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Fabrication and Characterization of MR Damper as a Semi-active Device for Vehicle Suspension System

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Abstract: *Suspension systems play vital role in vehicle dynamics, particularly for improving the ride performance characteristics like, ride comfort, vehicle handling and vehicle compactness. The limited scope of the passive viscous dampers in achieving the best results for suspension has paved way for active and semi-active vibration controls. Magnetorheological (MR) dampers as semi-active control devices are one such a feasible solution for improving vehicular suspension. As part of this study, a MR damper is developed using MR fluid consisting of carbonyl iron powder and silicone oil added with additive. The characteristics of this damper is established by conducting experiments, further these results are used to identify the parameters of Spencer model for MR damper using Matlab / Simulink.*

Keywords: *Semi active suspension systems; Magnetorheological dampers; Spencer model.*

1. Introduction

The suspension systems have a crucial role in reducing the vibration and improving ride comfort to an acceptable level. The suspension system consisting of springs and the damper along with tires is responsible for achieving this objective [1]. The three main classes of control systems used in vehicle suspension are Passive and active and semi-active control systems. Passive and active controls represent the two ends of the spectrum in the use of damping strategies for vibration isolation from the rider on a vehicle [2].Passive dampers, though they are simple in design and economical, are tuned devices and provide a constant damping response, irrespective of the operating conditions. On the other hand, the active control devices can address all these issues related to ride comfort and vehicle handling at all frequencies, they are complex in design, require more power for operation and expensive [3]. Semi-active control systems combine the best features of both approaches, offering the reliability of passive devices, yet maintaining the versatility and adaptability of fully active systems.

Magnetorheological fluids, are a kind of smart fluids, which are amongst controllable fluids that respond to applied magnetic fields with dramatic changes in rheological behaviours. The interesting feature of the MR fluids is their ability for reversible change from free-flowing viscous liquid to semi-solid with controllable yield strength in milliseconds when exposed to a magnetic field. It is to say that the primary advantage of these fluids stems from their large and controllable dynamic yield stress due to the high magnetic energy density that can be established in the fluids [4].

During the past two decades, MR fluids technology has gained significant developments in different aspects from the manufacture of MR fluid compositions, including metal particles, basic fluid or carrier fluid, and stabilizing additives to performance evaluation and fast-growing applications of innovative MR fluid-based devices in civil engineering, safety engineering, transportation, life science, and so on [5]. Noticeably, one of the most important applications of these fluids is development of dampers or shock absorbers, in which MR fluids are controlled by amagnetic field to allow the damping characteristics of the device to be continuously adjusted by varying the power of the electromagnet.

MR damper is very much like a hydraulic damper in construction, but with an electrical coil wounded around the piston head and basically consists of MR fluid which consists of suspensions of non-colloidal, multi-domain (0.05-10µm) and magnetically soft particles in organic or aqueous liquids. Compared with conventional semi-active devices such as variable orifice dampers, MR dampers have advantages that they are fast responding, low power requirement, and no moving parts that make them reliable. A yield stress of nearly 100 kPa can be obtained for MR fluids with magnetic suspensions containing carbonyl iron powder. MR fluids can operate at temperatures from -40^{0}Cto 150 ^{0}C [6].

Among different operational modes of MR fluids, flow mode (i.e. valve mode) is used in hydraulic controls, servo valves, dampers, shock absorbers, and actuators. In this mode, the fluid flows as a result of a pressure gradient between two stationary plates [7].

2. BASIC STRUCTURE OF MR DAMPER

The basic design of an MR damper involves a piston and cylinder and MR control valve. The cylinder is usually filled with MR fluid and separated by a moveable piston for outputting mechanical motion. The MR control valve is employed to produce the damping effect under the control lable magnetic fields using electromagnets [8]. The MR fluid cylinders are mainly of three types, namely, mono tube, twin-tube and double ended structure. In the present work, monotube model is considered for fabrication and further experimentations.

