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Hysteretic Model for Magnetorheological Fluid Dampers using a Curve Fitting Approach

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This paper presents a novel and simple model that describes the hysteretic force-velocity relationship of Magneto-Rheological (MR) fluid dampers and proposes an approach for the model parameter identification. The model is developed by using the curve fitting technique. The MR damper hysteresis is represented as a mixture of sigmoidal and Gaussian functions, resulting in a significant reduction of model parameters. The identification is conducted by matching the simulated model output and experimental data while adjusting the model parameters for a minimum root-mean-square matching error. The results, compatible to the widely-adopted Bouc-Wen model, show advantages in reducing the model complexity and enabling a feasible control design for semi-active structural control with MR dampers.

Key Words: Magnetorheological fluid damper, Hysteresis modelling, Curve fitting.

1. Introduction

Natural hazards such as strong winds and earthquakes are challenges in the construction of structural buildings. As a result of this, many new and innovative concepts for structural control have been advanced and are at various stages of development. These control methodologies can be divided into three main categories: passive control, active control, and semi-active control approaches [1], [2]. The semi-active device has a prominent property in that it can be adjusted in real time without injecting energy into the controlled system. Since they offer the adaptability of active control without requiring large power sources, these devices can even operate on battery power alone, which is very important as the main power may fail during seismic events.

The Magnetorheological (MR) damper has been chosen as an attractive candidate incorporating into semi-active control applications. The damper contains the MR fluid, which has tiny magnetic particles immersed in a carrier such as silicon oil. The fluid may change rapidly from its liquid phase to the semi-solid phase under the influence of an external magnetic field, hence produces a change in the damping force [3]. However, a major drawback of the MR damper is the hysteresis in the force/velocity response. In order to use the device in building control systems, an accurate and simple model [4]-[8] is needed before controllers can be designed and implemented in practice [9].

The most commonly-used model in describing the damper hysteresis is the Bouc-Wen model. However, the identification of these model parameters is complicated due to a large number of parameters required and the coupled non-linear differential equations existing in the model.

An alternative model of hysteresis is presented in this paper, containing a smaller number of parameters. This method involves a sigmoid curve fitting of the hysteresis and a Gaussian curve to represent the thickness of the hysteresis. The resulting hysteresis is then derived from the addition and subtraction of these two curves. The accuracy will be assessed on the basis of the root-mean-square (RMS) error criterion against experimental data. The relationships between the input current and the parameters will also be identified.

The remainder of the paper is organized as follows. The MR damper is described in Section 2. The proposed model parameter identification procedure will be developed in Section 3. Results of model identification will be given in Section 4 and Section 5 contains the conclusion.

2. Magnetorheological Damper and Modelling

The MR damper may be viewed as a conventional hydraulic damper except that the contained fluid is allowed to change its viscosity upon the application of a magnetic field. The fluid is housed within a cylinder and flows through a small orifice and a magnetising coil is built in the piston or

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on the housing. Since the MR damper contains no moving parts other than the damper piston, this feature makes it more reliable and maintainable [4].

Among the models available for MR Dampers, the Bouc-Wen model is extensively used to represent hysteresis due to its ability in closely characterising the damper force and velocity relationship. A schematic of the model is shown in Fig. 1(a) while Fig. 1(b) shows typically the characteristics of hysteresis versus different applied currents to the MR damper.

The Bouc-Wen model hysteresis in the relationship between velocity and the damper force is described by:

$$F(x) = c_0\dot{x} + k_o(x - x_0) + \alpha z \tag{1}$$

where variable z is given as

$$\dot{z} = -\gamma z\,|\dot{x}|\,|z|^{n-1} - \beta\dot{x}\,|z|^{n} + \delta\dot{x} \tag{2}$$

In the equations above, x is the damper displacement, z is the hysteresis variable, $\alpha, \beta, \gamma, \delta, n, c_0, k_0$ are the model parameters to be identified. Here α is the hysteresis scaling factor, k_0 is the spring constant, c_0 is the dashpot constant, δ affects the rate of change of the hysteresis with respect to the piston velocity. The rest of the parameters (β, γ, n) affect the hysteresis rate. The Bouc-Wen model involves up to eight parameters to be identified and a time derivative ($\dot{z}$) that need to be solved for in order to represent the damper characteristics to a given accuracy. This will demand a heavy computational resource to accomplish the identification task. The focus of this paper is to propose a new characterisation of the behaviour of MR dampers, addressing both accuracy and simplicity, such that the model to be developed can be conveniently included in designing controllers for structure control.

3. **Hybrid Model Curve Fitting Approach**

In our proposed model, the average hysteresis is represented by a sigmoid function, as it is the most appropriate function for modelling the S-shape curve with the least number of parameters (three parameters required).

