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Finite Element Analysis And Simulation of A Magneto-Rheological Damper

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Abstract

The study was conducted to develop a procedure to analyse characteristics: current in the coils, velocity of the fluid and force on the piston of Magneto-Rheological (MR) fluid and its behaviour in a damper. Using COMSOL multyphysics values of force applied on the piston were obtained and compared with the values obtained by experiment of Y. K. Lau and W. H. Liao and also the values obtained by finite element analysis of Benedetto Allotta, Luca Pugi and Fabio Bartolini. It was observed that the ratio of the value obtained by Y. K. Lau and W. H. Liao to the results obtained in this study decreases as the current increases. The magnetization factor "α" to match the study result with experimental results of Y. K. Lau and W. H. Liao has been calculated as a function of current(I) as: $\alpha = 0.7858 \times I^{-0.375}$.

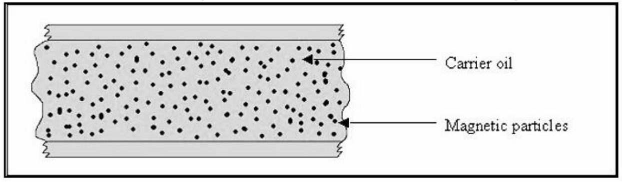
Keywords: Magneto-Rheological Fluid, shock absorber, damping force, Rheology; Rapid response interface, Biviscous model, Bingham plastic model, Newtonian fluid, Magnetostatics.

I. INTRODUCTION

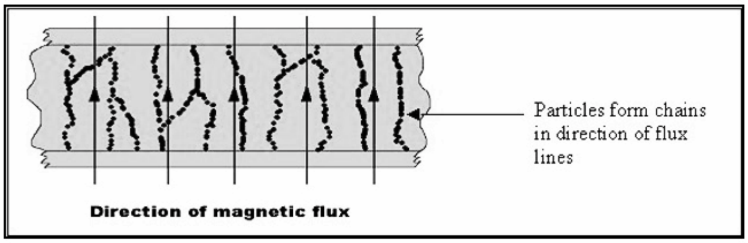
The term "magneto-rheological fluid" comes from a combination of *magneto*, meaning magnetic, and *rheo*, the prefix for the study of deformation of matter under applied stress. of material. Rheology is the study about flowing of matters. Magneto-rheological (MR) fluids contain suspensions that exhibit a rapid, reversible and tunable transition from a free-flowing state to a semi-solid state upon the application of an external magnetic field. These materials demonstrate dramatic changes in their rheological behavior in response to a magnetic field. MR fluids have attracted considerable interest recently because they can provide a simple and rapid response interface between electronic controls and mechanical systems. [1]

MR Fluid can be formed by mixing small particles of iron with a career liquid. Small magnetic particle includes iron or iron oxide powder, obtained either by grinding or filing a piece of iron. The powder is usually of 10^{-6} m scale. The liquid which is to be used as carrier fluid should be thicker or more viscous than water. Vegetable oil, Engine oil or hand soap are some good choices, but a non-toxic liquid is more preferable. The viscous carrier liquid helps the iron or iron oxide particles to stay suspended. This allows the particles to move about with minimal clumping when the MR fluid is stirred. When the MR fluid is exposed to a strong magnetic field the iron or iron oxide particles align with the magnetic field and form a network that traps the carrier fluid (as in figure 1).

MR fluid shows a transition from a liquid behavior to a solid one upon application of a magnetic field. The yield stress of the fluid when in its active state can be controlled very accurately by varying the magnetic field intensity.[2] This behavior has attracted significant attention in the development of dampers[3], shock absorption system[4], Military and defence system[5] and safety devices in aerospace engineering[6][7]. In case of Magneto-Rheological damper, the viscosity of the fluid, and hence the critical frequency of the damper, can be varied depending on the operator's preference [8]. Benedetto Allotta, Luca Pugi and Fabio Bartolini[9] worked on evaluating the behaviour of MR fluid using Carreau model (Equation- 2). This study has aimed to simplify the behavioural analysis of the MR fluid in a damper using Biviscous model (Equation 3). To validate the method, this study reconstructed the design and FEM model used by Benedetto Allotta, Luca Pugi and Fabio Bartolini.[9]



(a)



(b)

Fig. 1: (a) MR fluid without magnetic field and (b) MR fluid with a magnetic field.[10]

The objectives of the study were:

- To develop a simple procedure to analyze characteristics of MR fluid and
- To study the behavior of MR fluid in a damper

II. MRF DAMPER MODEL

Models for MR fluids play an important role in the development of MR fluid devices. Beginning with the work of Phillips, who addressed Bingham flow in channels with parallel walls and introduced non dimensional forms of the Bingham flow equations, modeling of MR fluids has received significant attention and, as such, the degree of accuracy available with existing models is quite good. A wide variety of nonlinear models have been used to characterize MR fluids, including the Bingham plastic model, the biviscous model and the Herschel–Bulkley model.