3. MONOTUBE STRUCTURE

The fundamental and typical structure of a monotube passive damper is shown inFigure1. The monotube damper is basically based on a single-rod cylinder structure, which has only one reservoir for the fluid and the reservoir is divided into extension chamber and compression chamber by a moving piston [9]. During piston movement, MR fluids in the cylinder pass through the control valve that is assembled in the piston, which results in an apparent change in viscosity of the fluid, causing a pressure differential for the flow of fluids and consequently generating damping force proportional to the controllable magnetic field.[10]

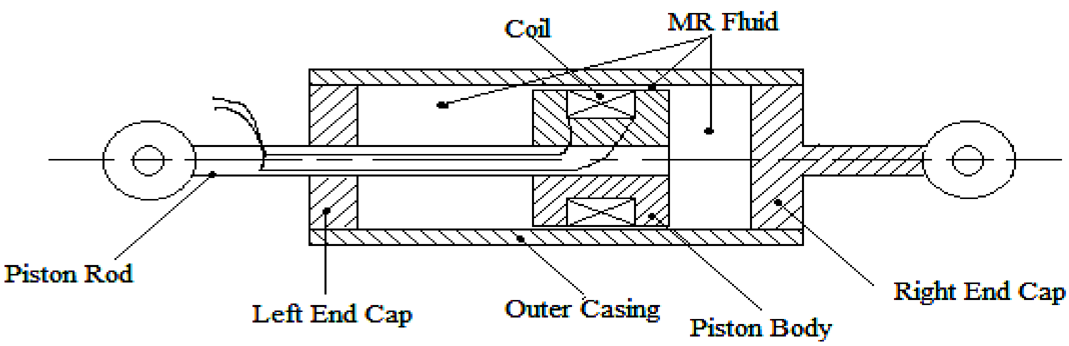


Figure 1. *Monotube MR damper*

The development and fabrication of the MR damper is done taking dimensions equal to commercially available conventional passive damper used in four wheeled automobiles, with a specially made piston of low-carbon steel with slot on piston head. The physical parameters of the proposed damper are summarized in Table 1.

The fabricated components of MR damper are as shown in Figures2 and 3.MR fluid consisting of Carbonyl iron of 80% weight suspended in Silicone oil base with Aerosil 200 as an additive. The coil consisting of double wired parallel winding with a copper wire of 25gauge and 200 turns, which has a resistance of 3.5 Ohms, is housed in the piston head assembly [11].

Table 1. *Geometric dimensions of the fabricated MR damper*

Damper Parameter	Dimension (mm)
Extended height	380
Compressed height	360
Stroke length	20
Damper tube length	300
Damper tube outer diameter	60

Damper tube inner diameter	50
Piston head diameter	48
Piston rod diameter	12

Table 2. *MR fluid composition*

Carbonyl Iron (≥99.5% Fe basis)		Silicone oil	
Parameter	Value	Parameter	Value
CAS number	7439-89-6	Vapor density	>1 (vs air)
Molecular weight	55.85	Vapor pressure	<5 mmHg (25 °C)
Boiling point	2750 °C	Viscosity	10 cSt(25 °C)
Melting point	1535 °C	Boiling point	>140 °C/0.002 mmHg
Density	7.86 g/ml at 25 °c	Density	0.93 g/mL at 25 °C

Figure 2. *Piston rod with solenoid and cylindrical casing*

Figure 3. *Assembly of the damper*

4. EXPERIMENTAL SETUP AND PROCEDURE

Experimental study is carried out on a test rig, a BISS (Bangalore Integrated System Solutions Pvt Ltd) make single station servo hydraulic test system shown in Figure 4.It consists of a damper test setup, with 25kN capacity two column load frame, mounted with 15kN load cell, 15kN fatigue rated double acting, double ended actuator and is driven by 65 LPM hydraulic power pack system through SS digital servo controller in built with testing software.

Figure 4. *Experimental set up*

The fabricated MR Damper is fixed between the actuator and fixed end on the top of the test rig, with the help of fixture. Electric power supply to magnetic coil is fed through a regulated power supply. The amplitude of vibration can be varied by varying actuator speed through a controller. Force, displacement and velocity are recorded by considering 6 steps of current as 0 A, 0.25A, 0.5A, 0.75A, 1A and 1.5A and results are recorded.

5. EXPERIMENTAL OBSERVATIONS

Using data acquisition system, the damping force data in relation to displacement caused by actuator is considered as sine wave of 1Hz and recorded at amplitude of 0.1m.

