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Algebraic Modeling of a field-controllable Magneto-rheological fluid damper

L.BalaMurugan
Anna University,
Chennai-600 025, India

J.Jancirani
Anna University,
Chennai-600 025, India

Abstract: In this paper a modified parametric algebraic model was proposed to capture the hysteretic behaviour of the Magneto-rheological (MR) damper. The superiority of the proposed modified model was shown by comparing it with the algebraic model. It is observed that although two models are comparable at lower voltage inputs of 1V, 2V and 3V the modified algebraic model is remarkably successful at higher voltage inputs of 5V and 7V at the highest excitation velocity of 200m/s over the algebraic model. Apart from its accuracy, modified algebraic model is also more preferable in terms of its low computational expenses compared to differential modified Bouc-Wen's model which is highly computationally demanding. Therefore it was concluded that the proposed modified algebraic model can be used to develop more effective control algorithms for such devices.
Keywords: MR damper; algebraic model; Bouc-Wen's model.

1. INTRODUCTION

For semi-active control the technologies available are based on devices with variable orifices (electrohydraulic dampers) or on devices with fluids capable of varying their viscosity as a function of electric or magnetic field (electro-rheological and magneto-rheological dampers).Recently, the semi-active suspension based on MR damper has attracted more attention [1–4] because of its fast response characteristic to magnetic fields, insensitivity to temperature fluctuations or impurities in the fluid, obtainment of convenient power and wide control bandwidth. However, the practical use of MR dampers for control is significantly hindered by its inherently hysteretic and highly nonlinear dynamics. The dislocation movement and plastic slipping among molecular chains or crystal lattices consume energy such that the restoring force of an MR damper always delays the input displacement or velocity. This phenomenon of energy dissipation is generally referred to as hysteresis. Therefore, a dynamic hysteresis model is needed to simulate the hysteresis phenomenon of MR dampers. To this end, various models have been proposed in the literature such as parametric viscoelastic-plastic model based on the Bingham model [5], the Bouc–Wen model [6], non-parametric models [7], and many more. Thus the success of MR dampers in semi-active control is determined by the accurate modelling of the MR damper.

In this paper the MR damper is modelled by the proposed modified algebraic model. Apart from its accuracy, modified algebraic model is also more preferable in terms of its low computational expenses compared to differential modified Bouc-Wen's model which is highly computationally demanding. Such a formulation is new which enhances the performance of the semi-active control. The MR damper parameters of the model used in the study correspond to an RD-1005 MR damper (made by Lord Corporation Ltd). The model parameters are determined such that the model characteristics fit very closely the experimental hysteretic behaviour of the MR damper using MATLAB curve fitting. It is obtained by minimizing the mean square error between the model and experimental results for the minimum (1V) and maximum (7V) input voltages.

2. MODELING THE HYSTERETIC BEHAVIOUR OF MR DAMPER

The MR damper used in the vehicle model with semi-active suspension is an RD-1005 MR damper (made by Lord Corporation Ltd). It is a twin tube MR damper whose schematic, the actual assembly and the components are shown in Fig. 1

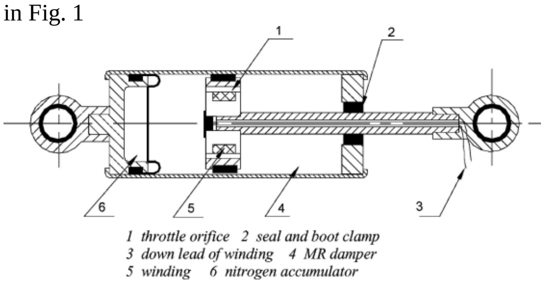


Figure-1. Structure of an RD-1005 damper [8].

As a controllable damper, it is subject to the maximal input displacement of 52 mm, the maximal voltage of 12 V. RD-1005 MR damper is tested by Guo and Hu[8] for sinusoidal excitation with a stroke length of 15mm and a fixed frequency of 2 Hz . The test has been performed for five cycles for voltages of 1.0, 2.0, 3.0, 5.0 and 7V. The measured force-velocity data for the RD-1005 MR damper is shown in Figure-2.

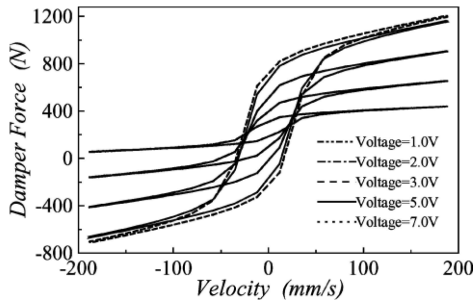


Figure-2. Force vs. velocity of RD-1005 MR damper at 2 Hz sinusoidal excitation [8].

