MAGNETORHEOLOGICAL FLUID - A REVIEW ON CHARACTERISTICS, DEVICES AND APPLICATIONS

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Abstract : Magnetorheological (MR) fluids belong to a class of smart fluids that exhibit dramatic but reversible change in the fluid characteristics in response to applied magnetic field. It consists of tiny ferromagnetic micro-particles suspended in carrier fluid. The MR fluid has the ability to change from a fluid state to a semi-solid or plastic state instantaneously upon the application of a magnetic field. The fluid exhibits visco-elastic behavior that is characterized by the field dependent yield stress in this semi-solid state. This highly desired characteristic of field dependent yield stress and their quick response time to the applied magnetic field has drawn attention of thousands to harness such technology in many applications. MR fluid technology has shown its presence in engineering and medical applications, though new applications continue to evolve. These emerging applications, and many current applications, subject the fluid to extreme flow conditions. Specifically, these flow environments or conditions include high shear and high velocity flow. The challenge in such devices becomes the lack of information regarding the behavior of MR fluid under these adverse operating conditions. This paper will review the fundamental behavior of MR fluid and present some of the existing and emerging MR fluid devices and hence provide relevant information to the budding researchers in MR fluid technology.

Keywords: **Smart fluids, MRF, Visco-elastic, Mixed mode, Magnetorheological fluid dampers.**

I. INTRODUCTION

Magnetorheological (MR) fluid was discovered by Rabinow in the late 1940s at the US National Bureau of Standards (Rabinow, 1948. MR fluid consists of a suspension of ferromagnetic particles of micro size ranging from 0.5 to 10 μm(Rabinow, 1951, Milecki, and Hauke, 2012) in a carrier fluid which includes synthetic mineral oil (Lim et al., 2005 and Jang et al, 2005) , hydrocarbon oil (Rodríguez-López et al., 2012), glycol (Zhang, and Gong, 2008) or water (Zite et al. 2006). MR fluids are available in various compositions with weight varying from 20 to 80 percent. When the magnetic field is applied, the ferromagnetic particle acts as micro-sized magnets with dipoles. These micro-sized magnets attach with each other along the magnetic flux lines to form a chain. This phenomenon increases the viscosity dramatically of the MR fluid. In the current study, the MR fluid characteristic, along with its modes of operation are reviewed. Further, MR fluid devices and applications are presented. The potential applications including MR damper, valve, brake, clutch and mount are considered.

II. OPERATION MODES OF MR FLUID DEVICE

When the MR fluid devices are energized by application of stimulus in the form of magnetic field, one of three modes of operation namely flow or valve mode, shear mode and squeeze mode are set into effect (Carlson and Jolly, 2000 and Wang and Meng, 2001). Figure. 1 depicts that the MR fluid is always held between the two parallel plates very close to each other which acts as magnetic dipoles. The magnetic field lines between these plates travel perpendicular to it. The micro ferromagnetic particle present in the carrier fluid gets polarized under the influence of the field. Consequently they align themselves in the direction of the magnetic flux lines forming numerous chains. These chains of particles accumulated in the region, restrains the free flow of fluid and the fluid turns into a semi-solid mass. This transformation from liquid to semi solid phase happens with in milliseconds. On application of external force sufficient enough to break these chains, the semi-solid mass shears off and the relative motion between the plate and the fluid can be obtained. However, these chains try to reform continuously as long as magnetic field is active.

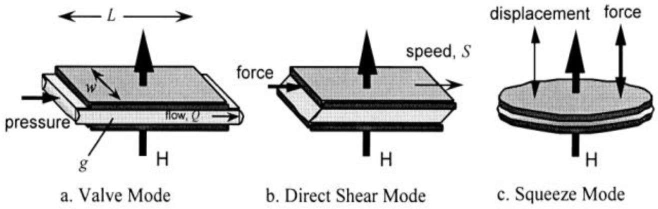

Fig. 1 Basic Operation Modes for MR Fluid (Carlson and Jolly, 2000 and Wang and Meng, 2001)

In the flow or valve mode of operation, both parallel plates were kept stationary and the fluid flows between the plates due to pressure difference in the direction along the plate. There may be two configuration identified corresponding to this mode i.e. annular and radial flow gaps. The contribution of field-dependent pressure drop in radial flow gap was found much higher than that of annular flow gap (Zeinali,et al, 2014). The flow mode is used in application of fluid flow regulator which includes dampers, shock absorber actuators, servo valves and hydraulic controls. The details on various types of flow mode are available such as valve mode as provided by Carlson and Jolly (2000), Poiseuille-flow mode as provided by Pappas and Klingenber (2006) and pressure-driven mode as provided by De Vicente et al.(2011).

