higher ratio of MR effect. This can be possible by squeeze mode but still research is being carried out in this mode in order to optimize the controllability as it generates very high yield stress.

5. CONCLUSION

Magnetic-rheological fluid technology has become very popular in recent years in many industries especially automotive applications. This technology has a lot of potential ahead in many applications. In every application where control of motion is served by fluid, solution for adapting MRF technology would benefit in functionality as well as overall costs. MRF which is considered good in one application may fail in other application. It depends on its application and specific environment to which fluid will be exposed and its duration. The most significant barriers for commercial success are the life and durability of MRF than stability and yield strength. Intelligent features and simplicity of MRF fluid makes itself as a prominent technology. Easy control, fast response and many other attractive features, which can be incorporated into simple design, makes MRF technology a better choice for many industrial applications. Several products using valve mode and direct-shear mode are already serving in the markets. MRF devices have good stability but it can effect on their performance on attempt to achieve absolute stability. New generation electronic systems can be easily synchronized with host systems such as Programmable Logic Controllers, Numeric Controllers or Robotic Controllers. The advancement in electronic control system has benefitted MRF devices in achieving high dynamic stability, accuracy, flexibility and operational safety. Quality of MR fluid for different applications would depend on the external stimuli which decides the type of MR fluid needed. This causes difficulty in increasing the life span of fluid. Additionally, life span can be increased by using better quality iron particles and solvents needed to make MR fluid. Future development would be achieving higher MR effect in accordance with increase in lifespan of the product with less dissipation of heat and more efficient control. Future challenges in development of MRF will be operation of fluid in high shear regime and also to be able to sustain high LDE.

REFERENCES

1. Carlson JD, Catanzarite DM, Clair KASt, 1995. Lord Corporation, Cary, NC 27511 USA, Commercial magneto-rheological fluid device. In: Proceedings of the 5th international conference on ER fluids, MR Fluids and Associated Technology, U. Sheffield, UK, 20–8.
2. Carlson JD, July 2001.. What makes a good MR fluid. 8th international conference on electrorheological (ER) and magnetorheological (MR) suspensions, Nice.
3. Carlson JD, 2004. Lord Corporation, Cary, NC 27511 USA, MRF workshop in Carry, North Caroline, Workshop handouts.
4. Hu ZD, Yan H, Qiu HZ, Zhang P and Liu Q, 2012. Friction and wear of magnetorheological fluid under magnetic field Wear 278-279, 48-52.
5. Kasemi B, Muthalif A, Rashid M, Rahman M, 2011. Optimizing Dynamic Range of Magnetorheological Fluid Dampers : Modelling and Simulation. 2011 4th International Conference on Mechatronics (ICOM) Kuala Lumpur, Malaysia.
6. Magnetic fluid clutch, 1948. Technical news bulletin, National Bureau of Standards, 32/4, 54–60.
7. Milecki A, 2002. Investigation of Dynamic Properties and Control Method Influences on MR Fluid Dampers' Performance. Journal of Intelligent Material Systems and Structures 2002 13- 453.
8. Olabi A, Grunwald A, 2007. Design and application of magneto-rheological fluid. Materials and Design 28, 2658-2664.
9. Simon T, Reitich F, Jolly M, Ito K, Banks H, 2001. The effective magnetic properties of Magnetorheological fluids. Mathematical and Computer Modelling 33, 273 – 284.
10. Wislow W, 1959. Field responsive fluid couplings, US Patent No. 2.886.151.
11. Wong PL, Bullough WA, Feng C, Lingard S, 2001. Tribological performance of magneto-rheological suspensions. Wear 247, 33–40.
12. Zhang XZ, Gong XL, Zhang PQ, Wang QM, 2004. Study on the mechanism of the squeeze-strengthen effect in magnetorheological fluids. J Appl Phys 96, 2359–64.