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Research Article

A Study of Some Nonparametric Models of Magnetorheological Fluid Damper for Vibration Control

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Abstract

Magneto-rheological (MR) dampers are semi-active control tools that have received a lot of attention in recent years due to their structural simplicity, wide range of applications, low energy consumption, high capacity and high reliability. MR dampers are being developed for a wide variety of applications where controllable damping is desired. MR fluids represent a class of smart materials whose rheological properties change in response to the application of a magnetic field. MR fluid dampers are new type of vibration control elements, having the advantages of rapid damping and stiffness changing in the presence of an applied magnetic field. Multiple types of devices have been designed to implement this versatile fluid. Some examples of devices in which MR fluids have been employed include dampers, clutches, brakes and transmissions, polishing machines and to control gun recoil on naval gun turrets. Automobile suspension and structural vibration control systems are among the most frequent uses of such dampers. The main challenge to the expansion of using these dampers is presenting a model capable of simulating their non-linear and complex hysteresis behaviors in a suitable manner. So far many different models have been presented for simulation of hysteresis of magneto-rheological dampers.

Keywords: *MR damper, nonparametric models, polynomial model.*

1. Introduction

Over the past decade, there has been a sustained interest in magnetorheological (MR) devices due to the controllable interface provided by the MR fluid inside the devices that enables the mechanical device to interact with an electronic system, which can be used to continuously adjust the mechanical properties of the device (Weng W. Chooi et al, 2008). A MR damper is a hydraulic monotube damper whose oil has metallic particles and its damping coefficient varies according to the supplied electric current. The essential feature of the MR fluids is that they can reversibly change their states from a Newtonian fluid to a semi-solid or even a solid with controllable dynamic yield stress within a few milliseconds, when they are subjected to a controlled magnetic field (I. Sahin et al, 2010; Guo D. et al, 2005). Effective control of an MR damper mainly depends on understanding its nonlinear hysteretic behavior under an applied magnetic field. Therefore, one needs to develop control algorithms that take maximum advantage of the unique features of MR dampers, and the models must adequately characterize the intrinsic nonlinear behavior of these devices (Spencer Jr. BF al, 1997). So far many different models have been presented for simulation of hysteresis of magneto-rheological dampers. Models such as Bouc-Wen parametric model and other non-parametric models are based on sigmoid functions. Nevertheless, many of these models demonstrate differences between results of experimental tests and simulations. Also, in most models the model characterizing parameters are not functions of frequency, amplitude and current of stimulation. Thus they must be recalculated for different stimulation conditions (Ardeshir Karami al, 2011). In order to characterize the performance of MR dampers, several models have been proposed to describe their behavior. Each model describes different aspects of friction and/or dynamic properties of the MR damper (Haiping Du et al, 2005).

The existing models can be classified into two main categories as parametric and non-parametric (H. Metered et al, 2010). Parametric models are the most desirable ones as their parameters have some physical meaning. These models consist of some mechanical elements such as linear viscous, friction, springs, etc. Parameters associated with these mechanical elements are estimated by comparing the models with experimental results (I. Sahin et al, 2010). Parametric models are useful for direct dynamic modeling of MR dampers i.e. the prediction of

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the damper force for given inputs (voltage signal and the time history of the relative displacement across the damper's ends) (H. Metered et al, 2010). Nonparametric models establish a relationship between measured quantities, by purely mathematical means; the occurring parameters do not have a direct physical meaning (Yan Cui et al, 2010). A literature survey would indicate that, although non-parametric models can effectively represent MR damper behavior (N. Aguirre et al, 2010).

