POLLACK PERIODICA
An International Journal for Engineering and Information Sciences
DOI: 10.1556/606.2020.15.3.4
Vol. 15, No. 3, pp. 37–48 (2020)
www.akademiai.com

PARAMETRIC STUDY OF DAMPING CHARACTERISTICS OF MAGNETO-RHEOLOGICAL DAMPER: MATHEMATICAL AND EXPERIMENTAL APPROACH

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Received 31 July 2019; accepted 20 April 2020

Abstract: The present research work is a part of a project was a semi-active structural control technique using magneto-rheological damper has to be performed. Magneto-rheological dampers are an innovative class of semi-active devices that mesh well with the demands and constraints of seismic applications; this includes having very low power requirements and adaptability. A small stroke magneto-rheological damper was mathematically simulated and experimentally tested. The damper was subjected to periodic excitations of different amplitudes and frequencies at varying voltage. The damper was mathematically modeled using parametric Modified Bouc-Wen model of magneto-rheological damper in MATLAB/SIMULINK and the parameters of the model were set as per the prototype available. The variation of mechanical properties of magneto-rheological damper like damping coefficient and damping force with a change in amplitude, frequency and voltage were experimentally verified on INSTRON 8800 testing machine. It was observed that damping force produced by the damper depended on the frequency as well, in addition to the input voltage and amplitude of the excitation. While the damping coefficient (c) is independent of the frequency of excitation it varies with the amplitude of excitation and input voltage. The variation of the damping coefficient with amplitude and input voltage is linear and quadratic respectively. More ever the mathematical model simulated in MATLAB was in agreement with the experimental results obtained.

Keywords: Magneto-rheological damper, Modified Bouc-Wen model, MATLAB/SIMULINK, Experimental test

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1. Introduction

Most of the natural occurrences, behavior of dynamic systems and operational machine processes do not follow a linear trend but are in character nonlinear. Due to the difficulties created in the design and studies of engineering processes by the nonlinear behavior, linearized model is considered for the ease and simplicity. But the linearization of models can be taken to only some extent as the study of nonlinear behavior of dynamic and mechanical systems could be of paramount importance to increase the efficiency and to develop an effective and accurate control depending on the area of application.

One particular analogy is the nonlinear behavior of Magneto-Rheological (MR) dampers, in particular its damping properties.

From the semi-active control devices available in the market, MR dampers are considered most reliable, for its flexibility and adaptability. MR damper consists of two chambers separated by piston head, which has an annular space as it is shown in *Fig 1*. Both chambers are filled by MR fluid, whose rheological property can be varied. The fluid consists of micron-sized, magnetically polarizable ferrous particles suspended in the carrier liquid, which can be water, glycol, synthetic or mineral oil [1]. The annular space in the piston head is provided with a system of electromagnets, which on the introduction of current create a magnetic field across space. The paramagnetic particles are suspended in the carrier liquid as it is shown in *Fig 2*. These ferrous particles line up to form chains in the direction of the magnetic field as it is shown in *Fig 3.* The changing magnetic field, thereby changes the rheological behavior of the MR fluid by increasing its viscosity. Therefore, the applied magnetic field changes the MR fluid from Newtonian to Non-Newtonian fluid of varying viscosity. The viscosity of the fluid is directly proportional to the applied current [2].

