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Electro and magnetorheological fluid damper study with controllable field-flow analysis for parallel plate duct

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Abstract
Electro and magneto-rheological shock absorbers made most attractive choice of semi-active vibration control systems. A mg fluid damper is a system in the magnetic fluid where a damper is filled with a magnetic fluid. A magneto-rheological fluid damper is a system where a damper is filled with a magnetic fluid. Within this system the external current (voltage) regulating the magnetic field varies as an electromagnet in the magnetic fields of the piston within the damper. By adjusting the magnetic strength of the piston, the damping force of the damper is controlled. This paper offers a conceptual mathematical method for analyzing the behaviour, by combining fluid-mechanic approach to the fundamental equation of Herschel-Bulkley, of the field controllable electro-and magneto-rheological fluid flow through the parallel plate duct. Electro and magneto-rheological shock absorbers are built with simple expressions for the pressure drop solution. The quasi-stable flow study from Herschel-Bulkley would then be extended to include accumulator pressure, shear thickening and shear thinning effects. This, thus, accounts for the nonlinear dynamic electro and magneto-rheological fluid damper behaviour. Non-dimensional plug thickness is calculated for the creation of simpler descriptions for the exact model. This article offers a theoretical model of magneto-rheological dampers that regulate the area to predict the established behaviour. This has been shown to be an electro and magneto-rheological fluid threshold modeling device, with the simplified H-Bulkley model for parallel plates. The results of the assessments show that the most promising magneto-rheological damper with less than 3 percent of the relative maximum errors are modern semi-active instruments for structural seismic response observed.

Keywords
Parallel plate duct, Rheological fluid, etc.

1.Introduction
Electro and magneto- rheological fluids (MRF) constitute the materials that respond to a field and change its rheological performance [1]. This change is usually characterized with the creation of a yield stress, which enhances monotonously in field applied. The electro and magneto-rheological fluids are mostly non-colloidal suspensions of polarizing particle suspensions in size of a few microns [2, 3].

Magneto-rheological fluid first discovered in 1948 and patented in 1951 at the US National Standards Bureau was developed by Jacob Rabinow [4−6]. This work was almost concurrently done by Winslow also. Winslow's first description of the effect was to use fine powder oil dispersions. Electro-rheological behaviour thus, also called the Winslow effect [7−9].

Magneto-rheological particles are magnetized to create a linear chain; with the changing magnetic field, the resulting drop intensity can be achieved, which results in changing fluidity. The MRF characteristics return to the Newtonian fluid if the magnetic field is removed. If the magnetic field is not

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applied by the MRF, the magnetic particles and a carrier liquid have a certain damping force [10].

The rheological response of electro and magnetic properties-rheological fluids results from the polarization caused by an external field of the particles suspended. The outer field causes dipoles in the dielectric particles, which are then aggregated [11]. They begin to create fibrous structures between the electrodes that align with the direction of the field being applied. They do so in order to reduce the interaction between dipole and dipole energy, since the minimization of potential energy meets stability [12]. Such a chain-similar to structures restricts the fluid movement and increase the suspension viscosity. It thus changes the rheology of the electro and magneto-rheological fluid to nearly a solid state [13]. The mechanical energy required to break such structures in the chains increases with the increase in the field leading to a yield stress depends on the surface. Electro and magneto-rheological fluids act like Newtonian fluids in the absence of an applied field. A Bingham model in which MR fluid is defined only by a particular threshold or yield stress as a Newtonian fluid is the simplest and most commonly known. Subsequently, Herschel-Bulkley fluid model was used that considered the post fluence pseudo plastic behaviour [14].

These materials' rheological behaviour can before and after execution be divided into two separate regimes [15]. Before the yield point, the force increases in a nearly linear fashion with an increase in the velocity [16]. It is known as action before yielding. When the absorber force reaches the yield point, transfer occurs from well before yield to the post - yield area due to stiction phenomena, which results in overshoot type behaviour in the system [17]. For most instruments, for example, clutches, dampers, the post-production action of magneto rheological fluids is the main method of action [18, 19].