The algebraic model proposed by Guo and Hu[8] is adopted and modified to give more accurate results. The model is given by

$$F(t) = f_0 + C_b\dot{x}(t) + \frac{2}{\pi} f_y \tan^{-1}\{k[\dot{x}(t) - \dot{x}_0 \,\mathrm{sgn}(\ddot{x}(t))]\} \qquad (1)$$

where F represents the damping force of the MR damper, f_0 the preload of the nitrogen accumulator, C_b the coefficient of viscous damping, f_y the yielding force, k the shape coefficient, $\dot{x}_0$ the hysteretic velocity, $\dot{x}$ and $\ddot{x}$ the excitation velocity and acceleration of the piston in the damper, respectively. This mathematical model is developed based on some physical phenomena. While the first term is to represent the preload force of the pressurized nitrogen gas in the accumulator, the second term is to describe the viscous force of the damper and the third one is to reflect the observed hysteretic behaviour, respectively. The mathematical descriptions of the first two terms come from classical mechanics, whereas of the third one is developed based on the definition of a trigonometric arctangent function which best resembles the characteristic force–velocity curve of the damper. Further, the two terms in the braces of the arctangent function are to account for the lag in the force response to a sinusoidal excitation. In the model $x(t) = a\sin(\omega t), \dot{x}(t) = a\omega\cos(\omega t), \ddot{x}(t) = -a\omega^2\sin(\omega t)$ where a is the displacement amplitude and ω is the angular velocity. In equation (1) f_0, C_b, f_y, k, and $\dot{x}_0$ are the unknown parameters and to be determined on the basis of experimental data by using least-square curve fitting method.

In order to validate the algebraic model, Guo and Hu[8] compared the measured damper force and the predicted damper force obtained from the algebraic model are shown in Figs. 3

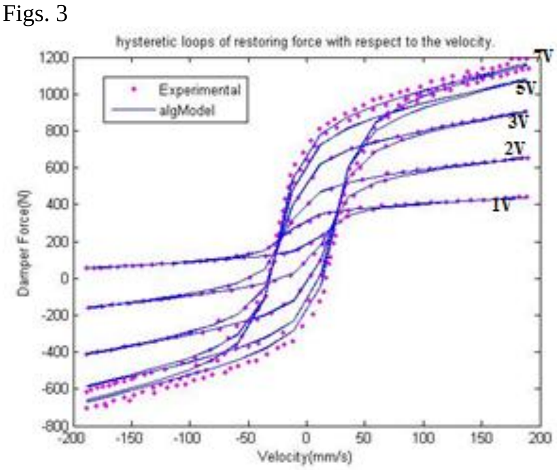


Figure-3. force vs. velocity comparisons between the algebraic model predictions and experimental data

It is observed that there is a general good agreement between the estimated and measured values except for higher voltage inputs of 5V and 7V at the highest excitation velocity of 200mm/s (see also Figure-4). The measured force-velocity data for the MR damper presented in Figure-2 suggests nonlinear dependence of the force on the applied voltage. Starting from this point, the model given in Eq. (1) is modified by multiplying an incremental nonlinear voltage function in order to improve the agreement.

$$f_d = f_0 + C_b\dot{x}(t) + \frac{2}{\pi} f_y \tan^{-1}\{k[\dot{x}(t) - \dot{x}_0 \,\mathrm{sgn}(\ddot{x}(t))]\} * \left(1 + \frac{k_2}{1+e^{-a_2((\frac{V}{0.16})+I_0)}} - \frac{k_2}{1+e^{-a_2 I_0}}\right) \qquad (2)$$

The nonlinear incremental behaviour of the voltage is characterized by an asymmetric sigmoid function with a bias in the lateral axis [9]. The function must also exhibit post-yield limiting behaviour of the damping force attributed to the rheological properties of the MR fluid. The nonlinear voltage function k_2 and a_2 are positive constants and I_0 is an arbitrary constant representing the bias. The parameters are determined on the basis of experimental data by using least-square curve fitting method.

For instance, one arrives at the following mathematical model of RD-1005 MR damper for model parameter estimates, when $a \le 15mm$ and $f = \frac{\omega}{2\pi} = 2Hz$, respectively. Substituting $\dot{x}(t) = a\omega\cos(\omega t)$ into equation (1) yields

$$f_d(-a\omega^2\sin(\omega t), a\omega\cos(\omega t), V) = 247 + \frac{1.51}{1+10.34e^{-1.04V}} a\omega\cos(\omega t) + \frac{2}{\pi}\frac{710}{1+e^{-1.1(V-2.3)}}\tan^{-1} * \{0.0725[a\omega\cos(\omega t) - \frac{40}{1+1.81e^{-0.2V}}\mathrm{sgn}(\sin\omega t)]\} \left(1 + \frac{500}{1+e^{-(0.00001)((\frac{V}{0.16})-0.1375)}} - \frac{500}{1+e^{-(0.00001)(-0.1375)}}\right) \qquad (4)$$