2. MR fluid models

There are two approaches to model damper: physical modeling based on physical and geometrical data called as parametric models, and nonparametric modeling based on experimental data. Each of them has particular advantages and disadvantages. Models can accurately represent the behaviour of MR dampers are essential in understanding the operation and working principles of the device. Such models can eliminate a great deal of uncertainties during the design process, which can subsequently enable control strategies for the damper to be developed efficiently and reliably (J. Wang & G. Meng, 2003).
These include the phenomenological model based on a Bingham model (J. Wang & G. Meng, 2003), Bouc–Wen hysteresis model (G. Z. Yao et al, 2002), modified Bouc-Wen Model (W. H. Liao & C. Y. Lai, 2002), Kowk model (N. M. Kwok et al, 2006) etc. They are usually computationally complex, requiring time consuming computations when implemented in a full vehicle simulation. They contain several parameters whose values can only be determined by expensive measurements with special testing equipment. And even a small change of the damper design may require an adjustment of the model and a new set of measurements (Yan Cui et al, 2010).
The principal non-parametric identification techniques proposed for MR dampers are interpolating polynomial fitting (Hassan Metered et al, 2009), neural networks (W. H. Liao & D. H. Wang, 2005) and neuro-fuzzy modelling (K. C. Schurter & P. N. Roschke, 2000). In the next section some nonparametric models has been presented.

3. Non-parametric models

An alternate to the parametric method of modeling MR dampers is the non-parametric method (GangRou Peng, 2011). Using this approach, the device is represented through purely empirical expressions and device working principles. Nonparametric models establish a relationship between measured quantities, by purely mathematical means; the occurring parameters do not have a direct physical meaning (Yan Cui et al, 2010; Boada M. J. L et al, 2011). The merits of the non-parametric modeling method are that they can avoid the pitfalls of parametric approaches while being robust and applicable to linear, non-linear and hysteresis system (GangRou Peng, 2011; Boada M. J. L et al, 2011).

3.1 Linear Damper Model

This is the simplest model used in simulation-based analysis. This model is based on an ideal damper response. For MR dampers, the relationship between force and velocity will change when a current is applied. As a result, the envelope of force output is defined by an area rather than a line in the force velocity plane. It only considers linear behaviour and current dependant model. The general form of the deterministic equation is given by

$$F_d = \alpha I \tag{1}$$

where, F_d is the damper force, I is the current supplied to the damper, α is the constant linear damping coefficient for the model (Russell Richards, 2007). Using experimental data, the linear damping coefficient is identified. The force-velocity plot for linear shock absorber model is shown in Figure 1.

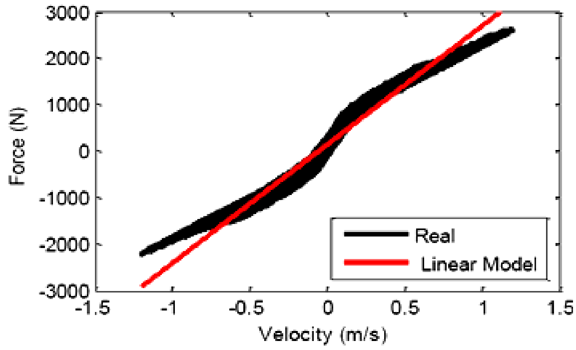


Figure 1. Linear Shock Absorber Model

3.2 Power function damper model

The second choice for the shock absorber model is a simple power function, as shown in equation (2) and (3). For rebound

$$F(v) = q_1 v^{d1} + l_1 \qquad v \ge 0 \tag{2}$$

and, for compression

$$F(v) = q_2 (-v)^{d2} + l_2 \qquad v \le 0 \tag{3}$$

The force-velocity plot for power function shock absorber model is shown in Figure 2.

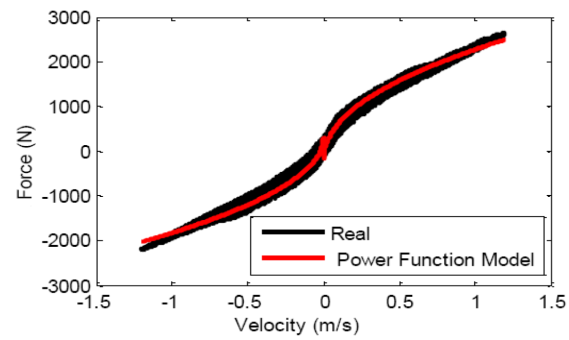


Figure 2. Power Function Shock Absorber Model

3.3 Polynomial model

This is one of the most commonly used non-parametric models.