One nonlinear phenomenon, shear thinning, referring to the reduction in apparent viscosity at high shear rates, has traditionally been modeled with power-law or exponential functions. In order to account for shear thinning/thickening, as shown in Fig.3, the Herschel–Bulkley model, in which the post-yield plastic viscosity is now dependent on shear strain rate, can be employed.

A. Bingham plastic model

The so-called Bingham model of an MR fluid includes a variable rigid perfectly plastic element connected in parallel to a Newtonian viscosity element, so that the stress–strain constitutive relationship can be expressed as (equation 1):

$$\tau = \tau_y(H)\mathrm{sgn}(\gamma) + \eta\gamma \qquad \ldots\ldots\ldots (1)$$

where τ is the shear stress in the fluid, τ_y is the yielding shear stress controlled by the applied field H, η is the Newtonian viscosity independent of the applied magnetic field, γ is the shear strain rate and sgn(·) is the signum function. That is, the fluid is in a state of rest and behaves visco-elastically until the shear stress is lower than the critical value τ_y, whereas it moves like a Newtonian fluid when such a critical value is exceeded. The Bingham plastic model is shown in figure 3 to represent the field dependent behavior of the yield stress. [9]

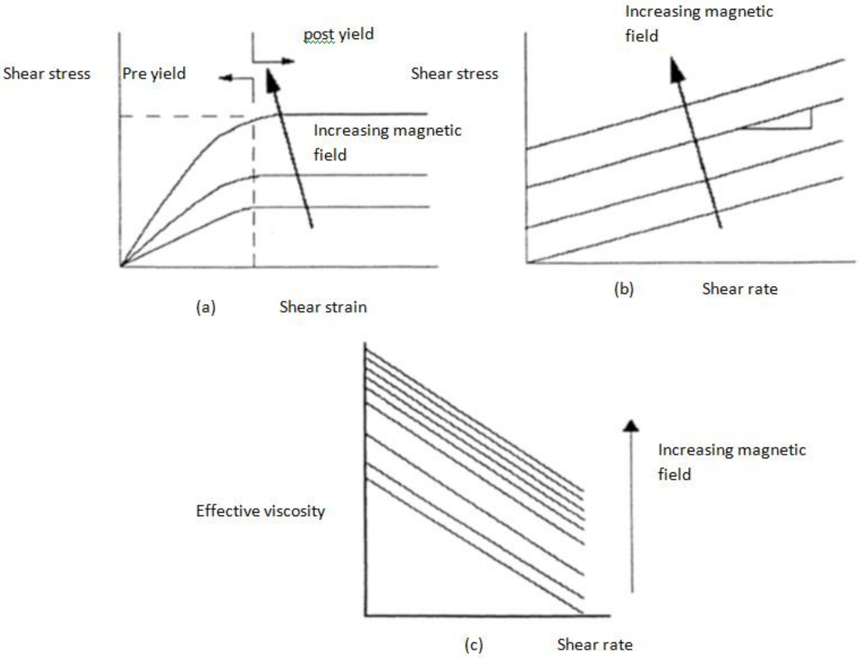


Fig 2: Variation of the shear stress and apparent viscosity with shear strain for an MR fluid under different magnetic field strengths: (a) the definition of the pre-yield and post-yield regions, (b) the non-Newtonian post-yield behavior and (c) the apparent viscosity

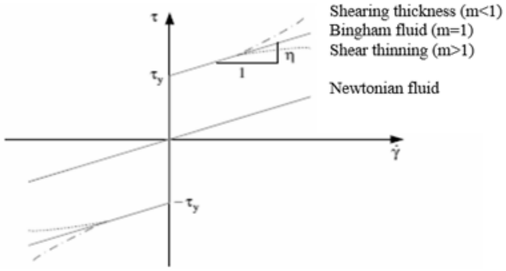


Fig. 3: Viscoplastic models often used to describe MR fluids

In the study of Benedetto Allotta, Luca Pugi and Fabio Bartolini[8], Carreau model was used (Equation 2).