This paper represents a theoretical model of area controllable magneto-rheological dampers for predicting the behaviour that has been developed. The Herschel-Bulkley method is constructed to define ideal expressions for rheological fluid flow among parallel plates in fluid flow. For determining the pressure drop, according to the material characteristics, morphology, and volume rate of these fluids, a basic expression is given. It is observed that simplified model may be taken as an outstanding estimation to the precise result. It is demonstrated that rheological fluid dampers exert the large force to damp the vibrations with a slight increase of current for the same damper configuration.

2.Mathematical modeling of electro and magneto-rheological fluid dampers

2.1Viscous fluid flow analysis:

Consider the laminar flow between two different parallel sheets or plates, located at a distance, *H*, apart (*Figure 1*). Considering a small rectangular fluid element of length, δz, thickness, δh and unit width, *w*, as shown in *Figure 2*. The constitutive equation for non-Newtonian fluid is given as.

$$\tau_{hz} = \mu\left(\frac{du}{dh}\right)^n \tag{1}$$

where *u* is the fluid velocity. The laminar flow momentum equation has given as

$$\tau_{hz} = -h\frac{dP}{dz} \tag{2}$$

From Equation (1) and (2)

$$\left(\frac{du}{dh}\right) = -\left(-h\frac{dp/dz}{\mu}\right)^{\frac{1}{n}} \tag{3}$$

The above equation shows that, $\frac{du}{dr} < 0$, i.e. velocity decreases with respect to *h*. Integrate Equation (3) with respect to *h* and applying boundary condition, i.e. at $h = H'$, $u = 0$ which gives the velocity profile of the fluid

$$u = \frac{n}{n+1}\frac{\mu}{dp/dz}\left\{\left(-h\frac{dp/dz}{\mu}\right)^{\frac{n+1}{n}} - \left(-H'\frac{dp/dz}{\mu}\right)^{\frac{n+1}{n}}\right\} \tag{4}$$

For the value of $n = 1$, velocity profile becomes

$$u = -\frac{1}{2\mu}\frac{dp}{dz}\left(H'^2 - h^2\right) \tag{5}$$

The velocity profile curve of the fluid is shown by the equation (5). It is parabolic in nature and the maximum velocity occurs at the centre. The Volumetric flow rate is given by [20]

$$Q = 2\int_0^{H'} uwdh$$

$$Q = 2w\int_0^{H'} \frac{n}{n+1}\frac{\mu}{dP/dz}\left[\left(-\frac{h}{\mu}\frac{dP}{dz}\right)^{\frac{n+1}{n}} - \left(-\frac{H'}{\mu}\frac{dP}{dz}\right)^{\frac{n+1}{n}}\right]dh$$

$$Q = 2w\frac{n}{2n+1}\left(\frac{H'}{\mu}\right)^{\frac{1}{n}}\left(\frac{dP}{dz}\right)^{\frac{1}{n}}H'^2 \qquad (6)$$

The Pressure gradient is, thus, given as

$$\frac{dP}{dz} = \left(\frac{2n+1}{n}\frac{2Q}{wH^2}\right)\frac{2\mu}{H} \qquad (7)$$

when n is substituted by 1, the above equation reduces to

$$\frac{dP}{dz} = \frac{12\mu Q}{wH^3} \qquad (8)$$

Which is a pressure gradient equation between two parallel plates for Newtonian fluid flow.

3.Electro and magneto-rheological fluid flow in a parallel duct

3.1Mathematical modelling based on the herschel-bulkley model

The gap between piston and cylinder housing is generally termed as flow gap. Due to the slight flow difference and the diameter of the damper piston the axisymmetric flow can be approximated by the flow through a parallel frame. Suppose parallel plates are fixed and the fluid flow between the plates is supplied through a steady pressure gradient, P'.