In this model, the hysteresis loop of the MR damper is divided into positive acceleration (lower loop) and negative acceleration (upper loop), and the lower loop or the upper loop is fitted by the polynomial with the power of the damper piston velocity as follows,

$$F = \sum_{i=0}^{n} a_i v^i \tag{4}$$

where F is the maximum damping force, a_i is the experimental polynomial coefficient to be determined from the curve fitting, v is the damper piston velocity and n is the order of the polynomial (Haiping Du et al, 2005).

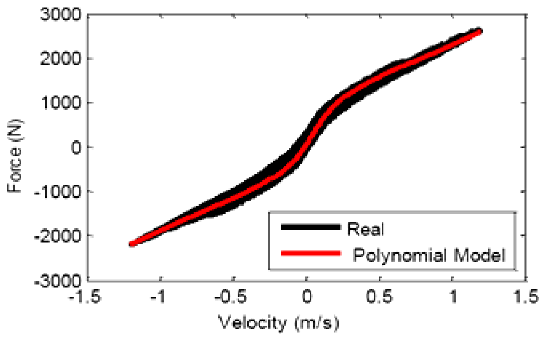
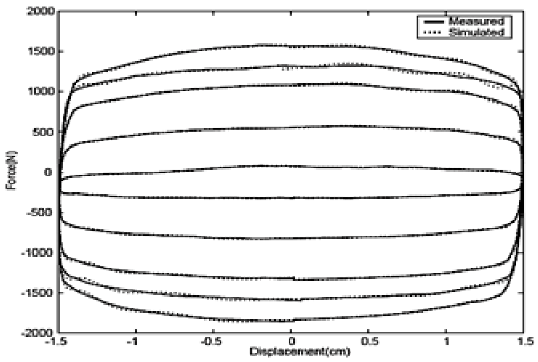
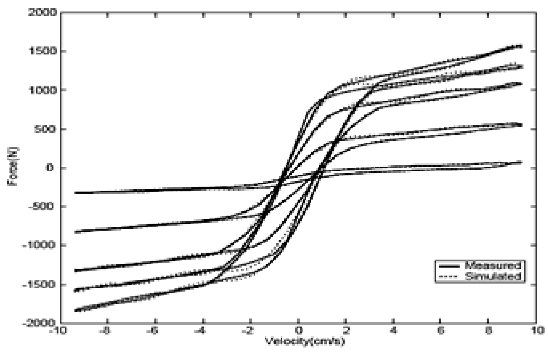


Figure 3. Polynomial Shock Absorber Model



(a)



(b)

Figure 4. Comparison of polynomial model and experimental results: (a) force vs. displacement; (b) force vs. velocity.

Equation (4) is used to describe the maximum damping force as a function of the applied current I to the MR damper.

The polynomial order n is chosen by trial and error. Based on the experimental data, a least-square optimization method is employed to determine the appropriate parameters a_i and n for the analytical model.

A New Polynomial Model is reported in research paper (Arjon Turnip et al, 2008) is given by

$$f_{mr}(\dot{z}_s - \dot{z}_u, I) = \sum_{k=0}^{n} (a_k^0 + b_k^0 I)(\dot{z}_s - \dot{z}_u)^k \tag{5}$$

where n is the order of the polynomial, I is the current supplied to the damper, $(\dot{z}_s - \dot{z}_u)$ is relative velocity and a_k^0 and b_k^0 are the coefficients that should be determined through experiments.