$$\eta = \eta_\infty + (\eta_0 - \eta_\infty)[1 + (\lambda Y)^2]^{(n-1)/2} \qquad \text{……….} (2)$$

where η = value of viscosity [Pa × s], η_0 = viscosity for shear rate equal to zero [Pa × s],
η∞ = viscosity for high shear rate [Pa × s], λ = Carreau constant [s], n = Carreau constant (n ≤ 1), Y = shear rate [1/s]

B. Biviscous model

For the analysis of MR fluid devices operating in the squeeze flow mode, the equation governing the shear stress τ in the Bingham plastic model can be generalized to the biviscous relationship [3]as follows.

$$\tau = \begin{cases} \tau_y(\mathrm{H}) + \eta\gamma, & |\tau| > \tau_1 \\ \eta_r\,\gamma, & |\tau| < \tau_1 \end{cases} \qquad \text{………….}(3)$$

where η_r and η are related to the elastic and the viscous fluid properties, respectively. The yield parameters $\tau_y(H)$ and τ_1 satisfy

$$\tau_y(H) = \tau_1(1 - \eta/\eta_r) \qquad \text{………….}(4)$$

It was pointed out by Wilson that the Bingham model should be regarded as a limiting case of the biviscous model. The Bingham plastic model is obtained for $\eta_r \rightarrow \infty$.

III. METHODOLOGY

A. Design Parameters

In this study the obtained values of force generated due to variation of applied current were compared with the experimental results of Y. K. Lau and W. H. Liao [11] and the results by the study of Benedetto Allotta, Luca Pugi, Fabio Bartolini. So the design of the damper was similar to the damper used by them (Figs. 4 and 5, Table 1[9]).

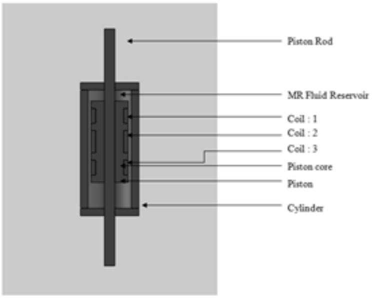


Fig. 4: Sectional view of the MR Fluid Damper

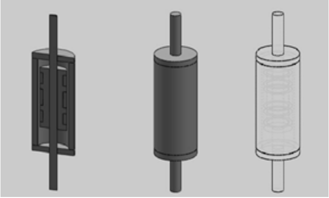


Fig. 5: 3D view of the MR Fluid Damper

Body tube inner diameter	80 mm
Thickness of the casing	4 mm
Piston rod diameter	25mm
Piston core diameter	40 mm
Thickness of the gap	0.8 mm
Cylinder Length	189.4 mm
Piston Length	74 mm
Space for middle coil(Coil : 2)	16 mm
Space for side coils(Coil 1 and 3)	28 mm

Table 1: Physical design parameters of the damper

In comsol multyphysics, 2D axisymmetric model was used for the study (Figure 6). And then mapped meshing was applied for finite element analysis (Figure 7).

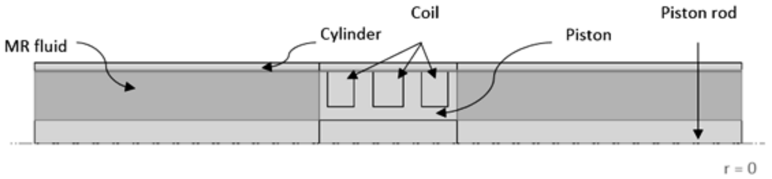


Figure 6: 2D axisymmetric view of the damper

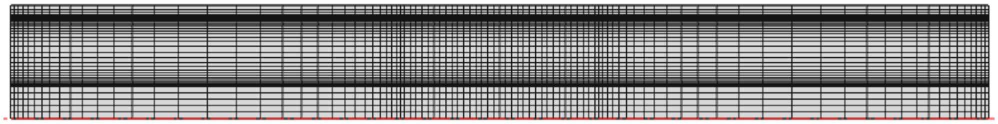


Fig. 7: Geometry of the damper with mapped meshing

B. Electromagnetic analysis:

Maxwell's equations can be expressed in the following manner:

$$\nabla \times \mathrm{H} = \mathrm{J} = \sigma(\mathrm{E} + \mathrm{v} \times \mathrm{B}) + \mathrm{J}^{\mathrm{e}}$$
$$(\nabla \times \mathrm{E}) = -\frac{\partial \mathrm{B}}{\partial \mathrm{t}}$$
$$(\nabla . \mathrm{B}) = 0$$
$$(\nabla . \mathrm{D}) = 0$$
$$(\nabla . \mathrm{J}) = 0 \qquad \text{.................. (5)}$$

Here J^e is an externally generated current density and v is the velocity of the conductor. The crucial criterion for a quasi-static approximation to be valid is that the currents and the electromagnetic fields vary slowly. This means that the dimensions of the structure in the problem need to be small compared to the wavelength. To derive the Magnetostatics equation, start with Ampère's law for static cases ∇ × H = J. The current is

$$J = \sigma \mathrm{v} \times B + \mathrm{J}^{\mathrm{e}} \qquad \text{.................. (6)}$$

Using the definitions of magnetic potential,

$$\mathrm{B} = \nabla \times \mathrm{A}$$

And the constitutive relationship, $\mathrm{B} = \mu_0 (\mathrm{H} + \mathrm{M})$,

We can rewrite Ampère's law as

$$\nabla \times (\mu_0^{-1} \nabla \times \mathrm{A} - \mathrm{M}) - \sigma \mathrm{v} \times (\nabla \times \mathrm{A}) = \mathrm{J}^{\mathrm{e}} \qquad \text{.................... (7)}$$

Which is the equation used in magnetostatics. The term involving the velocity only applies in the 2D and axisymmetric formulations.

When specifying a total current I_{coil}, the out-of plane component of the current density is defined as:

$$\mathrm{J_e} = \frac{NI_{coil}}{A} \qquad \text{................... (8)}$$

Where, N is the number of turns which have been specified and A is the total cross-section area of the coil domain. For the electromagnetic analysis it is necessary to describe the core, coil and MR fluid material. The parameters chosen are given below:

Core material	Steel AISI 4340
Coil material	Copper
Coil sectional area	1e-6 m^2
Number of turns (Side coils)	4800
Number of turns(Middle coil)	3150

Table 2: Design parameters for Electromagnet model

The electrical coil is split into three and wrapped in opposite ways; by doing so, it is possible to distribute the magnetic field along the damper duct in a more uniform way. The MR fluids which were used in this study have relative permeability varying from 5 to 9. For the simplicity of the analysis and as for different permeability the difference between the outcomes are negligible, relative permeability was considered as 8.

The following figures (Figs. 8 and 9) are for MRF-122EG with coil current of 1.5 A. The data sheets from Lord Corporation (Figure 10 and 11) were used to determine the yield stress of the fluids using the magnetic field evaluated from electromagnetic simulation

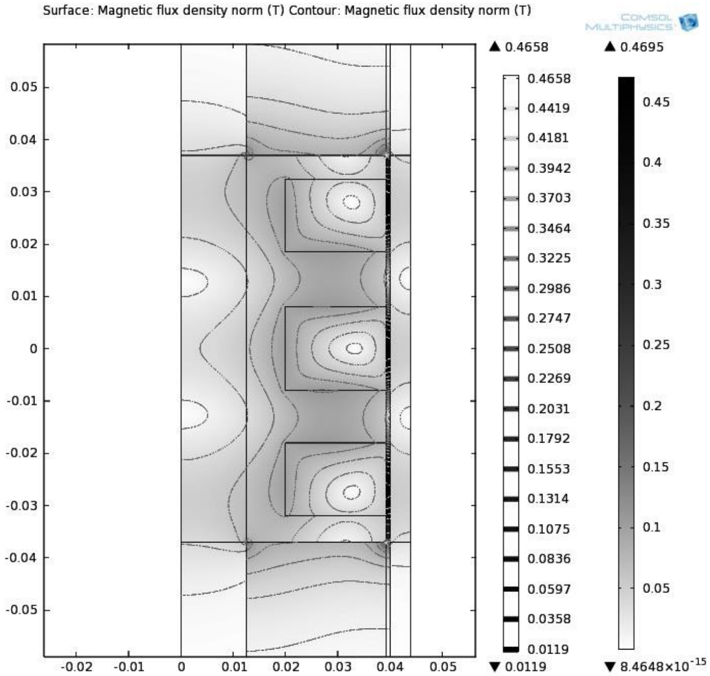


Fig. 8: Magnetic field behavior in a damper duct: Magnetic flux (T)