The Herschel-Bulkley constitutive equation [9] for parallel plates is given as

$$\begin{cases} \tau_{hz} = \tau_y + k\left(\dfrac{du}{dh}\right)^n & |\tau_{hz}| \geq \tau_y \\ \dfrac{du}{dh} = 0 & |\tau_{hz}| \leq \tau_y \end{cases} \qquad (9)$$

Where τ_{hz} is shear Stress, $\frac{du}{dh}$ is shear strain, τ_y is fluid yield stress and *K*, *n* are fluid index parameters [21].

Let us consider laminar flow between two parallel plates located at a distance *H* apart as shown in *Figure 1*. The flow rate is constant in the area of the plug flow and defined as a region lacking yield ($0 \leq h \leq h_p$) where h_p is plug thickness. At the boundary of non-yield region, i.e. at $h = h_p$, $\tau_{hz} = \tau_y$. Thus, plug thickness is given as

$$h_P = -\frac{\tau_y}{dP/dz} \qquad (10)$$

Substituting Equation (9) in Equation (2) gives;

$$\frac{du}{dh} = -\left(-\frac{dP/dz}{k}h - \frac{\tau_y}{k}\right)^{\frac{1}{n}} \qquad (11)$$

Negative sign indicates $\frac{du}{dh} < 0$ i.e. velocity decreases in yield flow region. Integrating Equation (11) with respect to *h* and applying boundary condition, i.e. at $h = H'$, $u = 0$ gives the yield flow velocity profile ($h_p \leq h \leq H'$) region as [22]

$$u = \left(\frac{n}{n+1}\right)\frac{k}{dP/dz}\left[\begin{array}{l}\left\{\left(-h\frac{dP/dz}{k} - \frac{\tau_y}{k}\right)^{n+1/n}\right\} \\ -\left\{\left(-H'\frac{dP/dz}{k} - \frac{\tau_y}{k}\right)^{n+1/n}\right\}\end{array}\right] \qquad (12)$$

Similarly, non-yield flow field velocity profile ($0 \leq h \leq h_p$) is derived as

$$u_p = \left(\frac{n}{n+1}\right)\frac{k}{dP/dz}\left[\begin{array}{l}\left\{\left(-h_p\frac{dP/dz}{k} - \frac{\tau_y}{k}\right)^{n+1/n}\right\} \\ -\left\{\left(-H'\frac{dP/dz}{k} - \frac{\tau_y}{k}\right)^{n+1/n}\right\}\end{array}\right] \qquad (13)$$

The volumetric flow rate is given by combining effect of yield and non-yield flow region:

$$Q = 2\int_{h_p}^{H'} uwdh + 2u_p wh_p \qquad (14)$$

$$Q = \left(P'H' - \tau_y\right)^{\frac{n+1}{n}}\frac{n}{2n+1}\frac{1}{k^{\frac{i}{n}}}\frac{2wH'^2}{P'H'}\left[\frac{n\left(\tau_y/P'H'\right) + (n+1)}{n+1}\right] \qquad (15)$$

Rearranging above equation, one gets

$$Q=\frac{wH^2}{2}\left(\frac{P'H}{2k}\right)^{\frac{1}{n}}\frac{n}{2n+1}\left[\frac{(1-Z_p)^{\frac{n+1}{n}}}{\left(1+\frac{n}{1+n}Z_p\right)}\right] \quad (16)$$

where $Z_p=\frac{\tau_y}{P'H'}$ and $H'=\frac{H}{2}$

Defining V as dimensionless variable as

$$V=\left(\frac{2n+1}{2n}\right)^n\left(\frac{4Q}{wH^2}\right)^n\frac{2k}{P'H} \quad (17)$$