3.1 Mean value of the hysteresis

The hysteresis loop of the MR Damper used, a Lord RD 1005-3, shown typically in Fig. 2(a), can be described by two curves. The upper curve is F_1 when $\ddot{x} \geq 0$ while the lower curve is F_2 when $\ddot{x} < 0$. Furthermore, the mean value of the hysteresis is calculated by taking the average of every vertical sector in the hysteresis.

The mean values, indicated by the continuous line shown in Fig. 2(b), are given by

$$M_i = \frac{1}{n}\sum_{i=1}^{n}(F_{1i} + F_{2i}) \tag{3}$$

where i is the index of the velocity of the hysteresis curves; and F_{1i}, F_{2i} are the corresponding damper forces determined by the displacement polarity. The calculated means is further described by a sigmoid using three parameters. That is

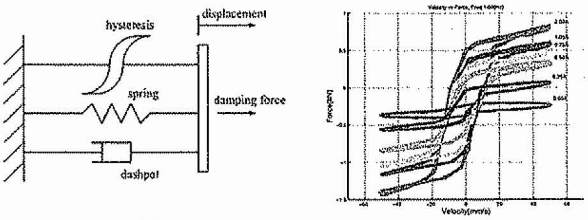
$$G(x) = a + \frac{b}{1 + \exp(c\dot{x})} \tag{4}$$

where a, b, c are the parameters to be identified.

3.2 Hysteresis thickness

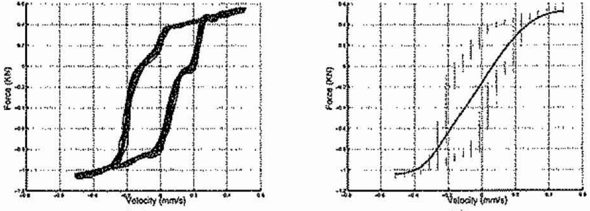
The thickness of the hysteresis can be estimated by taking the mean difference between the two upper/lower traces and the mean of the hysteresis. This is indicated by the discontinuous line in Fig. 3(a) and given by

$$T_i = \frac{1}{n}\sum_{i=1}^{n}(|F_{1i} - M_i| + |F_{2i} - M_i|) \tag{5}$$



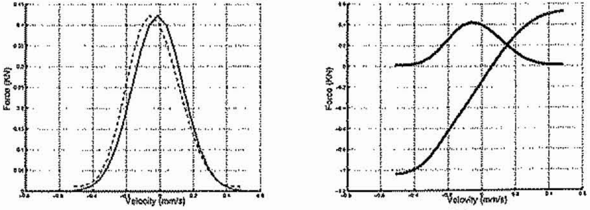
(a) (b)

Fig. 1. (a) Schematic of Bouc-Wen model (b) Hysteresis vs. current supplied



(a) (b)

Fig. 2. (a) Typical hysteresis (b) Mean curve of the hysteresis



(a) (b)

Fig. 3. (a) Thickness curve (b) Thickness and mean

To describe the thickness of the hysteresis more precisely, we use a Gaussian curve (continuous line), that also needs only a small number of parameters. The Gaussian curve is determined by

$$D(x) = r\exp(-0.5(\dot{x}/\sigma)^2)/(\sqrt{2\pi}\sigma) \qquad (6)$$

where r is the vertical scaling factor of the hysteresis, and the standard deviation σ here is the value that defines the width of the hysteresis.

Finally the addition and subtraction of these two curves, namely the mean and the thickness as depicted in Fig. 3(b), will form the hysteresis as eventually shown in Fig. 4. Now, the hybrid model hysteresis is proposed as described by the following equation:

$$F(x) = \begin{cases} F_1(x) = & G(x) + D(x), \quad \ddot{x} \geq 0 \\ F_2(x) = & G(x) - D(x), \quad \ddot{x} < 0 \end{cases} \qquad (7)$$

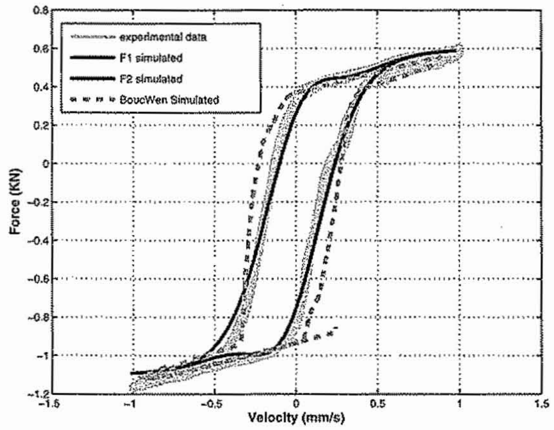


Fig. 4. Simulation of the new model, compared with the simulated hysteresis from the Bouc-Wen model

4. Results and Discussion

To verify that this model can handle a wide range of operating conditions, the displacements from different excitation and different currents were fed through the new model and results are compared with the recorded experimental data sets [3]. In test 1, the excitation was at 1 Hz and 4 mm peak value. In test 2; the excitation was 2 Hz and 8 mm peak. The control currents applied to the damper were set at 0 A, 0.25 A, 0.5 A, 0.75 A, 1 A and 2 A.

