

Nonparametric Identification Modeling of Magnetorheological Damper Using Chebyshev Polynomials Fits

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ABSTRACT

The magnetorheological (MR) damper is one of the most promising new devices for vehicle vibration suppression because it has many advantages such as mechanical simplicity, high dynamic range, low power requirements, large force capacity and robustness. The damper offers a compromise solution for the two conflicting requirements of ride comfort and vehicle handling.

In this paper, a new approach for studying the dynamical behavior of an MR damper is presented. It consists of a three dimensional interpolation using Chebyshev orthogonal polynomial functions to identify the damping force as a function of the displacement, velocity and input voltage. The identification and its validation are done in both simulation and experimentation. In the former case the data are generated by solving the modified Bouc-Wen model. In the experimental approach, the data are generated through dynamic tests with the damper mounted on a tensile testing machine. In either case, validation data sets representing a wide range of working conditions of the damper show that the use of Chebyshev interpolation to predict the damping force for known displacement, velocity and voltage is reasonably accurate.

INTRODUCTION

Magnetorheological (MR) dampers are semi-active control devices that have received considerable interest in recent years due to their mechanical simplicity, high dynamic range, low power requirements, large force capacity and robustness. They are useful devices for vibration control in many applications such as civil, aerospace and vehicle engineering. MR fluids respond to a magnetic field with a

dramatic change in rheological behavior. These fluids can reversibly and instantaneously change from a free-flowing liquid to a semi-solid with controllable yield strength when exposed to a magnetic field [1].

Identification techniques for modeling the dynamic behavior of MR dampers can be broadly classified into two categories: parametric and non-parametric identification techniques. Parametric models are based on mechanical idealization involving representation by an arrangement of springs and viscous dashpots [2-6]. The most recent parametric model is the modified Bouc-Wen model [2]. This is a semi-empirical relationship in which 14 parameters are determined for a given damper through curve fitting of experimental results.

Unlike parametric models, non-parametric models do not make any assumptions on the underlying input-output relationship of the system being modeled. Consequently an elevated amount of input/output data is used to identify the system, enabling the subsequent prediction of the system's response to arbitrary inputs. Proposed models in this category are based on neural networks, neuro-fuzzy modeling, and Restoring Force Surface techniques (e.g. Chebyshev polynomial interpolation).

So far, the nonparametric techniques used for identifying MR dampers have involved neural networks and neuro fuzzy models. In [7, 8] a feed forward neural network and recurrent neural network were used. The training of the network depends on the input and output data sets obtained from experimental results or from a mathematical simulation of the MR fluid dampers. The modeling of MR fluid dampers with an adaptive neuro-fuzzy inference system (ANFIS) was proposed in [9].

An alternative non-parametric identification approach is through the Restoring Force Surface method, specifically the Chebyshev polynomial fitting. The advantage of this method is that it offers an explicit functional representation of the output variable (damping force in this case), in terms of the instantaneous values of the inputs. This is in contrast to the Bouc-Wen parametric approach and the neural network approach, which require time histories of the input variables to produce a prediction of the force.

Up to now, the Restoring Force Surface method has only been used on electrorheological (ER) dampers. In [10], a Chebyshev polynomial fit was used to approximate the force generated by an ER test device. For fixed electric field strength (and fixed excitation frequency) the restoring force of the ER damper was predicted by an analytical function constructed by two dimensional (2D) orthogonal Chebyshev polynomials fits. An extension of the previous curve fitting method to three dimensions (3D) was done by [11]. They related the restoring force of an ER fluid damper to the displacement, the velocity, and the electric field strength.

In the present paper, Chebyshev orthogonal polynomials fits are applied for the first time for the non-parametric identification modeling of MR fluid dampers. The damping force will be expressed as a function of the displacement, velocity and input voltage. This functional representation could then be used to predict the damping force for different operating conditions, under any desired combination of voltage, amplitude, and frequency of the excitation signals, within the limits of the interpolation. It should be noted that in this research the MR damper force is regarded as independent of temperature. In fact in [2] it is observed that this assumption is reasonable over a broad temperature range (-40 to 150°C). The identification and its validation will be done for both simulated data (from the modified Bouc-Wen model) and experimental data.

The experimental setup is described in the next section, which is followed by a brief background to the modified Bouc-Wen model. The Chebyshev polynomial fitting procedure and the results obtained are then presented.