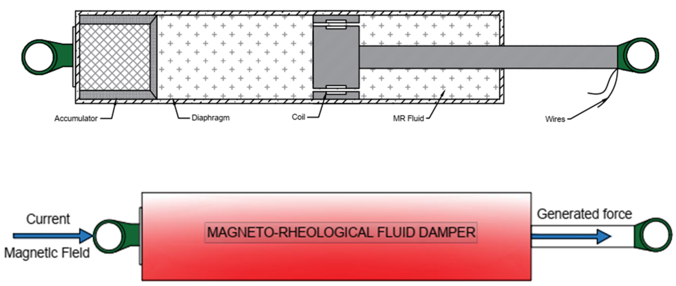


Fig. 1. Hardware and working principle of MR damper

Various mathematical model have been proposed from Bingham model [3], Dhal model [4], LuGre model [5], Bouc-Wen [6] to the latest modified Bou-Wen model (Spencer model) [7]. Various mathematical and experimental studies have been carried on each model and relation between forces; velocity and displacement have been established. The hysteresis nonlinear behavior of MR damper corresponding to the relation between damping force, piston velocity and displacement form the characteristics of MR fluid. The studies done over the years on each model showed highlighted their limitation from not considering the hysteresis behavior of damper [8], [9], stiffness [10] and internal damping of MR damper (MR fluid) [11], [12], [13]. From the previous studies the mathematical model for the damper has been improved, but little attention has been paid to determine the relation of input variables to the intrinsic characteristics of MR damper. Moreover, comparison between simulated mathematical models of damper in MATLAB/SIMULINK environment [14] to the corresponding experimental results is not performed extensively. As MATLAB is a high end multi-paradigm mathematical computing environment so a mathematical model should be simulated in it to be used for future researches on control strategies [15], [16] involving the same. The control strategies performed on an experimental model can then be verified by observing the same in MATLAB/SIMULINK effectively [17], [18].

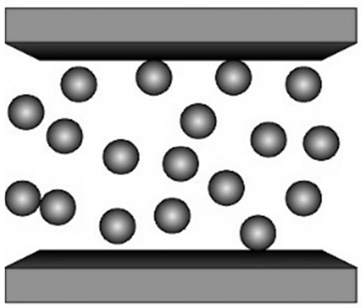


Fig. 2. MR fluid without magnetic field

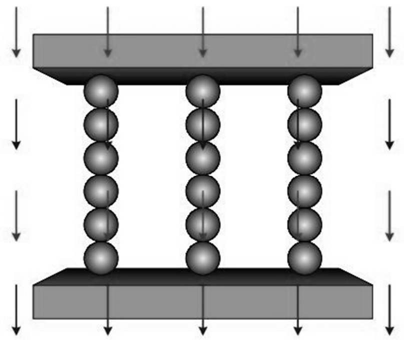


Fig. 3. MR fluid with magnetic field

This particular research paper focuses on the study of variation in damping properties of MR damper with respect to its input parameters using a mathematical model in MATLAB and validating the same experimentally. The relation of *damping coefficient* with change in input voltage *frequency* and amplitude of input excitation are observed both mathematically and experimentally. *Regression* analysis is done to obtain the fit of mathematical model to experimental data.

2. Mathematical model of MR damper

A relation between force and deformation is often detected in structural materials and elements, like reinforced concrete, steel, base isolators, dampers, and soil profiles. Many mathematical models have been proposed to efficiently describe the behavior of MR damper for use in time history and random vibration analyses. One of the most popular is the Bouc-Wen class of hysteresis models, which was originally proposed by Bouc [6]. As the research and development of MR damper models continued, Spencer et al. [7] proposed a modified form of already existing Bouc-Wen model. The schema of the model is illustrated in *Fig. 4:*

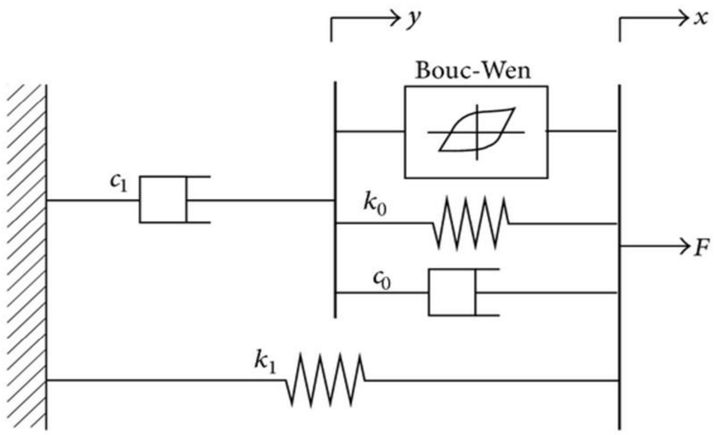


Fig. 4. Mathematical model of MR damper

$$c_1\dot{y} = \alpha z + k_0(x - y) + c_0(\dot{x} - \dot{y}), \tag{1}$$

$$z = -\gamma|\dot{x}_d| - y|z||z|^{(n-1)} - \beta(x_d - \dot{y})|z|^n + A(\dot{x}_d - y), \tag{2}$$

$$F = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0), \tag{3}$$

$$\alpha(u) = \alpha_a + \alpha_b u, \ c_1(u) = c_{1a} + c_{1b}u, \ \text{and} \ c_0(u) = c_{0a} + c_{0b}u, \tag{4}$$

$$\dot{u} = -\eta\,(u - v), \tag{5}$$

where F is the total damping force; k_1 is the accumulator's stiffness; c_1 is the damping at low velocities; c_0 is the viscous damping at large velocities; k_0 is the controls the stiffness at large velocities; x_0 is the initial displacement of spring k_1 and v is the applied voltage, y is the internal displacement of damper and x is the displacement of damper in longitudinal direction. Also α, β, γ and η as the internal resistance of MR damper is constant and the voltage being proportional to current (linear variation) the two terms mean the same.