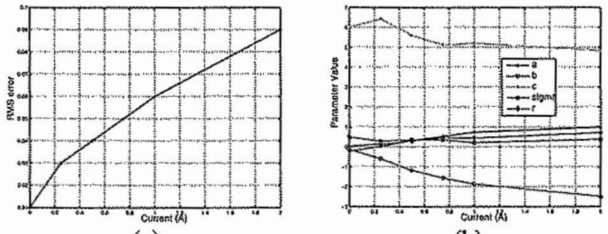
In order to choose the model parameters with a certain level of accuracy, a root-mean-square (RMS) error criterion (8) is used as given by

$$E_{rms} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(F_i^{Exp} - F_i^{Sim})^2} \qquad (8)$$

From the graph in Fig. 5(a), the RMS error versus the applied current indicates that the accuracy of this new model is acceptable as the RMS errors remain small as the current increases.

Furthermore, in order to investigate the relationship of the magnetisation current and other parameters in the new model, the values of all of the parameters are plotted against the supplied damper current. From the graph in Fig. 5(b), it is apparent that the relationships are linear for all parameters. Most of the values have a small rate of change except parameter c, this is due to the term $\exp(c\dot{x})$ in the sigmoid function. These values will have a strong influence on the shape of the hysteresis.

The results are shown below in comparison between the computed model and the experimental data. From these plots Fig. 6 and Fig. 7, it is observed that the identified parameters are able to reconstruct the hysteresis loop accurately, especially in the roll-off region where acceleration and velocity have opposite signs and the magnitude of the velocity is small.



(a) (b)

Fig. 5. (a) RMS error vs. supplied current (b) Typical current versus parameters value, frequency =1 Hz

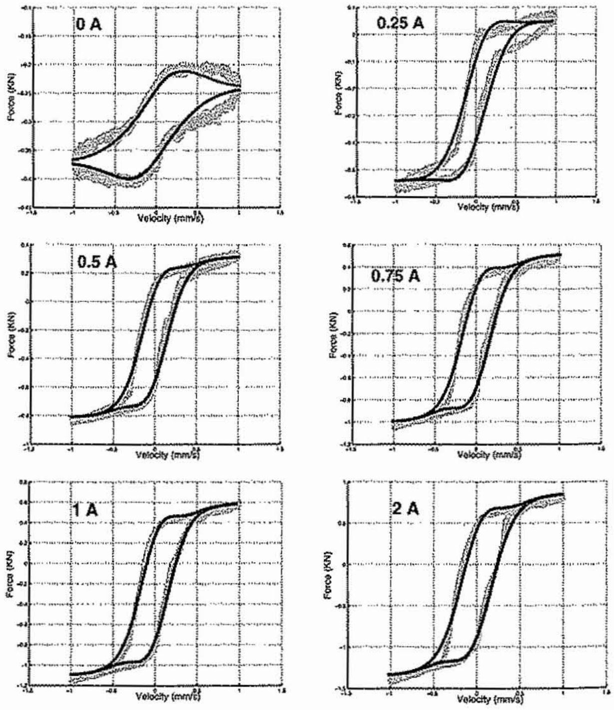


Fig. 6. Comparison of hysteresis from experimental (dotted) and simulated data (solid) - test 1