It is observed that peak force is increasing as current levels are increasing, but rate of increase is noticeably less beyond 1.0Aas shown in Figures 5 to 7. Hence, in the further work the MR damper is modelled and parameters required for modelling are arrived at 0.00 A, 0.25 A, 0.50 A, 0.75 A 1.00 A considering peak force at 1.0 A as major criterion.

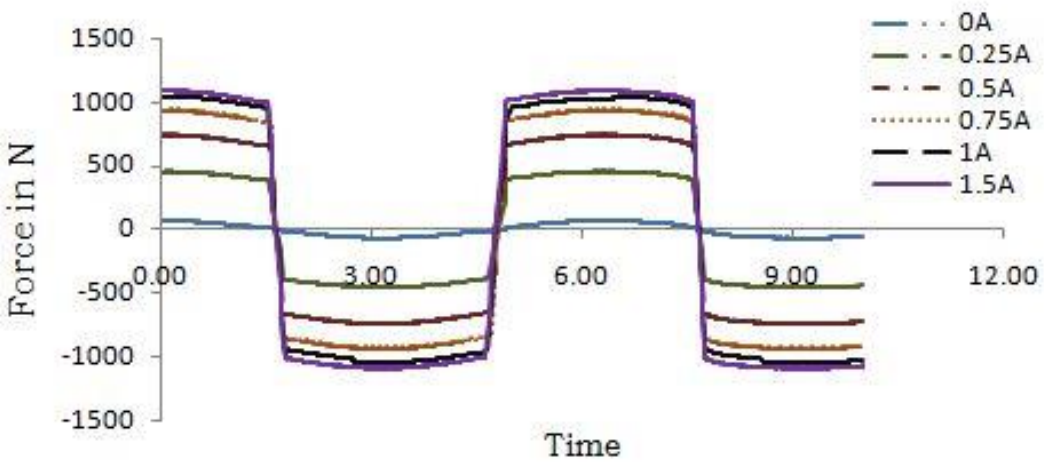


Figure 5. *Force Vs Time plot for MR Damper prototype*

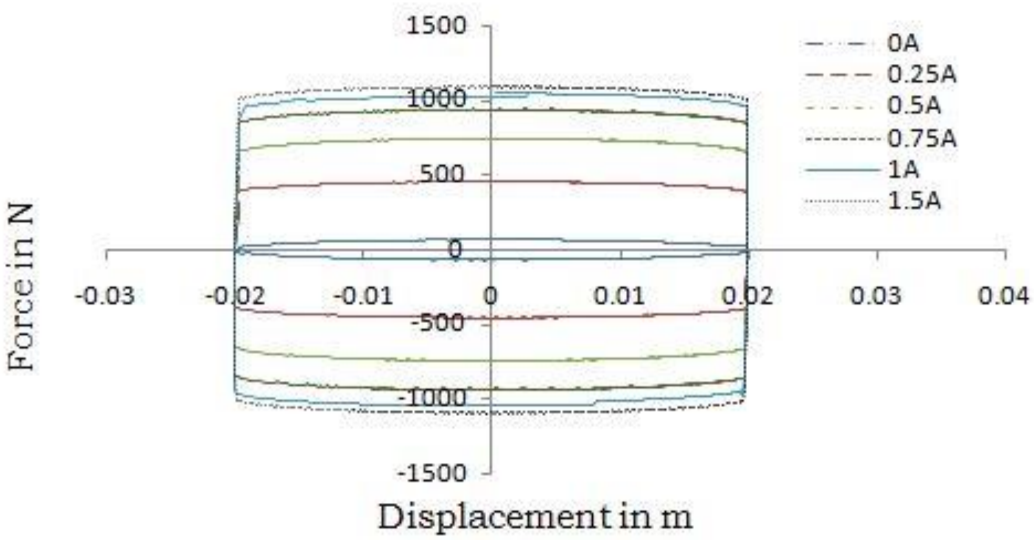


Figure 6. *Force Vs displacement for MR Damper prototype*

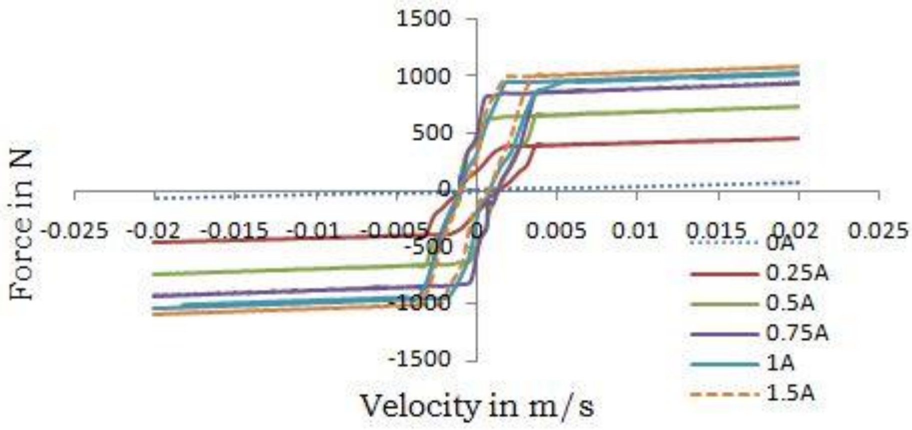


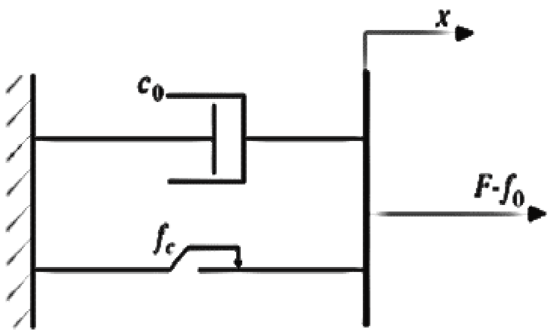
Figure 7. *Force Vs velocity for MR Damper prototype*

6. MODELLING OF THE MR DAMPER

Various parametric and non-parametric models were proposed in the literature to model the behaviour of MR damper and to identify various related parameters [12].In this study, MR damper prototype is modelled with three idealized mechanical parametric models, Bingham, Bouc-Wen and Spencer (modified Bouc-Wen) models and compared the output of each model with experimental data to identify best fit model, to use such model further for evaluation of ride performance of vehicular suspension systems.

a) Bingham Model: In Bingham model, a Coulomb friction element fc is placed parallel to the dashpot c_0 and is schematically represented as shown in Figure 8. According to Bingham's MR damper model, the damping force F for non-zero piston velocities $\dot{x}$, is given as

$$F = f_c \, sgn\, \dot{x} + c_0 \dot{x} + f_0 \qquad [1]$$