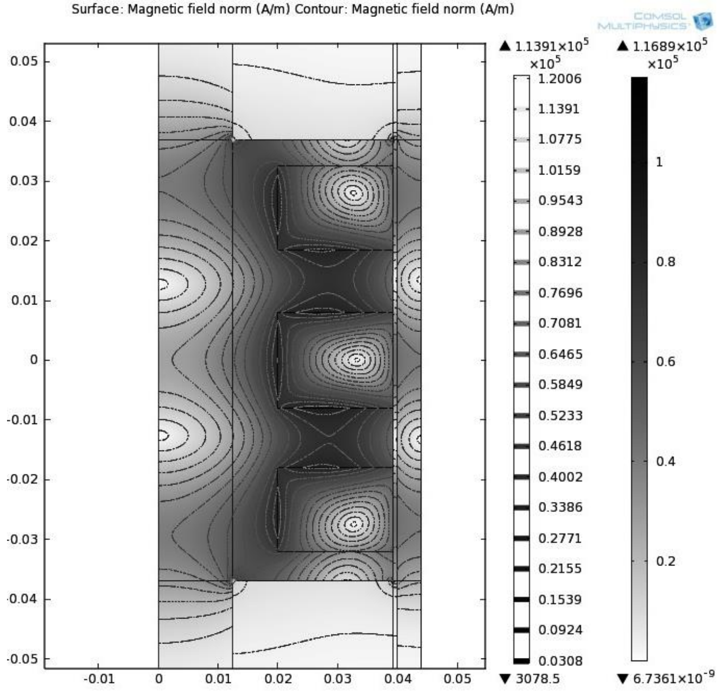


Fig. 9: Magnetic field behaviour in a damper duct: Magnetic field (A/m)

C. Typical Properties of MRF – 122EG

Appearance	Dark Gray Liquid
Viscosity, Ps @ 40^{o}C (104^{o}F) calculated as slope 500-800 sec^{-1}	0.042 ± 0.020
Density (g/cm$^{3)}$	1.28 - 2.46
Solid content by weight %	72
Flash Point ^{o}C (^{o}F)	>150 (> 302)
Operating Temperature ^{o}C (^{o}F)	-40 to +130 (-40 to +266)

Fig. 10: Typical properties of MRF - 122EG[12]

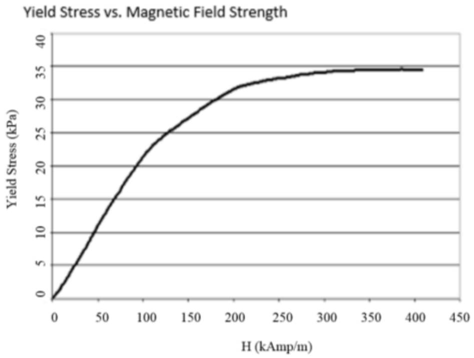


Fig. 11: Yield stress – magnetic field relationship of MRF - 122EG[12]

D. *Fluid Dynamic analysis*

After the electromagnetic analysis, FEM model was set to do dynamic analysis. Of course the analysis has been performed on the mesh where the fluid flows and taking into account the previous calculated values of the magnetic field.

Data sheets from Lord Corporation (Figs. 10 and 11) were used to find the value of yield stress which was then used in the following equation, which is rewritten from bi-viscous model (equation 3),

$$\mu = \mu_0 + \frac{\tau}{\gamma} \qquad \text{.....................} \ (9)$$

Here, shear rate (γ) was evaluated from the simulation by iteration. To perform a correct analysis the reference system was placed on the damper shaft. In this way the metallic part of the damper is fixed in the space and it is possible to analyze the damper behaviour only by moving the fluids on the opposite direction of the shaft. Boundary conditions are the velocity profile for the inlet port and the pressure for the outlet port. By knowing the pressure development in the chamber and the piston area of the damper it is possible to compute the force applied to the damper shaft (Fig. 12). Of course, in order to solve this kind of problem, it is necessary to describe the viscosity/shear rate and viscosity/magnetic field of the magneto-rheological fluid as the ones published by Lord TM Corporation (Fig. 10 and Fig. 11).