It is possible to write equation (17) as

$$V=\left[(1-Z_p)^{n+1}\left(1+\frac{n}{1+n}Z_p\right)^n\right] \quad (18)$$

Expansion of Equation (18) yields;

$$V=1+C_1Z_p+C_2Z_p^{\,2}+C_3Z_p^{\,3} \quad (19)$$

where

$$C_1=-\frac{2n+1}{n+1}\ ;\ C_2=\frac{n(1+2n)(1-n)}{2(n+1)^2}\ ;\ C_3=\frac{n(n^2+1)}{2(n+1)}$$

For $Z_p\le 0.5$, Suppose we have a linear relationship of V and Z_p as $V=1+BZ_p$. For all values of n linear approximation of Equation (19), gives

$$V=1+\left(C_1+\frac{3}{8}C_2+\frac{3}{20}C_3\right)Z_p \quad \text{for } Z_p\le 0.5 \quad (20)$$

Substituting values of V, Z_p, C_1, C_2 and C_3 in Eq. (20) provide us an expression for pressure gradient of a non-Newtonian fluid, in terms of yield stress as [23]:

$$\frac{dP}{dz}=B\frac{2\tau_y}{H}+\left(\frac{2n+1}{n}\frac{2Q}{wH^2}\right)^n\frac{2k}{H} \quad (21)$$

for $\frac{h_p}{h}\le 0.5$

where

$$B=\frac{2n+1}{n+1}-\frac{3n(1+2n)(1-n)}{16(n+1)^2}-\frac{3n(n^2+1)}{40(n+1)}$$

The yield stress can play an important part in the loss of pressure assessment when the plug radius exceeds, $Z_p>0.5$, half the pipe radius. A nonlinear relationship between V and Z_p is known to provide a simplified expression for Equation (19) as

$$V=B'Z_p(1-Z_p)^\beta \quad \text{for } Z_p>0.5 \quad (22)$$

where β and B' are power index function, n, as given in Table 2 and thus, pressure loss is determined from Equation (22) as

$$\frac{dP}{dz}=\frac{2\tau_y}{H\left[1-B_0\left(\frac{2n+1}{n}\frac{2Q}{wH^2}\right)^{\frac{n}{\beta}}\left(\frac{k}{\tau_y}\right)^{\frac{1}{\beta}}\right]} \quad \text{for } \frac{h_p}{h}>0. \quad (23)$$

where $B_0=(B')^{-\frac{1}{\beta}}$ For a Newtonian fluid, $\tau_y=0$ and n = 1. The parallel plate model Equation (21) is reduced to $\frac{dP}{dz}=\frac{12\mu Q}{wH^3}$. The yield stress, τ_y, is depends on the input current/magnetic field strength applied. The relation of yield stress to input current is given by

$$\tau_y=2.7\times10^4 I^{1.5} \quad (24)$$

where the τ_y and I are denoted in Pa and ampere respectively. The relation between the yield stress, τ_y, and the magnetic field is given as

$$\tau_y=\alpha B^{1.5} \quad (25)$$

Where α is the material constant (70 kPa/T) and B is the magnetic field strength in tesla (T). Using Equations (21) & (23), the pressure drop along Z direction may be written as

$$\Delta P=B\frac{2L\tau_y}{H}+\left(\frac{2n+1}{n}\frac{2Q}{wH^2}\right)^n\frac{2kL}{H} \quad \text{for } \frac{h_p}{h}\le 0.5 \quad (26)$$

$$\Delta P=\frac{2L\tau_y}{H\left[1-B_0\left(\frac{2n+1}{n}\frac{2Q}{wH^2}\right)^{\frac{n}{\beta}}\left(\frac{k}{\tau_y}\right)^{\frac{1}{\beta}}\right]} \quad \text{for } \frac{h_p}{h}>0.5 \quad (27)$$

Drop in pressure results in the force output and is given as

$$F=\Delta PA+F_f\,sign(V') \quad (28)$$

where the damper seal friction force is denoted by F_f and is assumed as 50 N.

