2014

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Gangrou Peng
University of Wollongong, gp191@uowmail.edu.au

Weihua Li
University of Wollongong, weihuali@uow.edu.au

Haiping Du
University of Wollongong, hdu@uow.edu.au

Huaxia Deng
Hefei University of Technology

Gursel Alici
University of Wollongong, gursel@uow.edu.au

Publication Details

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Disciplines
Engineering | Science and Technology Studies

Publication Details

This journal article is available at Research Online: http://ro.uow.edu.au/eispapers/3169
Modelling and Identifying the Parameter of a Magneto-rheological Damper with a Force-Lag Phenomenon

G.R. Peng¹, W.H. Li¹*, H. Du², H.X. Deng³, and G. Alici¹

¹School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Wollongong, NSW 2522, Australia
²School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Wollongong, NSW 2522, Australia
³School of Instrument Science and Opto-electronics Engineering, Hefei University of Technology, Hefei, Anhui, 230009, China

*Corresponding authors: weihuali@uow.edu.au

Abstract

In this study a model based on the Bouc-Wen-Baber-Noori (BWBN) method was proposed to describe the distorted hysteric behavior of a self-constructed magnetorheological (MR) damper whose mechanical performance was measured with an Instron test machine. The experimental results indicated that the MR damper exhibited a force-lag phenomenon. The parameters of the modified BWBN model were identified with the MATLAB SIMULINK design and optimization toolbox. A comparison between the experimental results and modeling predictions revealed that the proposed model could well present the force-lag phenomenon.

Keywords: MR damper, modeling, force-lag phenomenon, parameter identification, optimization

Introduction

Magneto-rheological fluids are suspensions of micro-sized magnetic ironic particles dispersed in non-magnetic carrying fluids that can form micro structures that look like chains, in the presence of an external magnetic field, and by doing so they exhibit increased viscosity and sound yield stress. Apart from that the fluids’ rheological properties can alternate continuously and reversibly in matter of milli-seconds, characteristics which have inspired the design of a large variety of MR devices [1, 2]. Among the numerous applications of MR apparatus, studies associated with an MR damper controlling semi-active suspension systems and vibration attenuation applications of civil structures are very attractive [3,4]. MR dampers have the advantage of being safe from faults, they consume low power, the force is controllable, they respond rapidly, and so on [5,6], but their non-linear force/displacement and hysteretic force/velocity characteristics are very complex. This hinders their widespread use because the design of a proper control strategy for MR dampers is based on a tractable model of their behavior. This means that having a reliable model of an MR damper is a prerequisite before any applicable controller can be designed [7, 8].

Many models, usually in the form of differential equations with several parameters to control their damping performance have been proposed because the damping force depends not only on the current that activates the magnetic field, it also depends on working conditions such as the stroke and frequency at which the MR damper moves.
In light of this description, the hysteretic characteristics of an MR damper can be expressed as follows, as a function of current, displacement, velocity, and acceleration:

\[ F(t) = f(I, x, \dot{x}, \ddot{x}) \]  

(1)

Where \( F(t) \) is the damping force, \( I \) is the applied current, \( x \) is displacement of the piston, and \( \dot{x} \) and \( \ddot{x} \) are the velocity and acceleration of the piston. Stanway et al. [9] developed a Bingham plastic model, which is a simple parametric model, to summarise the damping hysteresis phenomenon that contains a coulomb friction element as a signum function to vibration velocity in parallel with a viscous dashpot element. Li et al. proposed a visco-elastic plastic model by separating the varied working conditions of MRF in the damper system because the MR fluid is often considered to behave like a visco-elastic body in pre-yield mode and then viscous behaviour in the post-yield region where the effects of inertia begin to take effect. [10]. Bouc and Wen proposed a Bouc-wen hysteresis model which possesses an appealing mathematical simplicity and has the ability to represent a large class of hysteric behaviour [11, 12]. The Bouc-wen model has been used extensively to simulate hysteresis loops because it can describe the hysteric behaviour of the force displacement and force velocity accurately. In this model, the force in a non-linear hysteretic system is divided into two parts: a non-hysteresis component that possesses a functional relationship with instantaneous displacement and velocity; and an evolutionary component that represents the hysteretic nature with respect to the time history of imaginary displacement. Dyke et al. [13] further modified the typical class of the Bouc-Wen model by introducing another internal displacement and proposing that some parameters of the dampers’ model can be described as a function of external field excitation which would track the behaviour of the MR damper better at varied levels of magnetic field strength. Moreover, other models that use polynomial curve-fitting [14, 15], black box [16] and non-parametric approaches also exist [17], but these types of MR damper model are more flexible even though the physical definition of some parameters in the model cannot be expressed explicitly.