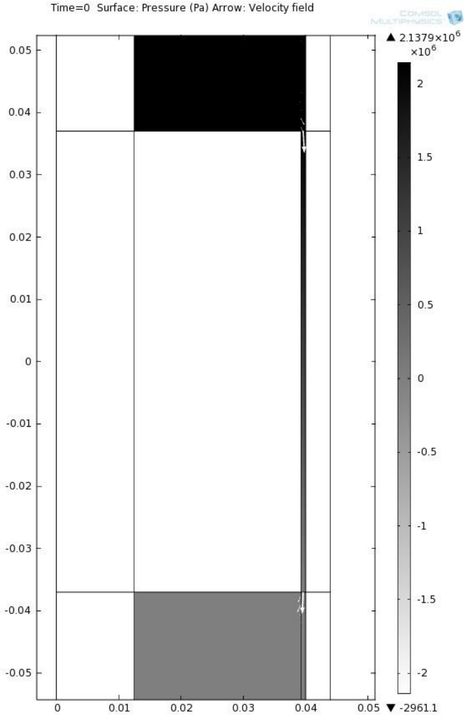


Fig. 12: Pressure development in the MR fluid (MRF -122EG, with current coil 1.5 A and inlet velocity 60 mm/s)

With the results obtained from this second simulation, which takes into account the result of the first magnetic simulation, it is possible to compare the force value obtained in this study with the ones obtained by Benedetto Allotta, Luca Pugi, Fabio Bartolini [8] and Y. K. Lau and W. H. Liao[10].

The second simulation used laminar flow model. Fluid properties were defined from the data sheets of Lord Corporation and the viscosity was calculated from equation 9. As for defining the boundary conditions, inlet boundary was given a uniform flow and outlet boundary was set to atmospheric pressure. After running the simulation force applied on the outline of the piston was evaluated using the line integral from derived values and it was multiplied by the perimeter of the circular piston to find the total force on the piston.

IV. RESULT AND DISCUSSION

The study was to develop a simple procedure to analyze characteristics of MR fluid and its behavior in a damper. The characteristic parameters considered are current in the coils, velocity of the fluid and force on the piston. Using COMSOL multyphysics values of force applied on the piston were obtained and compared with the values obtained by experiment of Y. K. Lau and W. H. Liao[11] and also the values obtained by Benedetto Allotta, Luca Pugi and Fabio Bartolini. [8]

It was observed that, the ratio of the experimental result to the obtained results decreases as the current increases. A magnetization factor "α" was calculated as a function of current. The functional form of "α" is given by the equation:

$$\text{Magnetization factor, } \alpha = 0.7858 \times I^{-0.375} \quad \text{…..............} \quad (10)$$

And the Force on the Piston, $F = \alpha \times F_{sim}$

Where, F_{sim} = Values obtained from the simulation

To validate the method used in the study, the obtained results were compared with the experimental results of Y. K. Lau and W. H. Liao and the FEM results obtained by Benedetto Allotta, Luca Pugi and Fabio Bartolini. (Table 3 and Fig. 13)

Current(A)	Force on the piston obtained from this study (kN)	Experimental results obtained by Y. K. Lau and W. H. Liao [10] (kN)	FEM results by Benedetto Allotta, Luca Pugi and Fabio Bartolini [8] (kN)
0.5	4.4	4.4	4.5
1.0	6.87	7.1	7.4
1.5	9.64	9.6	9.9
2.0	11.65	11.5	11.8

Table 3: Comparison of the FEM models and experimental result [9]

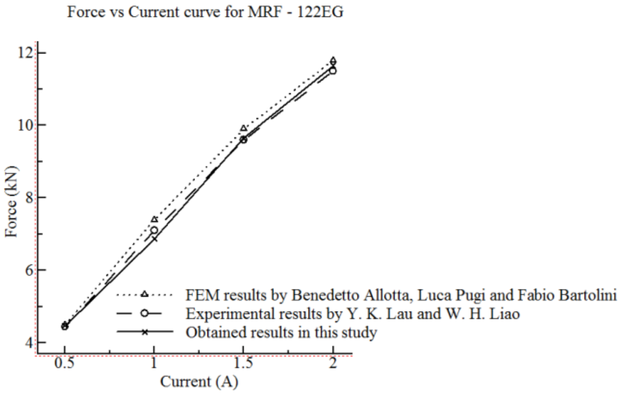


Fig. 13: Force applied on the piston as a function of current in the coil while the fluid is flowing at a constant velocity (60 mm/s) for MRF-122EG

After the validation of the FEM model, the method was used to evaluate different characteristic parameters and to generate relationship curves of current vs. force (Fig. 14) and Shear rate vs. viscosity (Fig. 15).