3.2Mathematical modeling based on the Bingham model

The Bingham plastic model can easily get after reduction of Herschel-Bulkley model for n = 1. Substituting the values of various parameters from *Table 1* and n = 1, pressure gradient is given as

$$\frac{dP}{dz}=\frac{12kQ}{wH^3}+2.85\frac{\tau_y}{H} \quad \text{for } \frac{h_p}{h}\le 0.5 \quad (29)$$

$$\frac{dP}{dz} = \frac{2\tau_y}{H\left[1 - 0.593\left(\frac{6Qk}{wH^2\tau_y}\right)^{0.380}\right]} \quad \text{for } \frac{h_p}{h} > 0.5 \quad (30)$$

4.Results and discussion

The Herschel-Bulkley and Bingham model provide a collation of the exact and simplified parallel-plate model solution. The exact Equation (18) and the simplified Equations (20) & (22) have been plotted for various values of non-dimensional plug thickness, Z_p, with the dimensionless volumetric flow rate, V, for parallel plate model in the fluid flow mode for different fluid parameters. As shown, in resulting graphs, *Figure 3 (a) & (b)*, the simplified model is shown to be a successful approach to the right solution with a cumulative relative error of less than 3 percent.

Using geometric properties of rheological fluids as given in *Table 2, Figure 4 & Figure 5* gives the graphical representation of the pressure drop and force relations with velocity for a parallel plate model of electro and magneto-rheological fluid damper for fluid parameter n = 0.4 and n = 1. Straight line shows the behaviour of viscous fluid flow without any current. It has a linear relationship between pressure drop and velocity for n = 1. Remaining curves show the pre-yield and post yield behaviour with current variation from 0.25 to 2 ampere for n = 0.4. A better estimate of the exact solution for simplified model is given by comparing the complex and simplified versions of the parallel model plate. For Herschel-Bulkley model of parallel plate, one may observe a considerable variation of pressure drop and force with applied current when $n \neq 1$. Hence, with the same damper configuration, damper having electro and magneto-rheological fluid exerts large force to damp the vibration with a slight increase of current. This may be supplied by battery of an automobile very easily.

For fluid parameter n = 0.4 and n = 1, a graph between shear stress and shear strain is plotted and it is shown in *Figure 6*. The plastic behaviour of Bingham with a steady plastic viscosity in the region of low magnetic field strength can be observed with magneto-rheologic fluids. It exhibits nevertheless pseudo-plastic behaviour with field-dependent yield stress at higher magnetic field strengths.

Table 1 B', β and β_0 for different values of n

n	β	B'	$B_0 = (B')^{-\frac{1}{\beta}}$
1	2.629	3.952	0.593
0.8	2.475	3.810	0.583
0.4	1.816	2.727	0.575

Table 2 The Materiel and physical properties of Herschel-Bulkley analysis

Parameter	**Value (units)**
k	430 *Pa-s*
n	0.4
μ	0.4 *Pa-s*
H	$1x10^{-3}$ *m*
L	$14x10^{-3}$ *m*
w	$10x10^{-3}$ *m*