The damping constants given in (1) - (3) vary linearly in MR dampers with the applied voltage, equation (4) reveal this relationship. The equation (5) defines the dynamics of MR fluid reaching rheological equilibrium. All the above equations have been employed as input and processing blocks in MATLAB /SIMULINK. The damping force (F) produced by the MR damper varies linearly with the change in input voltage. The change in voltage causes a change in magnetic field, which in turn changes the resistance (viscosity) of MR fluid to flow which changes the damping force.

The MR damper adopted in this research is a short stroke damper. The damper provided is a monotube with 10.8 cm stroke (full extension), but the maximum stroke of the damper is restricted to 10.4 cm to avoid any damage to the damper. The continuous working voltage range of the damper is between 0 - 8 V providing a damping force of 450 N at 0 V and 1800 N at 8 V for a velocity of 0.15 m/s and 0.04 m/s respectively. The input voltage of MR damper can be increased to a maximum of 12 V (intermittent). The voltage of the damper is varied from 0 - 8 V only, in order to protect the MR damper from any electric failure due to overloading.

The parameters introduced in above equations were experimentally determined by characterization tests conducted on the damper to be used in the research. In *Table I* all the parameters for the modified Bouc-Wen model are tabulated. The expanded and condensed modified Bouc-Wen model for MR damper in SIMULINK are shown in *Fig. 5* and *Fig. 6* respectively

Table I

Modeling parameters of MR damper

Parameters	Value	Parameters	value
c_{0a}	5.9 Ns/cm	α_a	33.7 N/cm
c_{0b}	3.5 Ns/cm V	α_b	11.1 N/cm V
c_{1a}	81.8 Ns/cm	η	60 sec^{-1}
c_{1b}	12.0 Ns/cm V	γ	23.2 cm^{-2}
k_0	5.8 N/cm	β	23.2 cm^{-2}
x_0	0 cm	A	154.6
k_1	0.01 N/cm	n	2