In the shear mode of operation, one of the two plates is stationary and the other plate slides over it. The relative motion between the plates can be translatory or rotary with respect to each other. The details regarding various types of shear modes are available which includes direct shear mode as provided by De Vicente et al.(2011), Couette flow mode as provided by Bossis et al (2002), clutch mode as provided by Carlson and Jolly (2000) and torsional mode as provided by Kulkarnicet al. (2003). This mode is adopted in applications such like brakes, clutches etc. In the squeeze mode of operation, one of the plate is stationary while the other plate moves in such a way that it comes relatively closer or moves away with respect to the stationary plate, the two plates being always parallel to each other. There can be two modes identified in this motion namely compression mode and tensile mode. A detailed study on squeeze mode has been carried out by Carlson and Jolly (2000) on squeeze film mode. Squeeze mode found its applications in devices such as impact dampers, engine mounts, vibration mitigation devices etc. It is worth noting her that the yield strength of squeeze mode was reported to be largest as compared with other two modes. However in pursuit of increasing the yield strength the combinations of these modes has also been developed. El Wahed et al. (2011) have studied combination of shear and squeeze modes by using two separate coils for creating magnetic flux. The shear mode occurs at the curved surface of the piston and simultaneously, the energized MR fluid at the bottom of the piston faces the squeeze mode. References (Yazid, and Mazlan, 2014 and Mughniet al, 2015) have also reported a similar concept of shear-squeeze mode but, multiple coils in the piston was used instead of single coil and the device was tested in static mode instead of dynamic mode. Reference (Yazid, and Mazlan, 2014) studied the combination of all three operating modes in a single device by using single electromagnetic coil. In this case, the movement of the piston imposes the radial flow in the gap between the piston and the cylinder, thus creating the squeeze mode ((Zeinali,et al, 2014). Further, the radial flow then causes flow along the sides of the piston (Yazid, and Mazlan, 2014), thus there is a presence of shear and the flow modes simultaneously.

III. CHARACTERISTICS OF MR FLUID

Usually, the ferromagnetic particles range from 3 to 5 microns in diameter. As the particle size increases it becomes difficult to maintain the stability in suspension. The properties of these fluids are sighted in Table 1.

Table 1 Properties of MR fluid

Property of MR fluid	**Typical value**
Initial viscosity	0.2 – 0.3 [Pa-s] (at 25^o C)
Density	3 – 4 [g/cm^3]
Magnetic field strength	150 – 250 [kA/m]
Yield point	50 – 100 [kPa]
Reaction time	Few milliseconds
Supply voltage and current intensity	2 – 25 V, 1–2 A
Work temperature range	-50 to 150 [^{o} C]

In the absence of magnetic field, MR fluids behave like a general Newtonian fluid. Under the action of applied field, the fluid drastically changes its characteristics to a Non- Newtonian fluid best approximated by Bingham plastic model which is field dependent (Siginer et al, 1999). Bingham plastic flow begins by overcoming yield strength of the fluid. Hereafter the rate-of-shear vs. shear stress curve becomes linear as dictated by Equation (1) and depicted in Fig. 2.

$$\tau = \tau_0(H) + \eta \dot{\gamma}. \qquad (1)$$

Where,

τ_0 -yield stress due to magnetic field applied, [Pa]

H - Magnetic field strength [A/m]

$\dot{\gamma}$ - shear rate, [s^{-1}]

η - Plastic viscosity, [Pa-s]

In addition to Bingham model, there are various models to represent MR fluids developed by Chen and Yeh (2002) and Zhou et al. (1988).

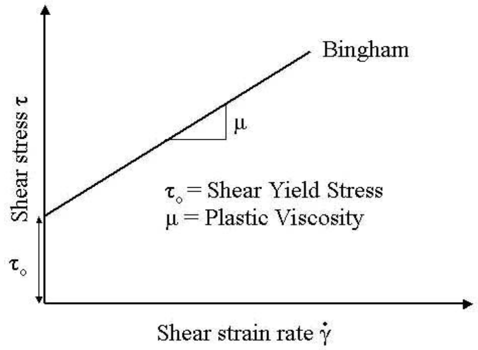

Fig. 2: Graph of shear stress v.s. Shear strain rate (Chen and Yeh, 2002 and Zhou et al.,1988)

Meanwhile, MR fluid exhibits a stable relationship between shear yield strength and the applied magnetic field. It restores its property and structure once the magnetic field vanishes with in milliseconds. It is this characteristic which makes MR fluid suitable in real time torque transmission applications (Gang et al, 2018). Figure 3 shows two characteristics of MRF-J01 whereas Fig. 3 (a) depicts the magnetic flux density v.s. magnetic field intensity and Fig. 3(b) shows the shear stress v.s. magnetic field intensity (Gang et al, 2018), where B represents the magnetic flux density, H represents the magnetic field intensity and τ_y is the shear stress in MRF-J01.