There are three major methods used to identify the parameters in the model, the separately constrained non-linear optimisation method, the analytical method, and stochastic search method. The constrained non-linear optimisation method [4, 12] is used the most. Due to there being more complex forms of Bouc-Wen type models, the analytical method that uses the relationship between the model parameters and hysteresis loops of MR damper models to identify parameters has been adopted [18, 19]. The Stochastic Search Method, like the genetic algorithm (GA), is widely used because of its flexibility in solving complicated dynamic problems [20, 21].

Established MR damper models have been successful applied to countless research projects and commercial applications of the MR damper [22, 23], but they fail to take the distorted hysteresis loops, which exist widely in many MR dampers [24], into consideration. For instance, the force–lag phenomenon, which is mainly caused by fluid compressibility and vacuum for flow block at active gap of MR dampers, is shown in Fig. 1. In this figure, the hysteretic loop of MR dampers has some distortions, phenomena that are commonly observed in many applications [25]. Most current studies focused on the measurement as well as the solution for these distortions, whereas modeling the force-lag phenomenon is rarely reported. Thus it is very necessary to study the method for modelling the deformed hysteretic loops of MR dampers.
In this study, a model that can describe the deformed hysteretic loops of MR dampers is proposed. To begin, the experimental setup of the dynamical test of the self-manufactured MR damper is introduced and the results of the hysteresis loops of the experiments are given, after which the conventional Bouc-Wen model was used for the analysis, and then the shortage of this model is discussed. A modified model is then presented and successfully validated by the experimental results.

**Fig.1 Distorted Force-Displacement Relationship Observed from the Damper Test**

**MR Damper and Experimental Setup**

An MR damper is structurally similar to a traditional fluid damper, except that the hydraulic fluid can change its viscosity when an external magnetic field is applied, because the magnetic carbonyl iron particles inside the MR fluid align themselves, an action that solidifies the MR fluid and generates considerable damping force. The MR damper shown in Fig.2, is designed with a fluid contained within a cylinder that can flow through a small orifice. An excitation coil is built into the piston head to guarantee the magnetic field needed to activate the MR fluid when the current is applied.
Fig. 2 (a) Schematic of MR damper (b) Side view of assembled MR damper

The experimental setup is given in Fig. 3. The damper is driven by an Instron tester, and the force sensor is used to collect the measured damping force data. In this experiment the frequency of the sinusoidal load was 1Hz, and the amplitude was 10mm, as shown in Fig. 4 (a), and the electrical excitation level ranged from 0-0.4 Amps. Because the phase of MR fluid inside the damper might not be transformed evenly when an excitation current is applied, this could create extra friction when the device is subjected to vibration; apart from which any air trapped inside the device would distort the hysteretic loop. The resulting damping force at a magnetization current of 0.4A is shown in Fig. 4 (b) and the corresponding hysteresis loops of force/displacement and force/velocity are presented in Fig. 4 (c) and Fig. 4 (d), respectively.

Fig. 3 (a) Schematic of the Instron system (b) Picture of experimental setup

(a) Damper displacement  
(b) Damper force
Fig. 4 shows the distortion of the hysteretic loop, which is unlike the hysteretic loop in a conventional MR damper. This means that a model which gives a suitable image of damper behaviour must be chosen.