MR FLUID DAMPER AND TEST SETUP

An MR damper typically consists of a piston rod, electromagnet, accumulator, bearing, seal, and damper cylinder filled with MR fluid (Figure 1). The magnetic field generated by the electromagnet changes the characteristics of the MR fluid, which consists of small magnetic particles in a fluid base. Consequently, the strength of the electromagnet's input current determines the physical characteristics of the MR dampers. The damper used in this research is the Lord RD-1005-3.

Continuously variable damping is controlled by the increase in yield strength of the MR fluid in response to magnetic field strength. In this damper, MR fluid flows from a high pressure chamber to a low pressure chamber through an orifice in the piston head. The damper is 209 mm long in its extended position, and the main cylinder is 38 mm in diameter. The main cylinder houses the piston, the magnetic circuit, an accumulator, and 50 ml of MR fluid. The damper has a ± 52 mm stroke. The magnetic field, which is perpendicular to the fluid flow, is generated by a small electromagnet in the piston head. Forces of up to 3 kN can be generated with this device.

The MR damper was tested by using the Electro-Servo Hydraulic (ESH) tensile testing machine, as shown in Figure 2a. The schematic diagram of the test setup is illustrated in Figure 2b. The ESH test machine has an upper and lower head with grippers that can grasp the dampers in the proper place. The upper head is attached to the hydraulic cylinder that can move up, down and take an external signal. The lower head incorporates a load cell allowing the operator to measure the force applied to the MR damper. The MR damper is first mounted in its position by the grippers; preliminary tests are then conducted to measure the response of the damper under various operating conditions. In each test, the hydraulic actuator drives the upper head, while the lower head is held fixed, according to data sets displayed in table 2. An LVDT sensor was integrated with the test machine to measure the displacement of the damper. Also, an OPTIPACT speed sensor was installed to measure the damper piston velocity. The damping force, displacement, and velocity are measured and fed through a data acquisition card to a PC computer. The current excitation was provided by a DC power supply and a thermocouple was also fixed on the damper body to assure that the test is accomplished within the range of $32 \pm 10^{\circ}\text{C}$

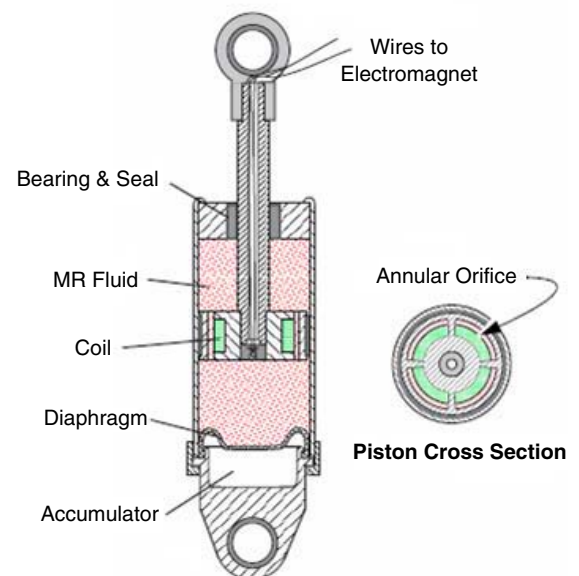


Figure 1 Small scale MR fluid damper

THE MODIFIED BOUC-WEN MODEL

The mechanical idealization on which the modified Bouc-Wen model is based is illustrated in Figure 3 [2]. The phenomenological model is governed by the following equations:

$F = c_1 \dot{y} + k_1(x - x_0)$ (1)

