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Magneto-Rheological (MR) and Electro-Rheological (ER) Fluid Damper: A Review Parametric Study of Fluid Behavior

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ABSTRACT
In last two decades research on the topic of synthesis, characterization and analysis of smart fluids like Magneto rheological (MR) and Electro rheological (ER) fluids is taking place. In this paper researchers working in experimentation, development of mathematical model by Bingham plastic model and Herschel-Bulkley method have been studied. MR/ER fluid have main advantage, that is its unique property, means Bingham plastic properties. The verification and validation of result of damping force and damping displacement depends on the application of an external magnetic field or no field. Developing the theoretical model of fluid flow for annular duct of two parallel plates or circular duct is done. And study of Newtonian and non Newtonian fluid flow by computational and numerical method.
Keywords – ANSYS parametric design language (APDL), Computational fluid dynamics (CFD), Electro-rheological fluid (ER), Magneto-rheological fluid (MR).

I. INTRODUCTION

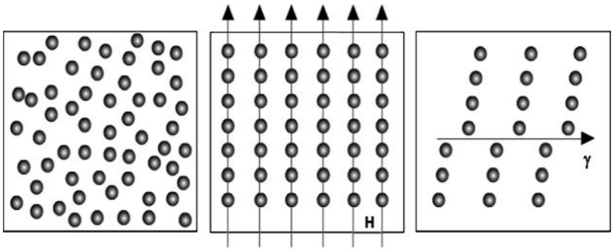
Many researchers have completed work in Magnetorheological (MR) and Electrorheological (ER) fluids from last two decades. The initial discovery and development of MR fluids and devices can be created to Rabinow's at the US National Bureau of Standards in the late 1940s. Willis M. Winslow (1949) was the first to discover an ER fluid. Winslow introduced the concept of controlling the apparent viscosity of an electro-viscous fluid by using an electric field. He observed a "fibrous" structure composed of particle chains generally aligned with the applied electric field. Winslow hypothesized that these fields affected particle chains which increased the viscosity of the fluid.

1.1 Properties of MR fluids:

MR fluids are suspensions that exhibit a rapid, reversible and tunable transition from a free flowing state to a semisolid state upon the application of an external magnetic field.

Normally, MR fluids are free flowing liquids, which are similar to motor oil. However in the presence of an applied magnetic field, the particles acquires a dipole movement aligned with the external field that cause particles to form linear chain parallel to the field. This phenomenon can solidifies the suspension and restrict the fluid moment. Consequently, yield stress is developed.

The following figure shows that, MR fluid behavior, with and without application of an external magnetic field.



(a) (b) (c)

Fig.1 Illustrations MR fluid Behavior
(a) and (b) MR fluid behavior without and with application of external field respectively, (c) fluid flow in shear mode.

1.2 Operational mode of MR fluid

The controllable MR devices based on the MR effect can be operated under three different fluid operational modes. Namely, flow mode, direct shear mode, squeeze film mode (shown in figure 2).

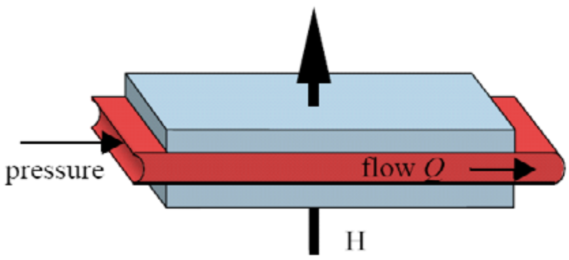


Figure (a)

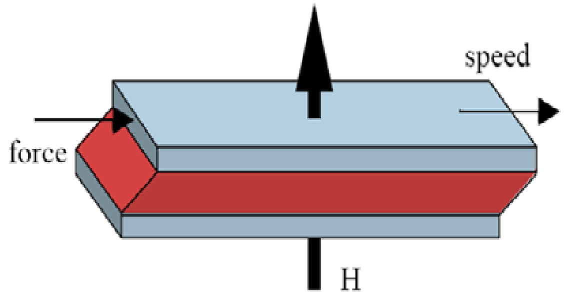


Figure (b)

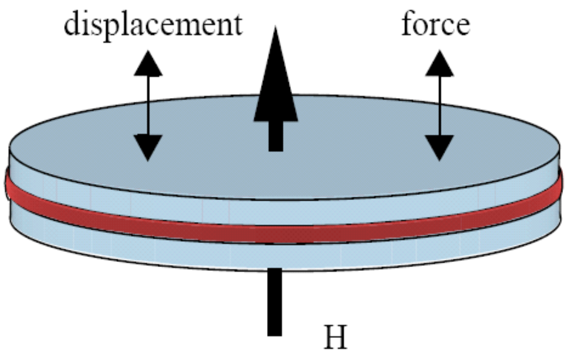


Figure (c)

Fig. 2 Illustrations of operational modes of MR fluid (a) Flow mode of fluid, (b) shear mode of fluid, (c) is squeeze mode [10].