**Identifying the Parameter with the Bouc-Wen Model**

In order to describe how the damper behaves, a conventional Bouc-Wen Model, which are widely used to describe the hysteretic loops of MR dampers accurately, was initially used to assess the capability of a conventional Bouc-Wen Model in the case of deformed hysteresis.

The Bouc-Wen model is a set of differential equations that describe the hysteretic characteristics of the MR damper whose schematic is presented in Fig.5. The equations are given as follows:

\[ F = c_0 \dot{x} + k_0 (x - x_0) + \alpha z \]  \hspace{1cm} (2a)

\[ \dot{z} = -\gamma |\dot{z}|^{n-1} - \beta |\dot{z}|^{n} + A \dot{x} \]  \hspace{1cm} (2b)

Where \( c_0, k_0, \alpha, \beta, \gamma, x_0, n \) and \( A \) are referred to as the parameters of the shape of the Bouc-Wen model. In equation (2a) the first term describes the force associated with viscous dissipation, the second term gives the proportion of stiffness of the total damping force and the last term is the evolutionary force due to hysteresis, which is related to the imaginary displacement \( z \), as presented in equation (2b) [26].
To estimate the parameters of the model, an error function is introduced as an objective function:

\[ J = \sum_{i=1}^{N} (F_{ei} - F_{pi})^2 \]  

(3)

where \( F_e \) and \( F_p \) are the experimental damping force and estimated damping force, as defined in Eq.(3), and \( N \) is the number of experimental data. Optimization was carried out using the SIMULINK Design and Optimization toolbox. In this optimisation process, the inputs are the measured displacement and velocity, together with the measured damping force. In this framework of the SIMULINK software, the measured displacement and velocity are used as initial parameters through interconnected iconic programming (as highlighted in Fig.6) to calculate the damping force by varying a vector of unknown parameters, and then this calculated value is compared with the experimental facts.

Fig.6 Schematic of SIMULINK iconic programming of the Bouc wen Model

In this identification, the parameters \( c_0, k_0, x_0 \) and \( n \) significantly affect the shape of the simulated hysteresis loops at different levels of excitation current so they are considered to be functions of the excitation current, while the others are kept as constants [27]. The estimated parameters are \( A=100, \alpha=70, \beta=50, \) and \( \gamma=50 \), while the results for the variables are listed in Table.1. The comparison between the predicted hysteresis characteristics and actual experimental results is presented in Fig.7 for an excitation current \( I=0.4A \), together with comparisons of the different levels of current shown in Fig.8 and Fig.9.

(a)  (b)
It is obvious from Fig.7-9 that the predicted hysteretic loops are more elliptical in shape, despite the scale being roughly coincident to each other, and they are unable to accurately match the deformed hysteretic characteristic exhibited by the experimental data.

In conclusion, the above analysis reveals that the conventional Bouc-Wen model is unable to scale the force-lag phenomenon, which means that a modified model that will accurately describe the hysteretic deformation of an MR damper is required.

**Table.1 Variables as function of excitation current**

<table>
<thead>
<tr>
<th>Current Level</th>
<th>$c_0$</th>
<th>$k_0$</th>
<th>n</th>
<th>$x_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0A</td>
<td>5.0743</td>
<td>5.106</td>
<td>1.1678</td>
<td>0.93249</td>
</tr>
<tr>
<td>0.05A</td>
<td>5.8399</td>
<td>8.4644</td>
<td>1.0858</td>
<td>1.7521</td>
</tr>
<tr>
<td>0.1A</td>
<td>6.4582</td>
<td>11.955</td>
<td>1.0017</td>
<td>1.3926</td>
</tr>
<tr>
<td>0.2A</td>
<td>8.6107</td>
<td>23.51</td>
<td>1.0029</td>
<td>0.91494</td>
</tr>
</tbody>
</table>
Modelling Analysis of the Force-Lag Phenomenon and Parameter Identification

If the structures are subjected to cycles of inelastic deformation, the structural response can be characterised by repeated excursions into the inelastic range, which is referred to as pinching [28]. As a result, the stiffness, strength, or both, may deteriorate, and energy will be dissipated through a degrading hysteretic behaviour. Based on the Bouc-Wen hysteretic model, Baber and Noori proposed a smoothed hysteretic slip model with a so called ‘slip-lock’ element that can describe the ‘pinching’ of the hysteresis loop [29]. Considering the onset of deformation of the MR damper experimental data and the fact that the standard Bouc-Wen model cannot describe the hysteretic behaviour of the damper, the BWBN model was adopted in its place.