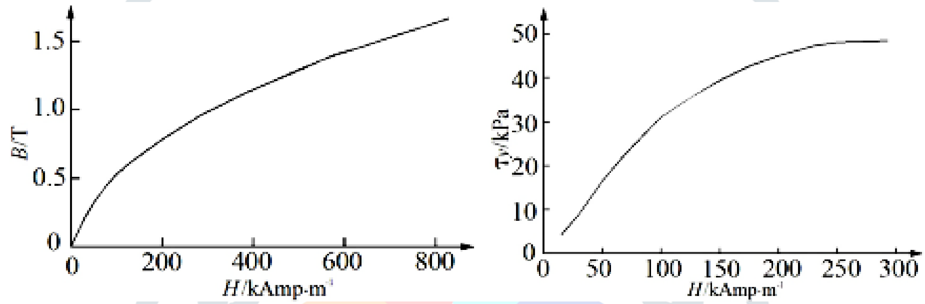

Fig. 3: Magneto-rheological Fluid Characteristics of MRF-J01: (a) Magnetic Flux Density v.s. Magnetic Field Intensity and (b) Shear Stress v.s.Mmagnetic Field Intensity(Gang et al, 2018)

IV. APPLICATION OF MR FLUID DEVICES

4.1 MR DAMPER

A damper is a device used for dissipating energy of a vibrating system in the form of heat or sound. MR damper is highly efficient energy dissipating device used for absorbing vibration of a system controllably. The damping coefficient of MR damper can be varied by varying magnetic field applied to the suspension (Poynor, 2001). MR dampers exhibit an extraordinary capability which makes it suitable to be employed in heavy applications including, automobiles, prosthetics, gun recoil system etc. A large number of MR dampers are developed and used successfully as vibration mitigation devices such as landing gear systems (Batterbeeet al, 2007 and] Saxena and Rathore, 2013), vehicle suspension systems ((Zeinali,et al, 2014, Yao et al., 2002 Gordaninejad and Kelso, 2012 and Choiet al., 2003), seismic protection devices as cited by Li et al., 2013 and Chaet al., 2013) and advanced prosthetic systems (Xie et al, 2013).

4.2 MR VALVE

MR valve regulates or slows down flow of MR fluid by magnetically altering its rheological property. This device utilizes flow mode or valve mode to carry out this activity (Zeinali et al, 2014). This mode has wide applications in development of other mechanical devices that can be hydraulically actuated (Zeinali et al, 2014).

4.3 MR BRAKE

The basic function of MR brake just like any other brake is to transmit the braking torque to slow down or stop a rotating disk. It does this by shear stress of MR fluid which can be controlled through applied magnetic field. MR brake operates in a shear mode i.e. the torque transmitted shears the fluid in the gap between the stationary and moving (sliding or rotating) surfaces (Kumbhar. Et al, 2015). A decent amount of work has been carried out to explore the possibility of considering MR brakes as an alternative to conventional brakes. Application of MR brake has been investigated on typical medium size vehicle, however it is unable to transmit the required torque. Experimental evaluation of MR brake application has been carried out at high speed to study performance parameters and it was found that a gap of 1 mm between the surfaces is suitable (Sukhwani and Hirani, 2008).

4.4 MR MOUNT

Vibration is associated with every walks of life, may it be daily human activity of speaking, walking listening or vibration in machine operations. It cannot be eliminated but its undesirable effect can be mitigated to some extent. One of the most common vibration mitigation systems is vibration mount.

The MR mount utilizes controllable fluid to isolate the vibration of system from its support. Due to its quick response time it can change its damping characteristics within milliseconds. Moreover, it has got a wide operating range as compared to conventional fluid dampers (Zeinali,et al, 2014). A lot of MR mounting has been developed till date. In earlier design, valve mode was entirely utilized to bring about the damping effect (Ahn et al.,1999). The damping effect is created by perturbing the flow of fluid between the chambers through the MR valve. Phu et al.(2015) and Nguyen et al. (2013) has come up with a similar concept. Whereas Choi et al (2003) initially proposed MR mount operated through shear mode. Finally the squeeze mode MR mount utilizes during the compression a large force characteristic. Even though the squeeze mode can be used in small displacement cases, they are found to be suitable in low amplitude vibration mitigation (Nguyen et al., 2013 and Ghaednia, and Ohadi, 2012).

V. CONCLUSION

This paper has presented an overview of the MR fluid characteristics, its operational modes and relevant devices. Three pure modes of operations are identified to be squeeze mode, valve mode and shear mode. Apart from these pure modes of operations, its combinations are also found to exist and were found to show better performance as found by many researchers cited in the paper. Each of these modes are found to have a specific characteristics which can be suitably harnessed in a particular applications. Finally based on each of these operational modes different MR devices are discussed. This paper provides a good knowledge about the MR fluid characteristics and its applications to the potential researchers in the domain related to MR fluids.

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