The flow and direct shear mode and their combination are used develop all kinds of linear and rotary MR damper [3]. Squeeze film mode is only used to develop linear MR damper with limited amplitude.

1.3 Models of MR fluids:

A model of MR fluids plays an important role in the development of MR fluid devices. A wide variety of nonlinear models have been used to characterize MR fluids, including the Bingham plastic model [1-3, 7] and the Herschel-Bulkley model [9].

1.3.1 Bingham plastic model:

A Bingham plastic model [3] is characterized by dynamic yield stress. The shear stress can be expressed as,

$\tau=\tau_y (B) \operatorname{sgn}(\gamma) + \mu\gamma$ ….. (1)

Where, τ is shear stress of fluid in non Newtonian stage, τ_y (B) is dynamic yield stress in applied magnetic field, μ is plastic viscosity independent of magnetic field, γ=(du/dy) is shear rate of MR fluid.

1.3.2 Herschel-Bulkley model:

Herschel-Bulkley model with a nonlinear relationship, which can be represented as,

$\tau_{xy} = \tau_y + K(du/dy)^n$ ……. (2)

Where, τ_y is shear yield stress, K is consistency index or plastic viscosity, *n* is flow behavior index: *n* =1 for Bingham fluid, *n* < 1 for post yield shear thinning condition, *n* > 1 for post yield shear thickening condition.

Based on those fluid flow modes, the various researchers have completed work in this field. These are mention in the next section.

II. RELATED WORK

Magneto-rheological devices are enabling new technologies for automation, shock isolation and vehicle suspension etc. The various researchers have completed work in the smart fluid from last decade. Mostly researchers have done the design of dampers with MR fluid up to 100 kpa yield stress. Today's many researchers are working in design of MR damper in theoretical, experimentation and testing are carried out of the damper. But optimizations of MR damper, the computational analysis are mostly useful. Many researchers are working in fluid behavior [1-3], magnetic analysis using magneto static analysis [8]. This type of dampers is used in military application, artillery gun recoil system [4] and army vehicle. There are summery of some research paper given below.

Zekeriya Parlak et al. [1] have studied non Newtonian fluid in annular gap in quasi-static analysis, to calculate plug thickness and damper force. CFD analysis of MR damper in transient and deform mesh in moving of piston in non Newtonian region. The validation result in experimental, CFD analysis of moving mesh of piston in non Newtonian region and quasi-static in annular gap and validation are performed and examine the effect of stroke and velocity in the damper, the investigation of pressure drop, plug thickness and non dimensional Bingham number of fluid flow through annular gap from following equations.

$$\frac{1}{2}\bar{\delta}^3 - \left[\frac{3}{2}+\frac{6}{Bi}\right]\bar{\delta} + 1 = 0, \qquad 0 \le \bar{\delta} \le 1$$

$\bar{\delta} = \frac{\delta}{g}$, $\quad Bi = \frac{\tau_y}{\mu(\frac{\mu 0}{g})}$ ……. (3)

Where, $\bar{\delta}$ is non dimensional plug thickness, Bi is non dimensional Bingham number, g is distance between two shearing piston, δ is thickness of plug region.

Tahsin Engin et al. [2] have study of MR damper in design optimization method is carried out of target damper force and maximum flux density of MR damper. In optimal design, use finite element analysis of MR damper, electromagnetic analysis of magnetic field and CFD analysis of MR flow. In newly use of magnetic field and MR flow simultaneously is applied. In Magnetic analysis of MR fluid, investigate the shear stress for variation of magnetic flux from following equations,

$B = \frac{\mu_0 \mu_{m,r} N_c I}{2g}$ ……. (4)

$\tau_y (B) = 52.962B^4 -176.51B^3 + 158.79B^2 + 13.708B + 0.1442$ ……. (5)

where, B is magnetic flux density, μ_0 is relative permeability of vacuum, $\mu_{m,r}$ is relative permeability of MR fluid, N_c is number of coil winding, I is current, g is gap between two plate, τ_y (B) is dynamic shear stress depends upon variation of magnetic field.

Norman M. Wereley et al. [3] have done research on the various fluid flow models (such as, flow model, shear-flow model and mixed flow model). They have performed and develop nonlinear quasi-steady electrorheological (ER) and magnetorheological (MR) damper model using Bingham plastic shear-flow mechanism. And also have studied the three non-dimensional groups, which introduced damping analysis, namely Bingham number (Bi), the nondimensional plug thickness δ and area coefficient (ratio of the piston head area A_p to cross sectional area of the annular bypass A_d). These three non dimensional groups are introducing the three fluid flow models.