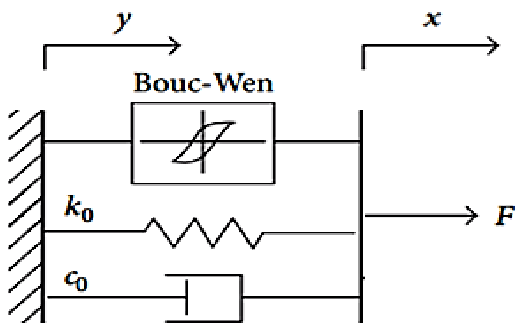


Figure 8. *Bingham model*

Figure 9. *Bouc-Wen model*

b) Bouc-Wen model is developed to represent structures showing hysteresis, in which the restoring force depends not only on the moment of the displacement, but also on the past events of the structure. Bouc-Wen model is indicated schematically as shown in Figure 9, and the damping force is given as

$$F = c_0 \dot{x} + k_0 (x - x_0) + \alpha z \qquad [2]$$

Where k_0 and c_0 are spring stiffness and dashpot damping coefficient respectively, α is the Bouc-Wen model parameter related to the MR material yield stress and z is hysteretic deformation of the model and is defined by following equation:

$$\dot{z} = -\gamma |\dot{x}| z |z|^{n-1} - \beta \dot{x} |z|^n + A\dot{x} \qquad [3]$$

The coefficients A, β, γ, and n are dimensionless quantities that control the linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region. The parameters of the Bouc-Wen model have the following range criteria:

$\alpha > 0$, $c_0 > 0$, $k_0 > 0$, $x_0 > 0$, $A > 0$, $n > 1$, $\beta > 0$, $\gamma > 0$.

In earlier studies, the prediction accuracy of structures with hysteresis is satisfactory as compared with the experimental results gained for n = 2 using this method.

c) Spencer Model: This model is obtained by modifying the Bouc Wen model by including a dashpot, represented by c1, and a spring with stiffness k1 are introduced to improve better depiction at low velocities and nominal damper force due to the accumulator respectively [13].