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

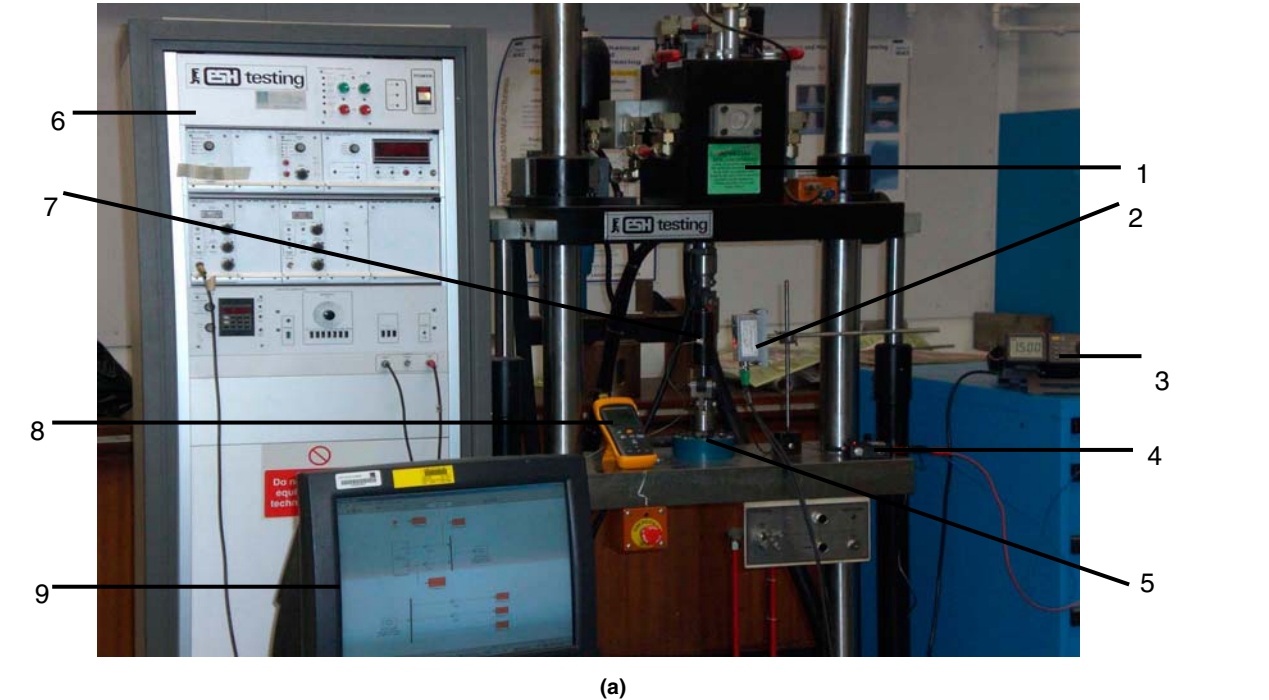
$\dot{y} = \frac{1}{c_0 + c_1}[\alpha z + c_0 \dot{x} + k_0(x - y)]$ (3)

$\alpha = \alpha(u) = \alpha_a + \alpha_b u$ (4)

$c_1 = c_1(u) = c_{1a} + c_{1b} u$ (5)

$c_0 = c_0(u) = c_{0a} + c_{0b} u$ (6)

$\dot{u} = -\eta(u - v)$ (7)



- 1- Hydraulic actuator 2- Speed sensor 3- Voltmeter 4- Wonder box 5- Load cell 6- Control panel 7- MR damper 8- Thermometer 9- PC computer 10- Upper head 11- Lower head 12- Interface part 13- Voltage signal 14- Displacement signal 15- Force signal 16- LVDT

Table 1: Parameters for the model of MR fluid damper [5]

Parameter	Value	Parameter	Value
c_{0a}	784 Nsm ⁻¹	α_a	12441 Nm ⁻¹
c_{0b}	1803 NsV ⁻¹ m ⁻¹	α_b	38430 NV ⁻¹ m ⁻¹
k_0	3610 Nm ⁻¹	γ	136320 m ⁻²
c_{1a}	14649 Nsm ⁻¹	β	2059020 m ⁻²
c_{1b}	34622 NsV ⁻¹ m ⁻¹	A	58
k_1	840 Nm ⁻¹	n	2
x_0	0.0245 m	η	190 s ⁻¹

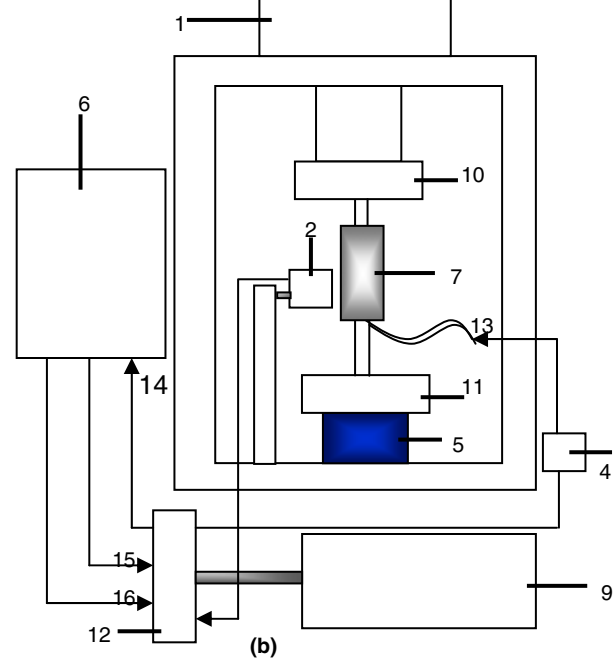


Figure 2. (a) Photo of Experimental Setup and ESH Machine
(b) Schematic Diagram of the Test Setup