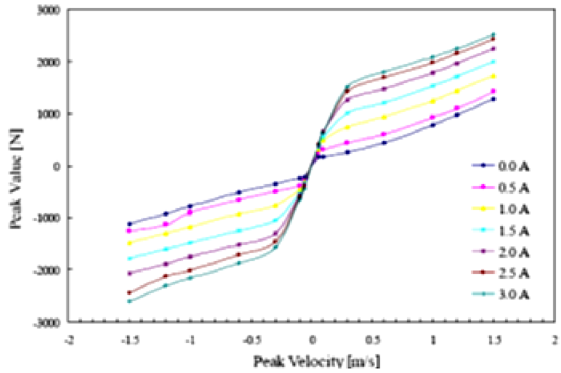
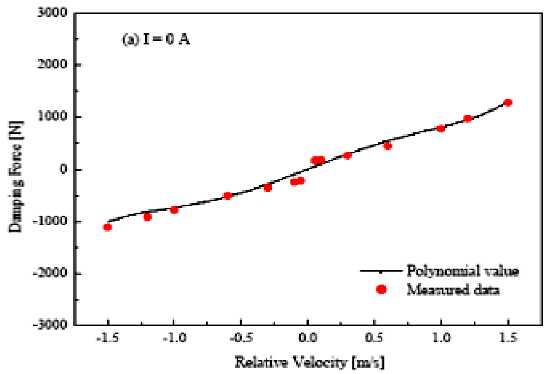
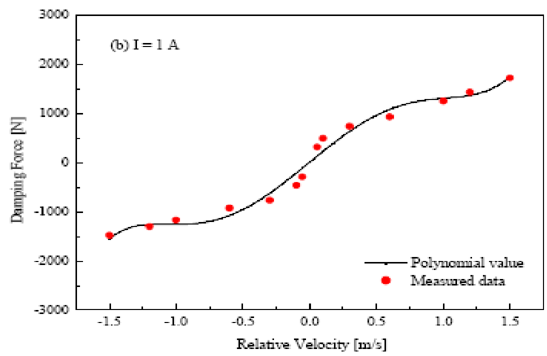


Figure 5 Peak values of a typical MR CDC damper for various current inputs

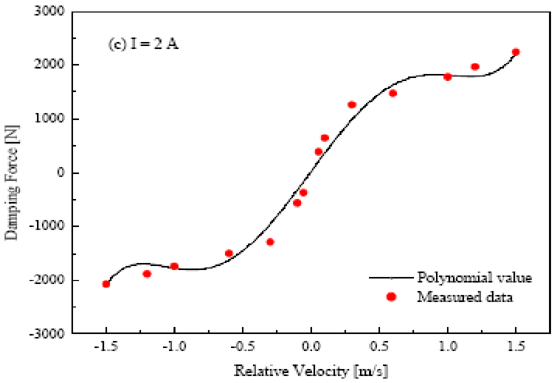
Figure 5 demonstrates the closeness between experimental data and the values calculated from the polynomial model of equation (3) of order six and for three different current inputs: 0, 1, and 2 A.



(a)



(b)



(c)

Figure 6. Comparison between measured data and polynomial model (for n=6).

3.4 Chebyshev polynomial

As a function of three variables, the damping force can be approximated as triple series involving variables x, $\dot{x}$ and v.

$$F(x,\dot{x},v) \approx \hat{F}(x,\dot{x},v) = \sum_{k,l,z=0}^{K,L,Z} C_{klz} T_k(\tilde{x}) T_z(\tilde{v}) \tag{6}$$

where C_{klz} are constants, T_k , T_l ,T_z constitute the polynomial basis over which the force is projected and K , L , and Z are the polynomials' truncation orders. The coefficients C_{klz} can be determined by invoking the orthogonality properties of the chosen polynomials.

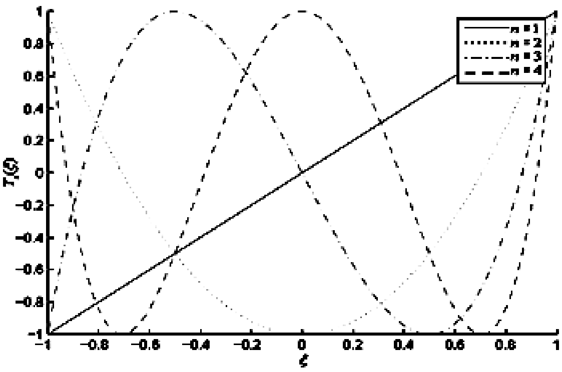


Figure 7. Chebyshev polynomials of different orders

The use of the Chebyshev polynomials makes the integrals required to evaluate these coefficients quite straightforward. These polynomials are given by:

$$T_n(\xi) = \cos(n \arccos(\xi)) \tag{7}$$

where $-1 \le \xi \le 1$ $\quad n = 0,1,2,.....$

and satisfy the following weighted orthogonality property:

$$\int_{-1}^{1} w(\xi) T_n(\xi) T_m(\xi) d\xi = \begin{cases} 0 & n \ne m \\ \pi/2 & n = m \ne 0 \\ \pi & n = m = 0 \end{cases} \tag{8}$$

where $w(\xi) = (1-\xi^2)^{-1/2}$ is the weighting function. Note that this orthogonality property applies only when x is within the interval [-1, 1]. Therefore, the variables x, $\dot{x}$ and v have to be normalized, using the change of coordinates.