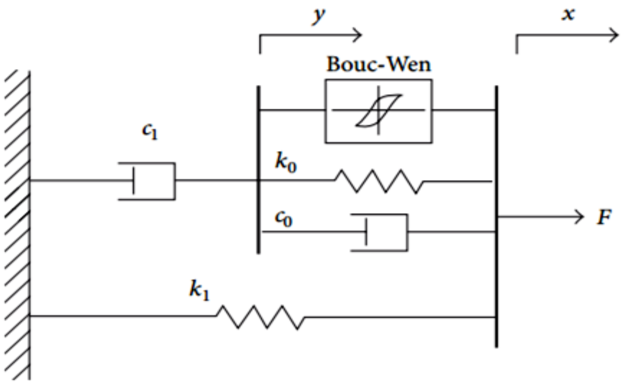


Figure 10. *Spencer model*

According to Spencer model, the damping force produced due to the MR damper is given by

$$f_{MR} = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) \quad [4]$$

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \quad [5]$$

$$\dot{y} = \frac{1}{c_0 + c_1}\{\alpha z + c_0\dot{x} + k_0(x - y)\} \quad [6]$$

Where k_1 represents the accumulator stiffness, c_0 is the viscous damping observed at larger velocities. $c_1$represents a dashpot that is included to produce the roll-off at low velocities, $k_0$is stiffness at large velocities, andx_0 is the initial displacement of spring associated with the nominal damper force due to the accumulator. The parameters of the Spencer's model have the following range criteria:

$\alpha > 0$, $\beta > 0$, $\gamma > 0$, $A > 0$, $K_1 > 0$, $K_0 > 0$, $C_1 > 0$, $C_0 > 0$, $X_0 > 0$, $n > 1$

After comparing the output force in terms of time, displacement and velocity of damper prototype of these three models, Bingham, Bouc-Wen and Spencer models with experimental data, for one of the currents i.e at 0.5A as shown in Figures 11 to 13, Spencer's model is identified to be more accurately matching with experimental data.