The set of differential equations that express the restoring force is as follows:

\[
F = c k_e (u(t) - u_0) + (1 - \alpha) k_e z(t) + c \dot{u}(t) + f_d
\]  

(4a)

Eq. 4a represents the restoring force where the main parts are the elastic and hysteretic components, \( \alpha \) is the ratio of post-yield stiffness to elastic stiffness, and \( k_e \) is considered to be the elastic stiffness. The original form of the BWBN model only consisted of these two parts to calculate the elastic and inelastic deformation, and they were unable to describe the bending that occurred at the peak of each damping cycle in the Force/Time (Fig.4b) figure of the experimental data. This is also why finding a proper \( k_e \) in Force/Displacement (Fig.4c) figure was difficult. In order to solve that problem, a small dashpot element of \( c \) and an initial offset force were introduced into the proposed model as the last two items presented. \( u(t) \) is the MR damper’s displacement as a function of time and \( z(t) \) is the imaginary hysteretic displacement which is given by the following equations:

\[
\dot{z} = h(z) \left\{ \frac{A u(t) - v \left( \beta \mu \left| u^\nu \right| u + \eta u \left| u^\nu \right| \right)}{\eta} \right\}
\]

(4b)

\[
h(z) = 1.0 - \zeta_1 \exp \left[ -\left( z \text{sgn}(u) - q z_u \right)^2 / \zeta_2^2 \right]
\]

(4c)

\[
z_u = \left[ \frac{1}{\nu(\beta + \gamma)} \right]^{1/2}
\]

(4d)

\[
\zeta_1(\varepsilon) = \frac{\xi_0 (1 - \exp(-p \varepsilon))}{\zeta_2 (\varepsilon) = (\psi_0 + \delta_\nu \varepsilon)(\lambda + \zeta_1)}
\]

(4e)

\[
\varepsilon = \int z u d t
\]

(4f)

\[
\nu(\varepsilon) = 1 + \delta_\nu \varepsilon
\]

(4g)
The parameters $A$, $\beta$, $\gamma$, and $n$ control the shape of hysteresis loop, while $\nu$ and $\eta$ are respectively the strength and stiffness degradation parameters. $0 \leq \varsigma < 1$ controls the severity of pinching or magnitude of the initial drop in slope $(dz/du)$, $\varsigma_2$ causes the pinching region to spread, $z_u$ is the ultimate value of $z$ and is given by Eq. (4d), and $q$ is a constant that sets a fraction of $z_u$ as the pinching level, $\varepsilon$ represents the dissipation of hysteretic energy as given in Eq.(4g), which thus decides the magnitude of $\varsigma_1$ and $\varsigma_2$. Moreover, $p$ is a constant that controls the rate of initial drop in the slope, $\xi_{10}$ is the measure of total slip (a larger value of $\xi_{10}$ produces a more severe pinching), $\psi_0$ is a parameter that contributes to the amount of pinching, $\delta_\nu$ is a constant specified for the desired rate of pinching spread, $\lambda$ is a parameter that controls the rate of change of $\varsigma_1$ as $\varsigma_2$ changes. It is also worth noting that if $h(z)=1$ and $\delta_\nu=\delta_\eta=0$, this pinching model is reduced to the Bouc-Wen model. By observing the differential equations, the total number of unknown parameters is 16, with $\xi_{10}$, $\delta_\nu$, $\delta_\eta$, $k_c$, $f_d$, $u_0$, $c$ being variables, $\alpha = 5e^{-4}$, $\beta = 0.5$, $n = 2$, $q = 0.1$, $\lambda = 0.05$, $p = 1$, $\psi_0 = 0.2$, $\delta_\nu = 0.003$ are the estimated constants [30].

