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REAL-TIME IDENTIFICATION OF MAGNETO-RHEOLOGICAL DAMPERS [1]

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Abstract: Modeling of magneto-rheological dampers to be used in semi-active control of civil engineering structures is addressed. The behavior of this kind of dampers is modeled through a first order Lugre dynamic friction model whose structure is analytically simpler than other dynamic friction models used in the literature. With this structure real-time parametric identification of the magneto-rheological damper is possible. Forces obtained with this modeling approach are in good agreement with those produced by other models.

Keywords: Semiactive control, adaptive control, nonlinear observers

1. INTRODUCTION

Protecting civil engineering structures from the damage induced by earthquakes is a subject of great importance. The tragic consequences of Kobe and Los Angeles earthquakes, to name just two of the most recent large events, are well known and remark the importance of structures protection. In recent years, there has been a significant amount of research in the areas of active, semi-active and passive control to protect civil engineering structures and reduce the damaged sustained by them when subject to seismic motion (Ramallo *et al.*, 1999; Ribakov and Gluk, 1999; Xu *et al.*, 2000; Nagarajaiah *et al.*, 2000; Zeng *et al.*, 2000).

In (Dyke *et al.*, 1996) and (Ramallo *et al.*, 1999) the benefits of semi-active control techniques are compared with those of active control. The authors conclusion is that both active and semi-active control techniques achieve better performance than passive technique when protecting multiple story buildings. They also point out that the performance of active and semi-active control techniques is very similar, although the later is less expensive and more reliable because of the limited power supply required for its operation.

One of the main devices used in semi-active seismic isolation and protection are magneto-rheological dampers (MR) (Dyke *et al.*, 1996; Spencer *et al.*, 1997). These devices are similar to viscous dampers although the fluid that they contain can change dramatically its viscosity properties when exposed to a magnetic field. These changes, in turn, induce a change in the dynamic properties of the structure in which MR are placed. Adjusting in real time this viscosity so as to optimize a given criteria is the basic goal of the semi-active control approach. There are several applications of this technology currently

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implemented (interested readers can consult, for example, (Xu *et al.*, 2000; Nagarajaiah *et al.*, 2000)).

To evaluate the effect of using and properly operate MR-dampers it is convenient to have a good mathematical representation of its dynamic behavior. In (Spencer *et al.*, 1997) the modeling of these dampers is extensively analyzed. The authors used a Bouc-Wen hysteric dynamic model (Wen, 1976) to represent the behavior of the damper. The results showed in (Dyke *et al.*, 1996) and (Spencer *et al.*, 1997) used experimentally generated curves of force versus velocity to optimize the parameters of such a model. The force versus velocity curves generated by using the mathematical model with the optimized parameters show good agreement with the experimental curves.

When using MR to implement semi-active control schemes for building seismic isolation, the characteristics of the damper, magnetizable fluid and the structure are not perfectly known, as is normally the case with parameters of models in all engineering modeling applications. The traditional approach has been to use the parameters derived from the experimental data for a similar damper as the true parameters in the control applications.

In this paper a different approach is used for MR-damper modeling. A LuGre dynamic friction model (Canudas *et al.*, 1995) is introduced to describe the behavior of the MR-damper. There are two main advantages gained with this new model structure: 1) It is analytically simpler than the structure of the Bouc-Wen model (Wen, 1976) although it can still reproduce the most important phenomena of MR-dampers behavior and 2) This model can be linearized in the parameters after proper manipulation and therefore is suited for real-time parametric identification. The use of real-time parametric identification avoids the problem of parameter calibration.

There are other attempts to use different modeling paradigms for MR-dampers, such as neural networks like in (Kim and Roschke, 1999). Although the authors achieve good results in terms of MR-damper force response, the neural network model is not physically motivated and it is therefore more difficult to use when combined with the model of the structures. This is important when attempting real-time control.

This paper is divided into four sections. The first one deals with MR-damper modeling. In the next section, the parametric identification of the Lugre dynamic friction model for the MR-damper is introduced. The third section contains comparative results of the force responses of the MR-damper using both the Bouc-Wen model and the model introduced in this paper. Finally, the last section contains concluding remarks and directions of ongoing work.