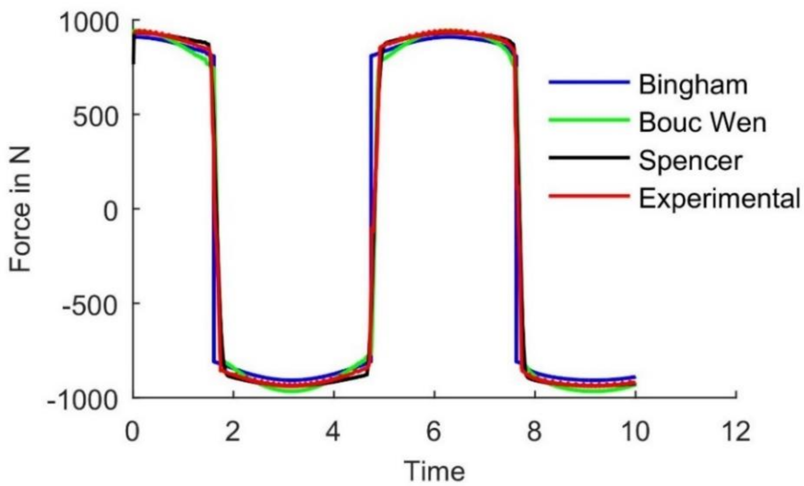


Figure 11. *Output force Vs time of damper prototype*

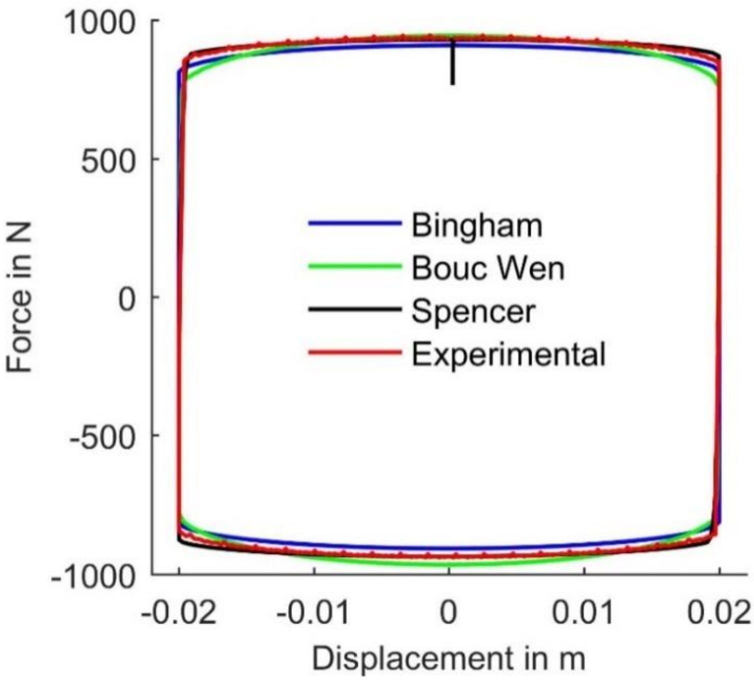


Figure 12. *Output force Vs displacement of damper prototype*

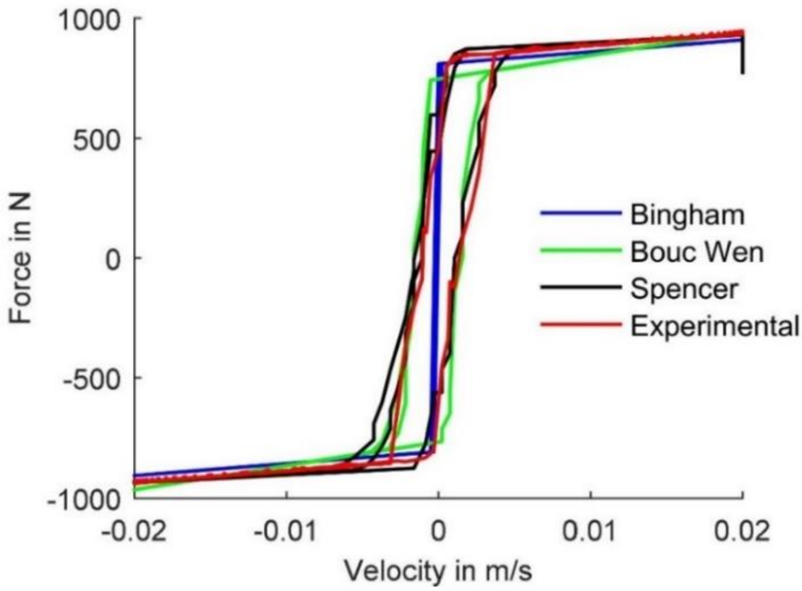


Figure 13. *Output force Vs velocity of damper prototype*

It is observed that Bingham model does not exhibit the nonlinear force-velocity response observed in the data for the case when the acceleration and velocity have opposite signs and the magnitude of the velocities are small. Even though the Bouc-Wen model envisages the force-displacement behaviour and force-velocity behaviour closely to the experimental data, the nonlinear force-velocity response does not resemble in the region where the acceleration and velocity have opposite signs and the magnitude of the velocities are small.

7. PARAMETER IDENTIFICATION

As Spencer's model, in comparison with other parametric models, has accurately predicted the response of the MR damper over a wide range of operating conditions, it is considered for further analysis and evaluation in this work. Simulink block diagram for the Spencer model of MR damper is shown in the Figure 14.