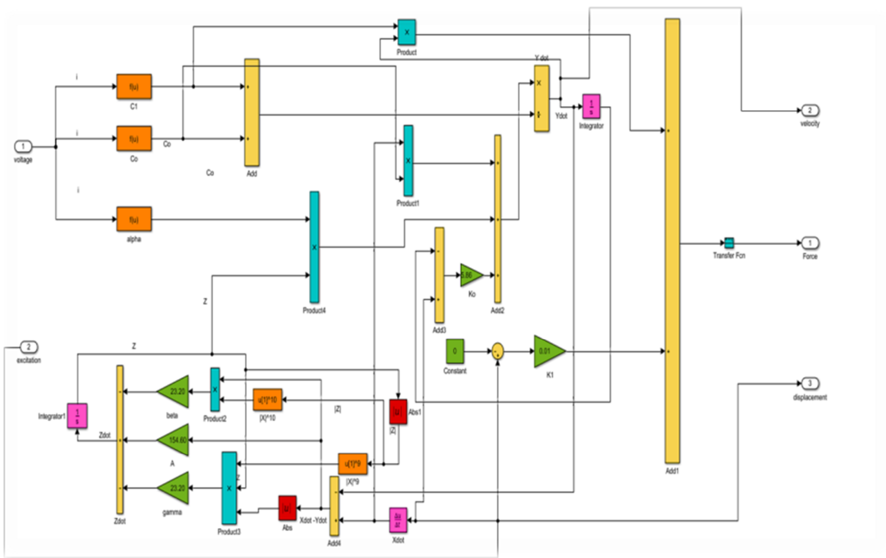


Fig. 5. Expanded SIMULINK model of MR damper

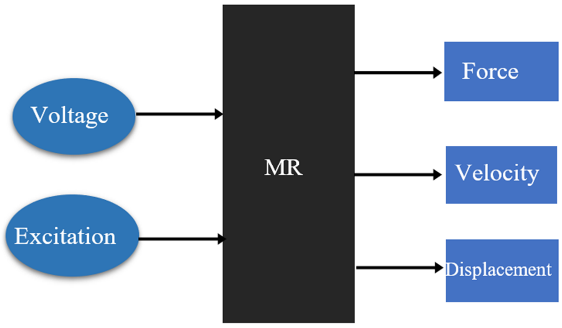


Fig. 6. Condensed model MR damper

Here *SIMULINK* modeling environment has been used to produce a numerical model of MR damper that precisely simulated its dynamics. The relationship between 1) damping force vs time; 2) damping force vs displacement; 3) damping force vs velocity; and 4) damping coefficient and voltage were obtained for varying amplitudes and frequencies were obtained.

3. Experimental test

The experimental procedure consists of testing the MR damper (shown in *Fig. 7*) in INSTRON 8800 (shown in *Fig. 8*) under the same periodic excitation, which the mathematical model in SIMULINK/MATLAB was put through. In periodic excitation, MR damper is tested for excitations of varying amplitudes, frequencies for varying input voltages. The damper is subjected to a sinusoidal wave of amplitudes full stroke (s) 10.4 cm, 6.9 cm (2s/3) and 5.0 cm (s/3) for frequencies of 0.2, 0.5, 0.7 and 1 Hz.

Fig. 7. MR damper

Fig. 8. Performance testing machine

4. Results

Based on the resulting parameters of the mathematical model of MR damper subjected to sinusoidal excitations, the relationships between different variables are compared with corresponding experimental observation obtained. Observations are compared for a constant frequency of 1 Hz at amplitude of 10.4 cm at maximum and minimum input voltage of 8 V and 0 V respectively. The comparison between the mathematically predicted value and the corresponding experimental data is provided in *Fig. 9* - *Fig. 14*. From the figures, it can be easily observed that the proposed model in SIMULINK predicts the behavior of MR damper satisfactorily and that the same model can be used in mathematical modeling of structure with MR damper in MATLAB.

The plot between damping coefficient and voltage for mathematical and experimental values is shown in *Fig. 15*.

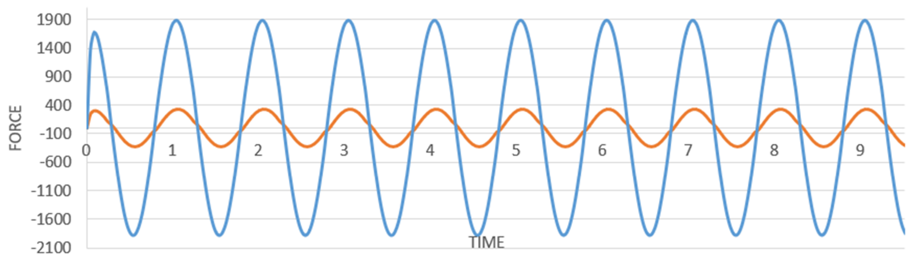


Fig. 9. Mathematical graph of force vs time for MR damper subjected to a sinusoidal excitation of constant amplitude and frequencies of 10.4 cm and 1Hz respectively at voltages of 0 V and 8 V, —— 0 V —— 8 V

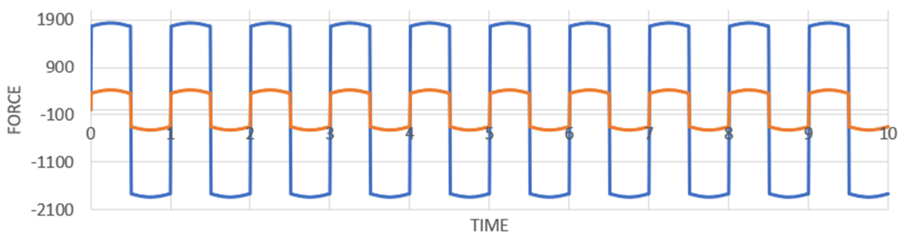


Fig 10. Experimental graph of force vs time for MR damper subjected to a sinusoidal excitation of constant amplitude and frequencies of 10.4 cm and 1Hz respectively at voltages of 0 V and 8 V, —— 0 V —— 8 V

Also, the damping coefficient determined as the function of voltage and can be expressed as shown in equations (6) and (7) from mathematical and experimental data respectively,

$$c = 0.2159v2 + 9.6462v + 80.768, \text{(mathematical model)}, \tag{6}$$

and

$$c = 0.4426v2 + 8.9612v + 88.84, \text{ (experimental observation)}, \quad (7)$$

where c is the damping coefficient and v is the input voltage.