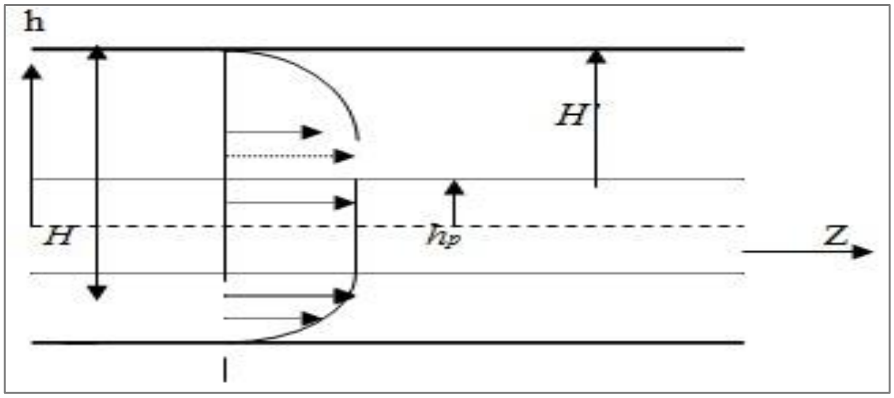


Figure 1 Non-Newtonian fluid flow description by parallel plate

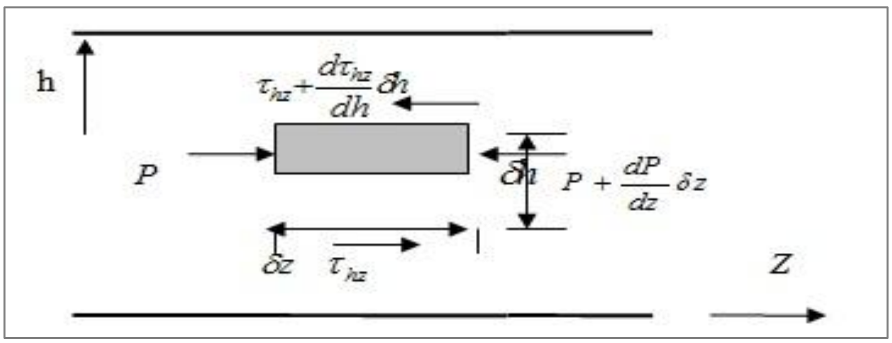
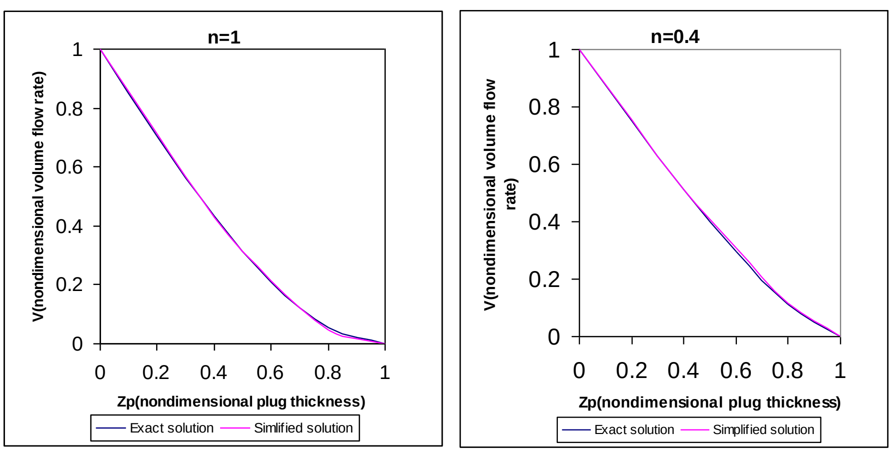


Figure 2 Free body diagram of laminar flow through parallel plate



(a) (b)

Figure 3 (a, b) A distinction between Herschel-Bulkley parallel plate flow accurately and simplified formulations for n = 1 and n = 0.4