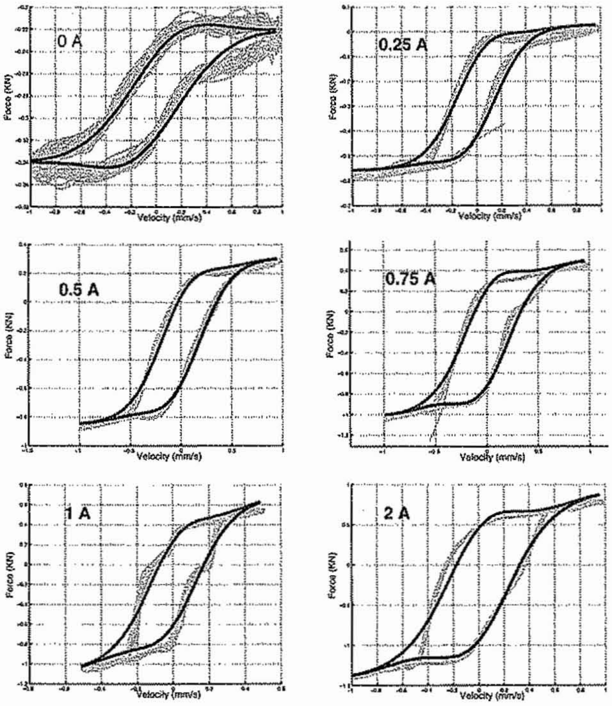


Fig. 7. Comparison of hysteresis from experimental (dotted) and simulated data (solid) - test 2

Table 1. Identified MR damper parameter vs. current at frequency = 1 Hz

Current(A)	*a*	*b*	*c*	*α*	*r*	rms
0.00	-0.24	-0.13	6.00	0.60	0.07	0.01
0.25	0.05	-0.59	6.43	0.35	0.15	0.03
0.25	0.32	-1.13	5.60	0.28	0.32	0.04
0.75	0.52	-1.52	5.11	0.28	0.45	0.05
1.00	0.60	-1.70	5.20	0.28	0.51	0.06
2.00	0.87	-2.22	4.83	0.30	0.65	0.09

Table 2. Identified MR damper parameter vs. current at frequency = 2 Hz

Current(A)	*a*	*b*	*c*	*α*	*r*	rms
0.00	-0.22	-0.12	4.75	0.50	0.04	0.01
0.25	0.03	-0.59	5.56	0.29	0.15	0.02
0.25	0.32	-1.18	4.40	0.36	0.30	0.04
0.75	0.53	-1.57	3.85	0.35	0.45	0.05
1.00	0.74	-1.86	5.64	0.22	0.45	0.06
2.00	1.00	-2.49	3.06	0.38	0.72	0.08

One drawback of this new model may be in that the resultant hysteresis loop does not fit very well at the high velocity region at a higher frequency (2 Hz), as can be seen in Fig. 6 and Fig. 7 in particular at currents of 0 A and 0.5 A. However, the error still remains small in the overall acceptable performance, as compared to the results given in [10], but here involving a smaller number of parameters.

The identified parameters, corresponding to different test conditions are summarized in Tables 1 and 2 above. The parameters listed are lying in the same order of magnitudes at different values of supplied currents. This observation supports the view that the proposed model is able to handle a wide range of operating conditions.

6. Conclusion

In this paper we have presented a new model for the MR damper force/velocity hysteresis characteristics. A hybrid curve fitting approach is proposed by using sigmoid and Gaussian functions to describe the force-velocity hysteresis. Our model requires as smallest as five parameters in comparison to eight parameters of the standard Bouc-Wen model and other models available in the literature. When compared with experimental data, the resulting model is also accurate in predicting the damper behaviour under a wide range of operating conditions. These results indicate that the proposed model can be effectively used for the controller design in the context of civil structure control

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References

[1] G. Yang, B. F. Spencer Jr, F. Billie, H. J. Jung and J. D. Carlson, *J. Eng. Mech.*, pp. 1107-1114, 2004.

[2] B. F. Spencer Jr. and M. K. Sain, *IEEE Control Systems Magazine*, Vol. 17, No. 6, pp. 19-35, 1997.

[3] S. L. Djajakesukma, B. Samali, J. Li and H. Nguyen, *Proc. of the 6th Intl. Conf. on Motion and Vibration Control*, Saitama, Japan, pp. 1197-1202, 2002.

[4] T. Butz and O. Von Butz, *App. Math. Mach.*, Vol. 82, pp. 3-20, 2002.

[5] A. N. Vavreck, *Smart Materials and Structures*, Vol. 11, pp. 596-598, 2002.

[6] X. Q. Ma, E. R. Wang, S. Rakheja and C. Y. Su, *Proc. 41st IEEE Conf. Decision Control*, Las Vegas, USA, pp. 1675- 1680, 2002.

[7] G. Jin, M. K. Sain and K. D. Pham, *Proc. American Control Conf.*, Arlington, pp. 429-434, 2001.

[8] N. M. Wereley, L. Pang, and G. M. Kamath, *J. Intelligent Material, Systems and Structures*, Vol. 9, No. 8, pp. 642-649, 1998.

[9] L. M. Jansen and S. J. Dyke, *J. Eng. Mech.*, pp. 795-803, 2000.

[10] N. M. Kwok, Q. P. Ha, T. H. Nguyen, J. Li and B. Samali, *Sensors and Actuators Pt A*, Vol. 132, pp. 441-451, 2006.

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