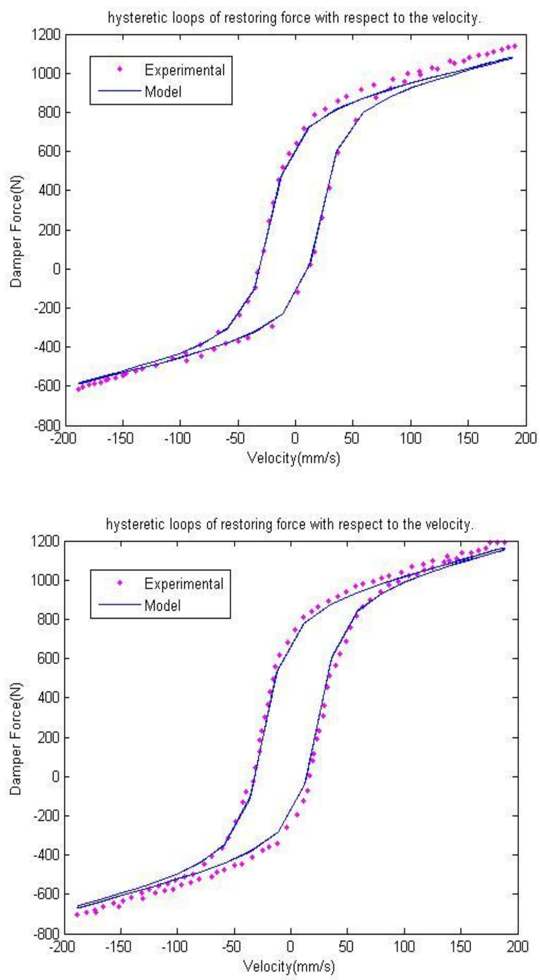
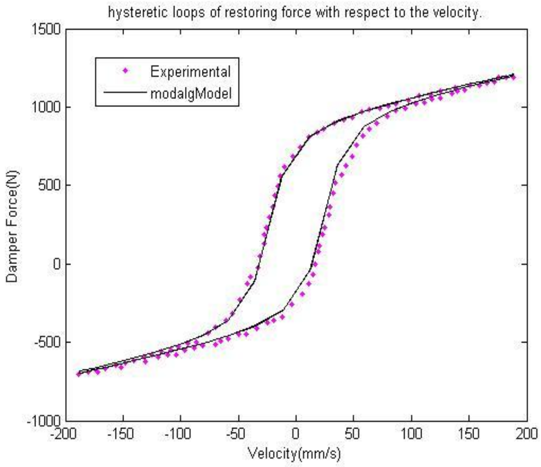


Figure-4. Hysteretic loops of damping force of RD-1005 MR damper with respect to velocity obtained from the model given by Eq.(1) at voltage inputs of 5 and 7V.



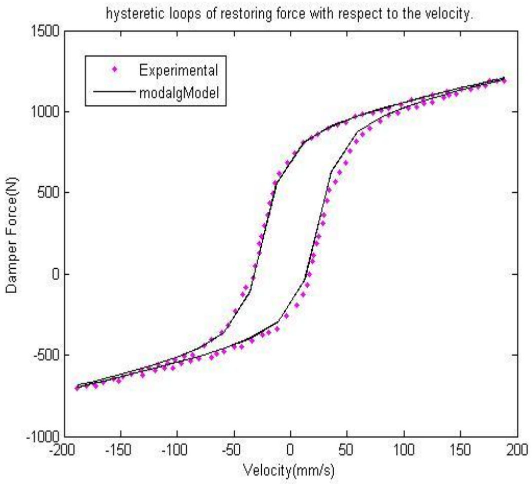


Figure-5. Hysteretic loops of damping force of RD-1005 MR damper with respect to velocity obtained from the model given by Eq.(2) at voltage inputs of 5 and 7V.

3. CONCLUSION

This paper presents a new modified algebraic model, in which algebraic model have been modified by multiplying an incremental nonlinear voltage function, was employed to describe the hysteretic behaviour of the MR damper. The unmodified and modified forms of the algebraic model, which are parametric in nature, were compared with the experimental data. It was shown that the proposed modified algebraic model removed the disagreement at the mention higher voltage input and higher velocity region. This is presumably due to effect of the multiplied incremental nonlinear voltage function to the algebraic model. Hence it was deduced that the proposed modified algebraic model could overcome the shortcomings of the original algebraic model. Apart from its accuracy, modified algebraic model is also more preferable in terms of its low computational expenses compared to differential modified Bouc-Wen's model which is highly computationally demanding. It is hoped that the present improved model will aid to develop more effective control strategies and algorithms for MR dampers.

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