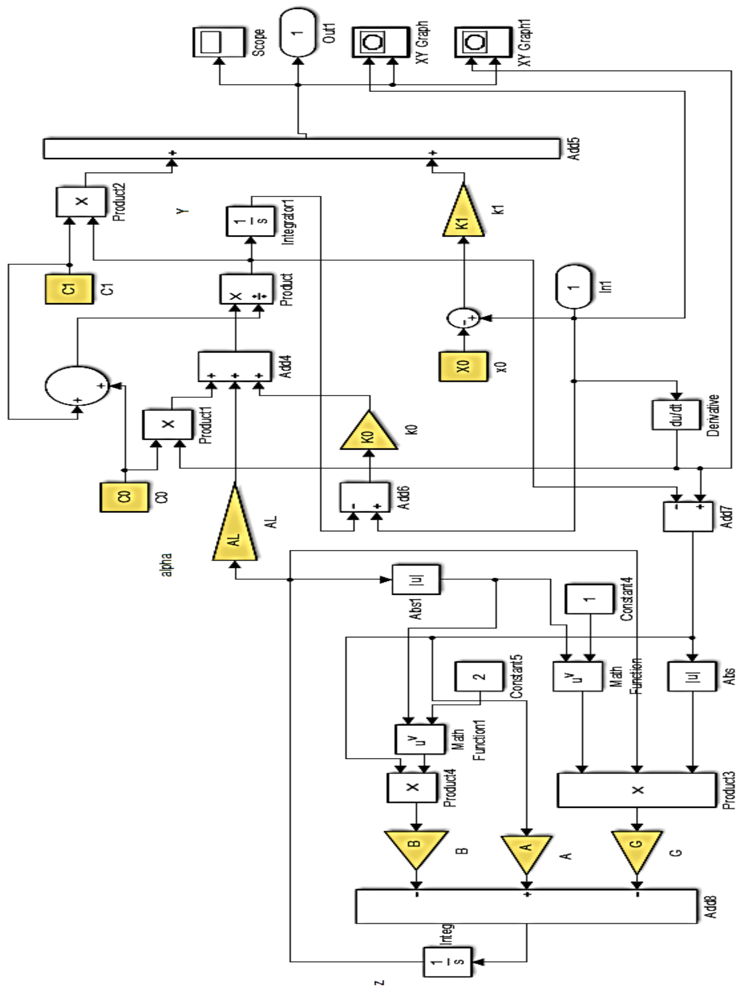


Figure 14. *Simulink block diagram of the Spencer model of MR damper*

The values of various parameters mentioned in the equations 4 to 6 at five distinct currents from 0 to 1 A are shown in Table 3.

Table 3. *Spencer damper model parameters*

Parameters	0 A	0.25 A	0.5 A	0.75 A	1 A
A	841.18	158.91	110.17	220.76	107.18
α (in N/m)	3785.5	14832	48410	29502	65992
β (in m-1)	6.34E+07	16111	3.62E+05	1.87E+05	3.03E+05
C_0 (in Ns/m)	3101.5	2847.2	3651.3	3397.2	3999.2
C_1 (in Ns/m)	23395	1.94E+05	4.17E+05	4.24E+05	3.68E+05
γ (in m-1)	4346.8	1.99E+05	2.08E+05	66035	1.94E+05
K_0 (in N/m)	332.42	28.104	66.422	113.28	273.95
K_1 (in N/m)	175.71	16.451	31.08	4.9029	36.22
X_0 (in N/m)	0.016	0.15	0.14	0.73	0.12
n	2	2	2	2	2

8. Conclusions

The comparison of Spencer model analysed in MATLAB/Simulink with experimental values is done and represented in plots for Force Vs Time; Force Vs Displacement and Force Vs Velocity in figures 15 (a) to 15(c). It is observed that the results obtained from Spencer model using MATLAB/SIMULINK fits very closely to the behaviour of the damper identified from experimentation than other two models. So, the Spencer model is adapted to represent behaviour of MR damper for further analysing vehicle models.

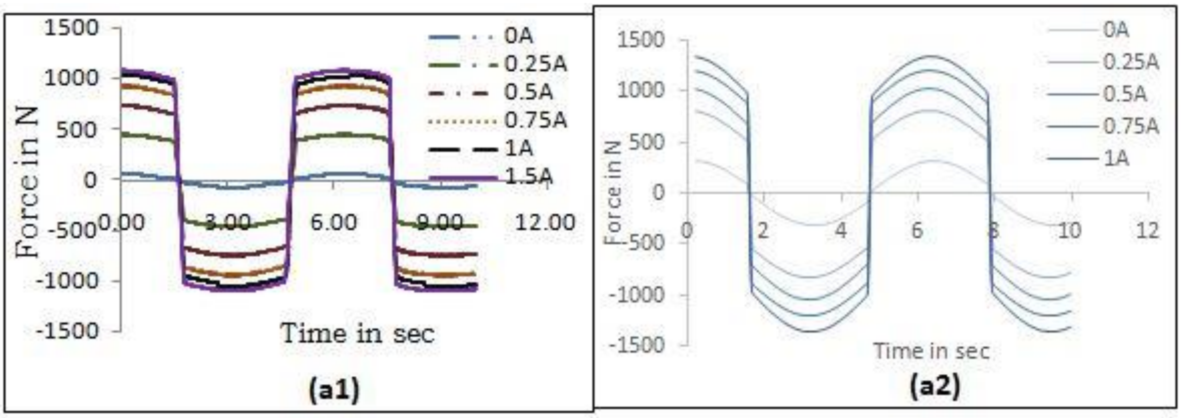


Figure 15. *(a): Comparison of experimental data (a1) with simulated data (a2) forForce Vs time*