The method of identifying the parameter of the proposed model is similar with the identification procedure presented in section 3. A similar objective function is applied to compare the discrepancy between the simulated and actual hysteretic loops under the framework of SIMULINK Design and Optimisation Toolbox, as given in Fig.10, where the SIMULINK programming for the modified BWBN model is presented. Fig.11-13 shows the comparison of predicted hysteretic MR damper behaviour and the experimental results. Table.2 summarises the variables as functions of the excitation current.

Fig.10 Schematic of SIMULINK iconic programming of modified Bouc-wen-Baber-Noori (BWBN) Model
Fig. 11 Comparison of predicted/experiment hysteresis characteristics at current level $I=0.4A$

Fig. 12 Comparison of predicted/experiment hysteresis characteristics at current level $I=0.3A$

Fig. 13 Comparison of predicted/experiment hysteresis characteristics at current level $I=0.2A$
Table 2 Variables as function of excitation current

<table>
<thead>
<tr>
<th>Current Level</th>
<th>$\xi_{10}$</th>
<th>$\delta_v$</th>
<th>$\delta_\eta$</th>
<th>$k_e$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0A</td>
<td>0.85</td>
<td>0.0099993</td>
<td>1.9725e-9</td>
<td>160</td>
<td>3.4</td>
</tr>
<tr>
<td>0.05A</td>
<td>0.89596</td>
<td>0.0099853</td>
<td>1.0474e-8</td>
<td>220</td>
<td>3.5</td>
</tr>
<tr>
<td>0.1A</td>
<td>0.93992</td>
<td>0.0035258</td>
<td>5.1763e-7</td>
<td>260</td>
<td>3.6</td>
</tr>
<tr>
<td>0.2A</td>
<td>0.95704</td>
<td>0.0027814</td>
<td>6.3162e-7</td>
<td>440</td>
<td>4</td>
</tr>
<tr>
<td>0.3A</td>
<td>0.97229</td>
<td>0.0045332</td>
<td>1.0188e-6</td>
<td>710</td>
<td>4.5</td>
</tr>
<tr>
<td>0.4A</td>
<td>0.98243</td>
<td>0.0011391</td>
<td>4.8445e-7</td>
<td>920</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Fig.11-13 clearly shows that the modified BWBN model can capture the distorted hysteretic behaviour of the MR damper. It should also be noted that the deformation of hysteretic loops in the experimental results are not symmetrical, which leads to some mismatches at the upper left corner or the lower right corner of the hysteretic Displacement/Force and Velocity/Force loops where the force-lag phenomenon takes place. Further theoretical study and modelling of this deformed hysteretic behaviour of MR damper will be carried out in the near future.

Conclusion

Current research regarding the modelling of MR damper has mainly focused on regular hysteretic loops or the novel numeric methodology applied in the procedure for identifying the parameters; any modelling of distorted hysteretic loops is rarely reported. In this paper we launched a study on the widely reported force-lag phenomenon of an MR damper based on a modification of the Bouc-Wen-Baber-Noori model, a model that can, to a certain extent, describe the pinching hysteretic behaviour. A conventional Bouc-Wen model was first used to describe the deformed hysteretic loops from the experimental results of MR damper tests. This investigation clearly showed that a conventional Bouc-Wen model was not valid for these deformed hysteretic loops, and the slip effect of an MR damper was not considered in that model. So to describe the behaviour of the deformed damper seen in the damper test, a modified BWBN model was proposed to analyse the experimental results. The result shows that the proposed model could describe the distorted hysteretic loops of MR dampers. Finally, the asymmetric characteristics of distortions in the hysteretic loops were discussed, and the need for a more accurate model was pointed out.

Acknowledgements

This research is supported by the University of Wollongong UIC grant, and National Natural Science Foundation of China (Grant No: 51328502, and 51205100)
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