Using the Chebyshev polynomials as defined by equation (7) when estimating the damping force, the following equation can be used,

$$T_n(\xi) = \xi^n - \left(\frac{n}{2}\right)\xi^{n-2}(1-\xi^2) + \left(\frac{n}{4}\right)\xi^{n-2}(1-\xi^2) \tag{9}$$

Some particular Chebyshev polynomials derived from this formula are presented (Hassan Metered et al, 2009)

$$T_0(x) = 1 \tag{10}$$

$$T_1(x) = x \tag{11}$$

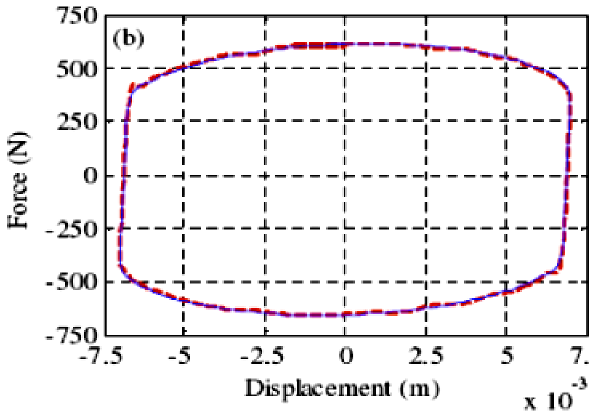
$$T_2(x) = 2x^2 - 1 \tag{12}$$

$$T_3(x) = 4x^3 - 3x \tag{13}$$

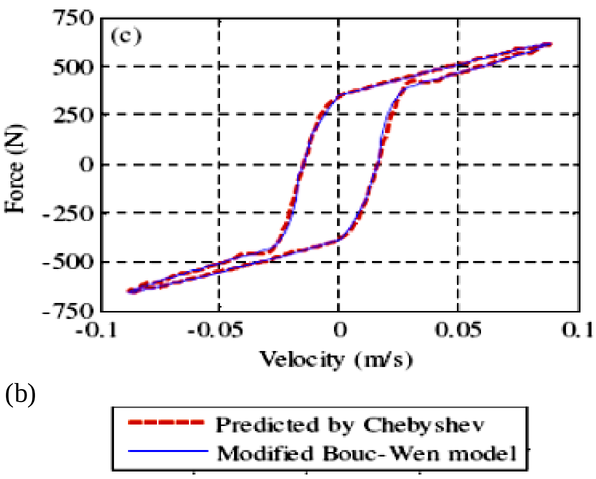
$$T_4(x) = 8x^4 - 8x^2 + 1 \tag{15}$$

$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x) \tag{16}$$

Caparison between Chebyshev polynomial and modified Bouc-Wen model is shown in Figure8.



(a)



(b)

Figure 8. Validation of Chebyshev polynomial with modified Bouc-Wen model

(a) Force-displacement loop (b) Force-velocity loop

4. Conclusion

In this paper, nonparametric models of MR damper are briefly reviewed. Nonparametric models establish a relationship between measured quantities, by purely mathematical means; the occurring parameters do not have a direct physical meaning. A literature survey indicates that, non-parametric models can effectively represent MR damper behavior. The merits of the non-parametric modeling method are that they can avoid the pitfalls of parametric approaches while being robust and applicable to linear, non-linear and hysteresis system. In order to validate the obtained model, the measured damper force and the predicted damper force obtained from the model are compared. It is clearly observed that the measured damper force is well predicted by the nonparametric MR damper model.

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