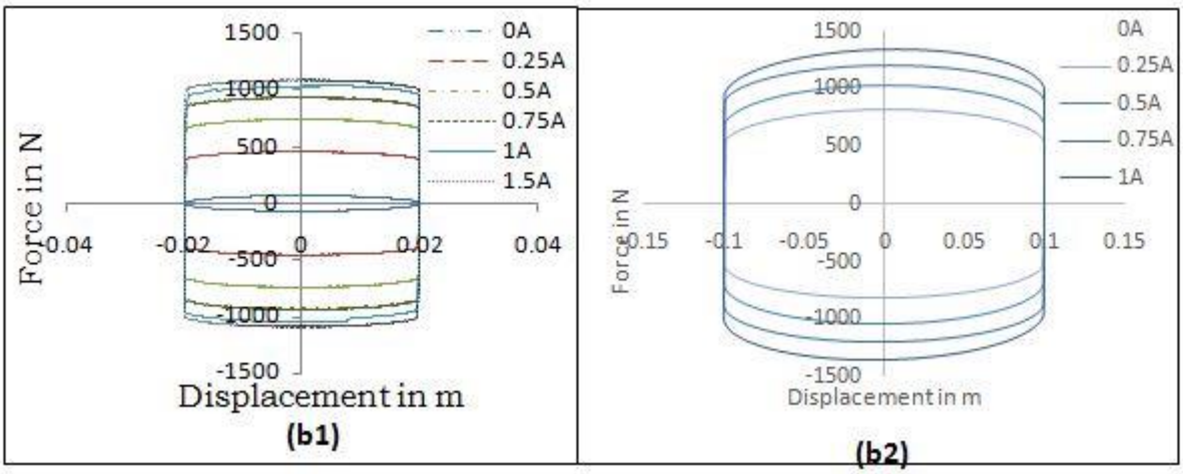


Figure 15. *(b): Comparison of experimental data (b1) with simulated data (b2) for Force Vs displacement*

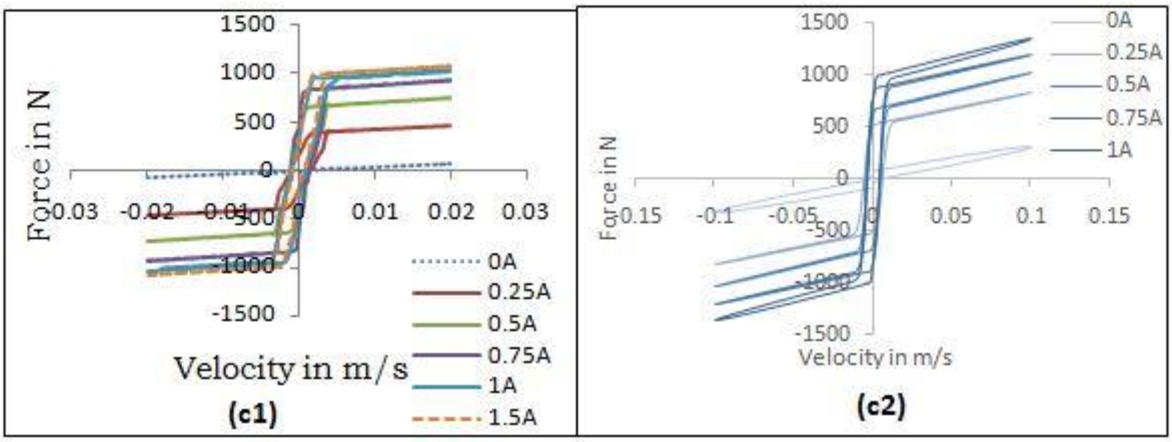


Figure 15. *(c): Comparison of experimental data (c1) with simulated data (c2) for Force Vs velocity*

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