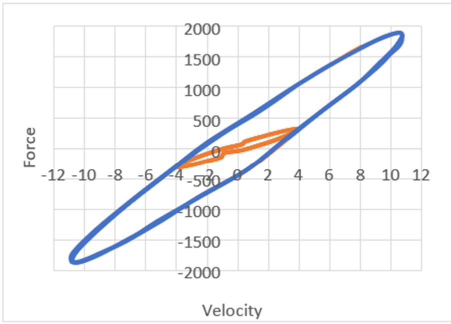


Fig. 11. Mathematical graph of force vs velocity for MR damper subjected to a sinusoidal excitation of constant amplitude and frequencies of 10.4 cm and 1 Hz respectively at voltages of 0 V and 8 V

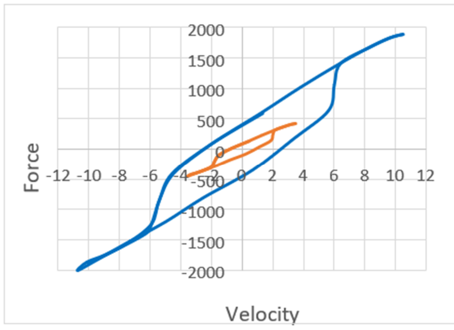


Fig. 12. Experimental graph of force vs velocity for MR damper subjected to a sinusoidal excitation of constant amplitude and frequencies of 10.4 cm and 1 Hz respectively at voltages of 0 V and 8 V

0 V — 8 V

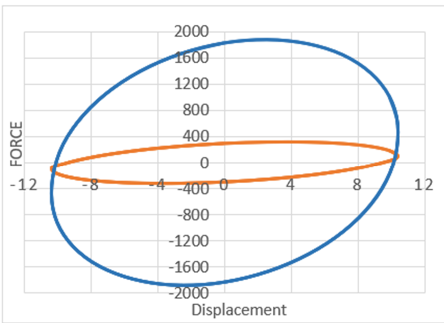


Fig. 13. Mathematical graph of force vs displacement for MR damper subjected to a sinusoidal excitation of constant amplitude and frequencies of 10.4 cm and 1 Hz respectively at voltages of 0 V and 8 V

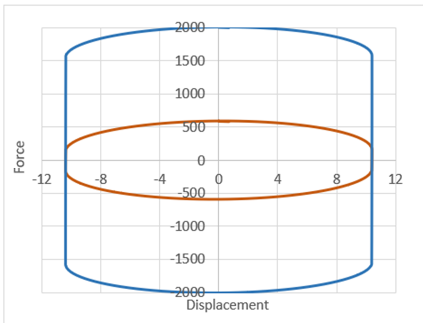


Fig. 14. Experimental graph of force vs displacement for MR damper subjected to a sinusoidal excitation of constant amplitude and frequencies of 10.4 cm and 1 Hz respectively at voltages of 0 V and 8 V

0 V — 8 V

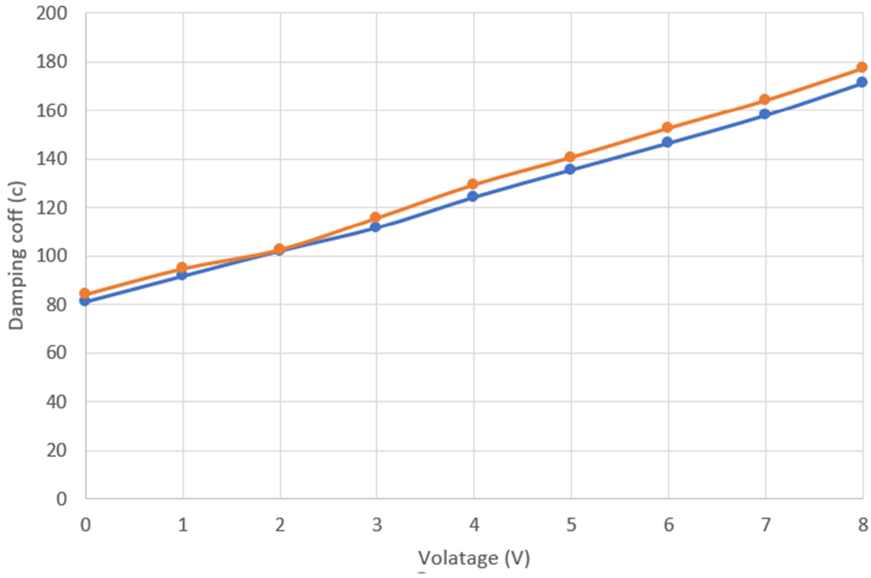


Fig. 15. Mathematical and experimental graphs between damping coefficient and voltage of MR damper