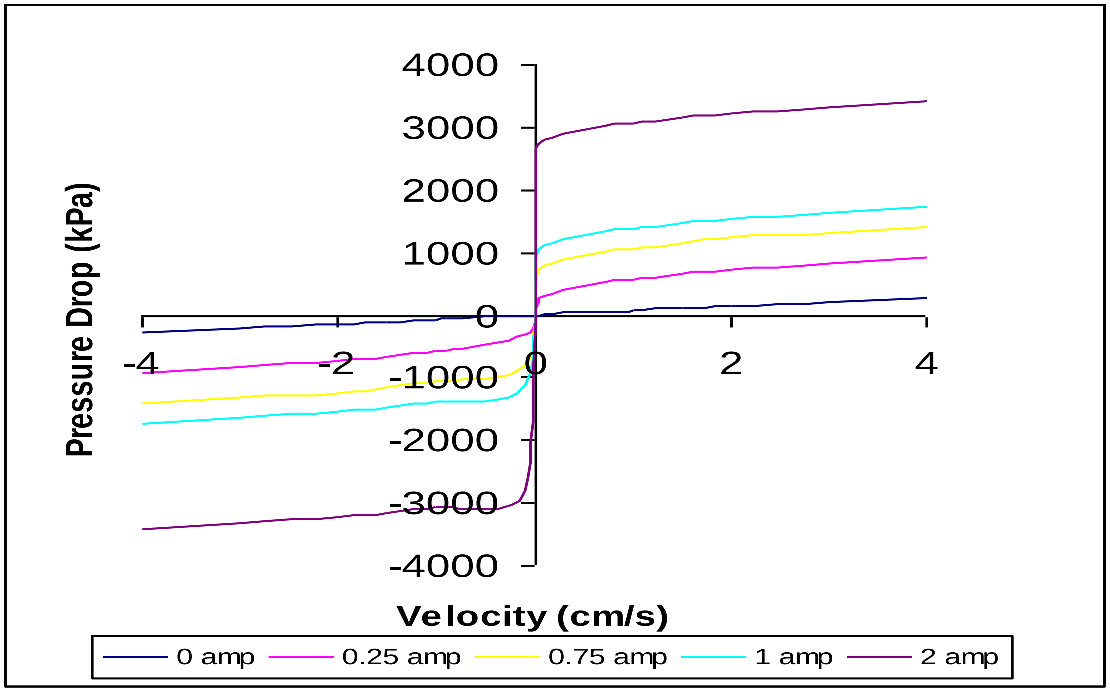


Figure 4 Pressure drop versus velocity relationship for parallel plate model

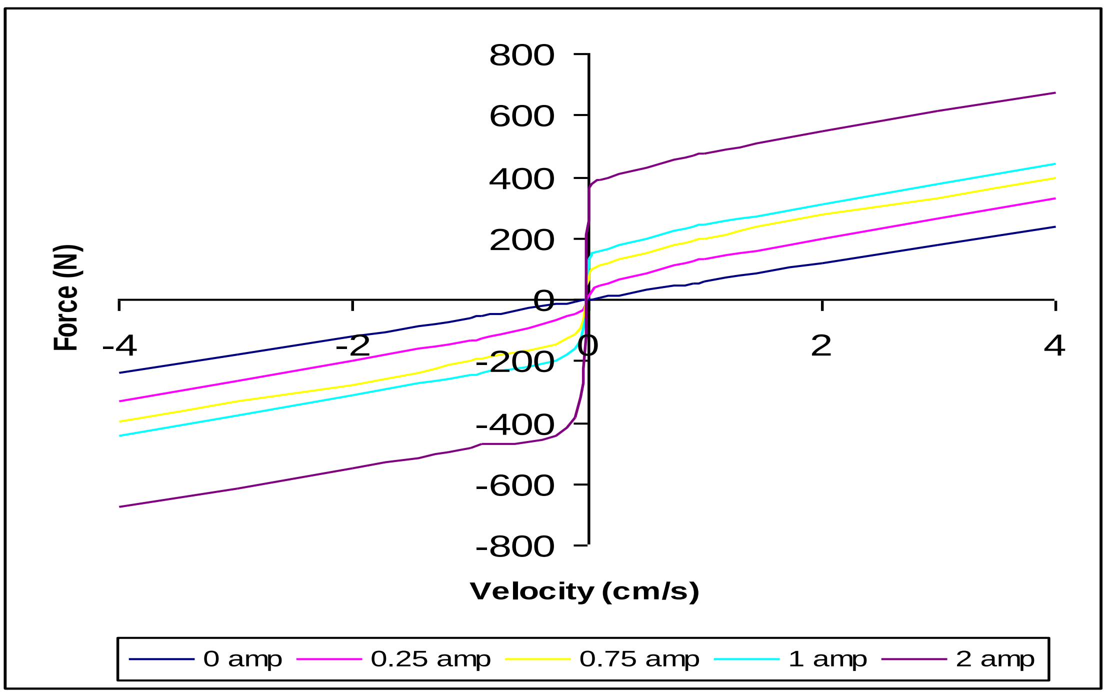


Figure 5 Force versus velocity for parallel plate model

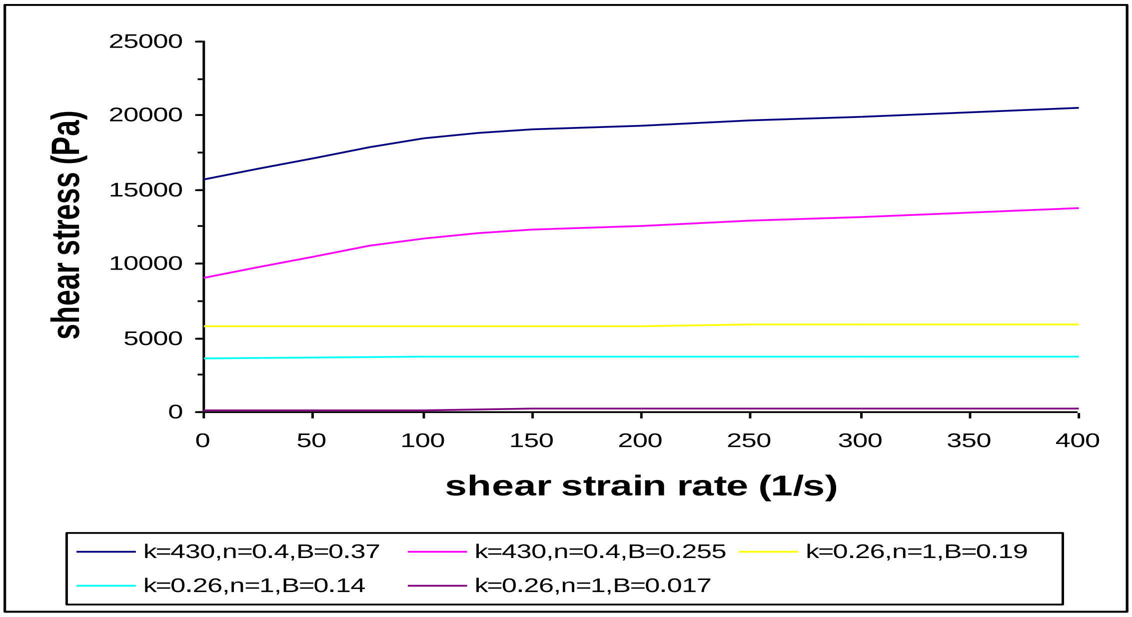


Figure 6 Shear stress and shear strain at different strengths of the magnetic field

Notation

B	Magnetic flux density
B_0	Constant which depends on fluid index parameter, n
C_1, C_2, C_3	Constants which depends on fluid index parameter, n
E	Electric field intensity
F_f	Damper seal friction force
H	Gap between parallel plate
h_p	plug thickness for parallel plate
I	Current
k	Fluid index parameter
L	Length of parallel plate
n	Fluid index parameter
Q	Discharge rate
T^*	Dynamic range
u	Flow velocity
w	Plate width
μ	Dynamic viscosity
τ_y	Yield stress in shear
τ_{rz}	Shear stress along radial direction

5.Conclusion

The pressure drop (gradient) must be defined with a simplified closed-form expression in terms of the material characteristics, morphology and volume flow rates. Comparing the detailed and simplified versions of the parallel plate model provides a better estimation to an accurate solution for simplified model. It is observed that less than 3% of the relative maximum error is found. For magneto-rheological fluids that can observe Bingham's plastic behaviour for steady plastic viscosity in the area of low magnetic field strength. Analytical results show that the modern semi active tools for structural seismic response, reduction or broadband excitation control are the most promising magneto-rheological damper.

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Conflicts of interest

The authors have no conflicts of interest to declare.

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