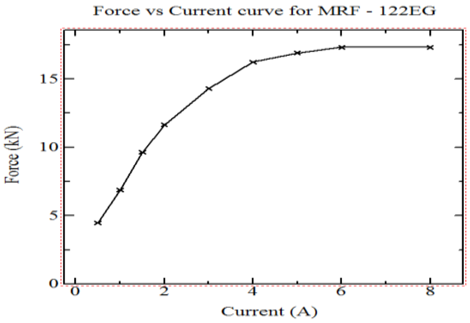


Fig. 14: Force applied on the piston as a function of current in the coil while the fluid is flowing at a constant velocity (60 mm/s) for MRF-122EG

Variation of force applied on the piston was shown as a function of current in figure 14. The relationship was evaluated keeping inlet velocity constant at 60 mm/s. Damping force increases with the increment of magnetic field which can be explained by the increment of magnetic field. After a certain value of current, magnetic field is saturated and force stops increasing making the curve flat. This force actually signifies the damping force of the liquid on the piston when the setup will act as a damper.

Change of dynamic viscosity with the increasing shear rate is showed in the Fig. 15. As can be seen, an increase in dynamic viscosity occurs as the shear rate decreases from around $1500s^{-1}$ to $120s^{-1}$. Further decrease in shear rate yields high viscosity to a point of solid behavior.

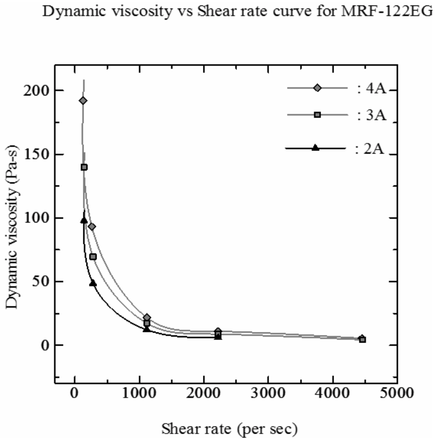


Fig. 15: Dynamic viscosity as a function of shear rate for coil current 2A, 3A, 4A for MRF-122EG

We have done the simulation by using only one type of MR fluids (i.e.MRF122EG), the number of data points was not sufficiently large to verify the work by doing experimental work. To mitigate error, primarily we used MRF122DG in simulation to compare the result of present study with the result of Y. K. Lau and W. H. Liao's experimental values [11] and also the values obtained by Benedetto Allotta, Luca Pugi and Fabio Bartolini. [9]. We found an ignorable error between them which prompted us to use further analysis with FEM model simulation and generated results.

The comparative economic feasibility and cost of comparison can be performed between magneto rheological fluid damper and typical dampers. The other relevant characteristics of damper can also be studied and performed in order to validate the work.

In COMSOL for designing a particular damper for magneto rheological fluids, viscosity has a minimum value and if it is attenuated, the simulation does not give satisfactory result. This is mainly due to the fact that at lower viscosity the degree of freedom of the viscous fluid becomes very large. Hence, the computer cannot run the simulation. The magnetization factor obtained in this study was based on only four data from Y. K. Lau and W. H. Liao[11]. There is scope for verifying the correction factor through experimental works.

V. CONCLUSIONS

The Magneto-rheological fluid technology has a vast potential to be used in the coming era. This fluid technology is widely applicable and useful in those fields where controlled fluid with varying viscosity is required. The ratio of the experimental value by Y. K. Lau and W. H to the results obtained in this study decreases with the increasing current. The Magnetization factor "α" was calculated to match the obtained result from this study with that of Y. K. Lau and W. H. Liao has been obtained as a function of current as: $\alpha = 0.7858 \times I^{-0.375}$**.** There is insignificant error between results obtained using magnetization factor with the experimental result of Y. K. Lau and W. H. Liao.

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