where x and F are the displacement and the force generated by the MR fluid damper respectively; y is the internal displacement of the MR fluid damper; u is the output of a first-order filter and v is the command voltage sent to the current driver. In this model, the accumulator stiffness is represented by k_1 ; the viscous damping observed at large and low velocities are represented by c_0 and c_1 , respectively. k_0 is present to control the stiffness at large velocities; x_0 is used to account for the effect of the accumulator. α is the scaling value for the modified Bouc–Wen model. The scale and shape of the hysteresis loop can be adjusted by γ, β, A and n . A total of 14 model parameters [5], which are given in table 1, are obtained to characterize the MR fluid damper using experimental data and a constrained nonlinear optimization algorithm. The modified Bouc–Wen model is the most popular model for studying the dynamic behavior of MR dampers theoretically. It is used in various engineering systems with different control strategies to implement the MR damper and study system performance.

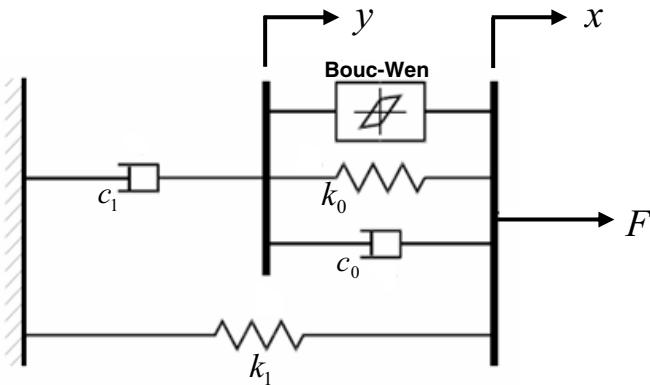


Figure 3 Modified Bouc-Wen Model

CHEBYSHEV POLYNOMIALS FITS

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

$$F(x, \dot{x}, v) \approx \hat{F}(x, \dot{x}, v) = \sum_{k,l,z=0}^{K,L,Z} C_{klz} T_k(\tilde{x}) T_l(\tilde{\dot{x}}) T_z(\tilde{v}) \quad (8)$$

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

$$T_n(\xi) = \cos(n \arccos(\xi)) \quad (9)$$

where

$$-1 \leq \xi \leq 1 \quad n = 0, 1, 2, \dots$$

and satisfy the following weighted orthogonality property:

$$\int_{-1}^1 w(\xi) T_n(\xi) T_m(\xi) d\xi = \begin{cases} 0 & n \neq m \\ \pi/2 & n = m \neq 0 \\ \pi & n = m = 0 \end{cases} \quad (10)$$

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

$$\begin{aligned} \eta &= \frac{2x - x_{\max} - x_{\min}}{x_{\max} - x_{\min}}; \\ \omega &= \frac{2\dot{x} - \dot{x}_{\max} - \dot{x}_{\min}}{\dot{x}_{\max} - \dot{x}_{\min}}; \\ \psi &= \frac{2v - v_{\max} - v_{\min}}{v_{\max} - v_{\min}} \end{aligned} \quad (11)$$

The damping force fit is performed over data generated from not only numerically solving the Modified Bouc–Wen model but also experimental dynamic results with an ESH test machine. Thus, the normalization limits $x_{\min}$, $x_{\max}$, $\dot{x}_{\min}$, $\dot{x}_{\max}$, $v_{\min}$, and $v_{\max}$ are defined beforehand. Obviously, these limits depend on the mechanical system in which the damping force is incorporated. Hence, in order to avoid incorrect evaluations of the damping force, the normalization limits should be set so that a wide range of instantaneous motions is covered. Using the Chebyshev polynomials as defined by Eq. 9 when estimating the damping force, one would better use the form

$$T_n(\xi) = \xi^n - \binom{n}{2} \xi^{n-2} (1 - \xi^2) + \binom{n}{4} \xi^{n-4} (1 - \xi^2)^2 - \dots \quad (12)$$

Some particular Chebyshev polynomials derived from this formula are presented in the appendix A. It was observed during numerical tests that the use of equation (12) permits a certain level of extrapolation without distorting the values of the damping force. The presence of the arc-cosine in equation 9 prevents the normalized variables from exceeding the limit values of 1 and -1, thus preventing the possibility of extrapolation if this equation is employed [12].