——— Mathematical ——— Experimental

4.1. Regression analysis

The curve fitting technique embedded in MATLAB is used to determine the coefficient of determination (R2) which indicated the closeness of modeled data to the experimental data, which in turn indicated the accuracy of damper modeled in SIMULINK. The expression for r is mentioned under:

$$r = \frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (y)^2]}} . \qquad (8)$$

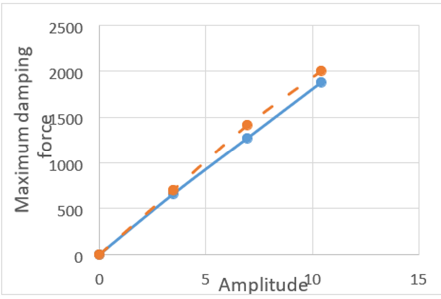
Here x and y are damping coefficients corresponding to mathematical model and experimental observation respectively. *Table II* displays the r_2=0.97 which indicates accuracy of the model predicting the experimental data.

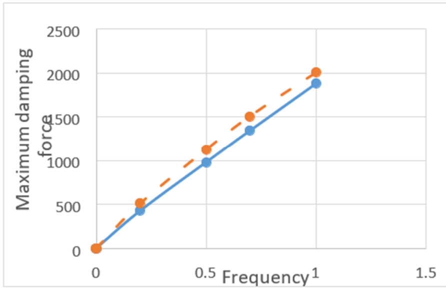
The variation of maximum damping force produced by MR damper with a change in amplitude at constant frequency and variation of maximum damping force produced by MR damper with a change in frequency at constant amplitude for both experimental and Mathematical model in SIMULINK are shown in *Fig. 16* and *Fig. 17*. From the plot, it is evident that the maximum damping force produced by the damper is directly proportional to amplitude as well as the frequency of input excitation.

Table II

r^2 value for mathematical to experimental values of damping coefficient (c)

Sno.	Voltage	Damping coefficient (Mathematical) (x)	Damping coefficient (Experimental) (y)	r^2
01	0	81.05	84.1	
02	1	91.6	94.6	
03	2	98.4	102.4	
04	3	111.6	115.6	
05	4	124.3	129.3	0.97
06	5	135.5	140.5	
07	6	146.5	152.5	
08	7	158	164	
09	8	171.3	177.1	





Mathematical Experimental

Fig. 16. Variation of max damping force with change in amplitude at constant frequency if 1 Hz

Fig. 17. Variation of max damping force with change in frequency at constant amplitude of 10.4 cm

5. Conclusion

The fundamental aim of this research was to understand comprehensively the behavior of MR damper developed through modeling in SIMULINK and validating the same through experimentation. Following conclusions were drawn after Mathematical and experimental studies:

- The damping force produced by MR damper increases with increase in input voltage and the variation is liner. Therefore, the force produced by MR damper depends upon the strength of the magnetic field applied across the annular space through which MR fluid flows;
- The damping force produced is in phase with the velocity and out of phase with the displacement of the damper. Hence velocity of the system should also be used as feedback for a new control strategy to be developed;

- Damping force produced by the damper doesn't only depend upon the input voltage but also depends upon the amplitude and frequency of the input excitation. Also, maximum damping force produced by damper for different amplitudes at a constant frequency follow a linear trend and so does maximum damping force for different frequencies at constant amplitude;
- The damping coefficient (c) of the MR damper is not constant but varies with the input voltage supplied. The variation of the damping constant is quadratic to the input voltage as shown in the previous section. The regression index r_2 = 0.97 predicts the compatibility of mathematical model to experimental results of damping coefficient for different input voltages;
- Damping coefficient (c) depends upon input excitation and increases with increase in the amplitude of excitation but is independent of the frequency of excitation.

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