Study of non dimensional group, that is the damping coefficient of flow mode from Bingham properties has given equations,

$$\frac{C_{eq,f}}{C_f} = 1 + Bi \quad \ldots\ldots (6)$$

Where, $C_{eq,f}$ is equivalent damping coefficient, C_f is viscous damping coefficient, Bi is Bingham number.
In this paper discussion on theoretical analysis of MR fluid mainly three modes (flow mode, shear mode and mixed mode.) have been done.
Z C Li et al. [4] have taken research in design and control of full scale gun recoil buffering system which works under real firing impact loading condition.

Experimentation on firing test rig which consist of a 30 mm caliber, multi action automated gun with MR damper mounted to the fixed base through a sliding guide. And comparison result of optimal control and passive control system. Optimal control is better than passive control, because it produce smaller variation in the coil force which achieves less displacement of the recoil body. This is presented in open loop with no feedback system means sensor free device.

Sevki Cesmeci et al. [5] have study this paper to experimental and theoretical study of dynamic performance of a linear MR fluid damper. After design and fabricated of MR fluid damper, its dynamic testing performed on mechanical type shock machine under sinusoidal excitation.

Theoretical flow analysis is based on Bingham plastic model. Theoretical result validated by comparing experimental data and flow model can capture dynamic force range of MR damper.

In flow model, modified the parametric algebraic model captured hysteretic behavior of MR damper and comparing with mAlg model as well as Bouc-Wec model through error analysis. Comparison of velocity of the model is improved 50% relative to unmodified at lower input current. Use mAlg model develop effective control algorithms.

G. Yang et al. [6] have study in this paper derived quasi-static axisymetric model of MR damper and comparison result both simple parallel plate model and experimental.

This is mainly used by civil infrastructure application against earthquake and wind loading. Prepare dynamic performance of MR damper and develop mechanical model based on Bouc-Wen hysteresis model.

Young Min Han et al. [7] have done research on the geometry optimization of the MR valve.
They have performed the optimization of MR valve geometry in order to improve valve performance, such as pressure drop. Their pressure drops are investigated on the basis of the Bingham model of an MR fluid. The valve ratio is derived by considering the field dependent (controllable) and viscous (uncontrollable) pressure drops of the MR valve.

The geometry optimization procedure using a golden section algorithm and a local quadratic fitting technique is done via analysis software of finite element method (FEM) like, ANSYS parametric design language (APDL). And also compare the optimization result for different types of MR valve.

H.H. ZHANG et al. [8] have done research on the magnetic design method of MR fluid damper. They have performed the magnetic design of an MR damper and finite element analysis on the magnetic saturation is discussed as per improvement of the damping force and variation current, the variation of current 0A to 1A with increment at 0.1A interval and 1A to 2A with increment at 0.2A interval. They have two area ergogram are observed, that is energy dissipated by viscous damping and energy dissipated by MR effect. Optimization has been carried out by structural ergogram. And also analyze potential saturation region in the magnetic loop.

The dissipated energy and the controllable force are important to the performance parameters of an MR damper. In the Experimental verification, the damper force is effective to the magnetic saturation. And compare the result with the finite element method for the MR damper energy dissipation to the experimental results.

Joko Widaja et al. [9] have done research on Elect rheological (ER) and magneto rheological (MR) duct flow in shear - flow mode using Herschel-Bulkley constitutive model. Herschel-Bulkley model is same as Bingham plastic model, details of this model is above section 1.3.1.

They have performed the study of a quasi-steady duct flow through a parallel plate model for ER and MR fluid, under shear-flow mode is investigated in mathematically. The investigate of damping force ratio *f*, that is ratio of damping force F_c to shear yield force F_y of the fluid damper. This force ratio indicates that, ratio of effective damping coefficient *c* for shear

flow mode damper with non Newtonian plug damping coefficient c_p, which can determine plug thickness.
In Herschel-Bulkley model for ER and MR is adopted in post yield shear thinning and shear thickening. To study of the all post yield region of the model and select the more flexible representation of ER and MR post yield behavior using Bingham plastic model.

III. CONCLUSION

The study of MR fluid flow behavior through, two parallel plates or circular duct of MR damper and experimentation has carried out synthesis as well as characterization of MR fluid.

It conclude that, damping force and damper displacement for Newtonian flow is linear, and non linear for non Newtonian fluid. The magnetic design of MR damper, magnetic field pass through fluid is saturation at certain limit. In shear mode, damping coefficient was linear function of Bingham number, whereas in flow and mixed mode dampers, damping coefficient was simple function of plug thickness. The non dimensional damping coefficient is proportional to a ratio of the Bingham number and the non dimensional plug thickness.

In optimization of MR damper structurally there are two functions, one is damping force and other is maximum magnetic flux density. The magnetic flux density depends upon current flow through coil, it conclude that at certain limit of current variation, the magnetic saturation are performed.
The design of MR fluid damper are theoretically depends upon three non dimensional groups, Bingham number, plug thickness and area coefficient. The fluid flow through annular duct concludes the three regions has formed, region I and III is post region and region II is plug region, in post region large viscous force and shear rate has performed and in plug region no viscous and shear rate are developed.

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