2. MAGNETO-RHEOLOGICAL DAMPER MODELING

In this section the modeling of MR is presented. A good model is of importance when real-time control of civil engineering structures is attempted. MR-dampers are dissipative devices whose behavior is much more complex than that of a normal viscous damper. They present several nonlinear phenomena that are not captured by this simple modeling paradigm.

A systematic approach to model MR-dampers is attempted in (Spencer *et al.*, 1997). The authors resort to a model based in a Bouc-Wen structure. This modeling structure is specially well suited to reproduce the hysteretic behavior that is observed in experiments when force versus velocity curves are obtained. The model proposed in (Spencer *et al.*, 1997) is based on the scheme shown in Fig. 1, and has the following form

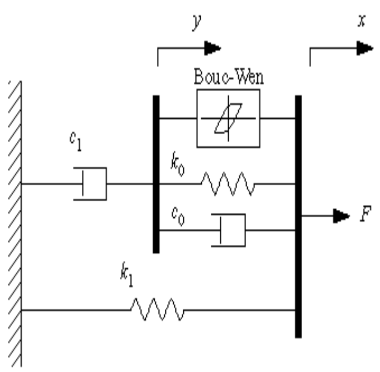

Fig. 1. Mechanical representation of an MR-damper.

$$c_1 \dot{y} = \alpha z + k_0(x - y) + c_0(\dot{x} - \dot{y}) \ , \tag{1a}$$

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

$$f = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) \ . \tag{1c}$$

where f is the force exerted by the MR-damper x is the relative displacement of one end of the MR-damper [4], y is an internal state included to represent rollover effects observed at low velocity and z is the Bouc-Wen internal state. k_0, k_1, c_0 and c_1 represent the value of the stiffness and viscous damping in springs and dampers in Fig. 1. γ, β and A are the parameters that control the shape of the hysteresis loop in the Bouc-Wen yielding element. Finally, α and n are other parameters that refer to the internal state z and determine its coupling with the force f and its evolution.

The model in Eqs. (1) does not explicitly include the effect of the magnetic field applied to the MR-fluid in the damper. To represent the possible variations of this field, (Spencer *et al.*, 1997) assume that this field is directly proportional to a control voltage and propose the following linear structure for parameters α, c_0 and c_1

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u \ , \tag{2a}$$
$$c_0 = c_0(u) = c_{0_a} + c_{0_b} u \ , \tag{2b}$$
$$c_1 = c_1(u) = c_{1_a} + c_{1_b} u \ . \tag{2c}$$

where α_a, α_b, c_{0_a}, c_{0_b}, c_{1_a} and c_{1_b} are constants and u is a filtered version of the input voltage v that obeys

$$\dot{u} = -\eta(u - v) \ . \tag{3}$$

In this paper the dynamic friction model introduced in (Canudas *et al.*, 1995) is used, this model has the following form

$$f = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 \dot{x} \ , \tag{4a}$$
$$\dot{z} = \dot{x} - \sigma_0 a_0 |x| z \ . \tag{4b}$$

where f is the force in the MR-damper, x is the relative velocity between its ends, z is an internal deformation state and $\sigma_i \ ; i = 0, 1, 2$ and a_0 are parameters.

In the original formulation in (Canudas *et al.*, 1995) the parameter a_0 is non-linear a function of the relative velocity [5]. To keep the simplicity of the model, and based in the model proposed by (Dahl, 1976), a_0 is kept constant in this paper.

[4] The other end is fixed in Fig. 1.
[5] Intended to represent the Stribeck effect.

To model the effect of the magnetic field, it is assumed that the current that determines the intensity of the field is proportional to an applied voltage. The model in Eqs. (4b) is then modified to incorporate this voltage v as

$$f = \sigma_0 z v + \sigma_1 \dot{z} + \sigma_2 \dot{x} \ , \tag{5a}$$
$$\dot{z} = \dot{x} - \sigma_0 a_0 |\dot{x}| z (1 + a_1 v) \ . \tag{5b}$$

If Eq. (5b) is substituted into Eq. (5a) then

$$f = \sigma_0 z v - \sigma_0 \sigma_1 a_0 |\dot{x}| z - \sigma_0 \sigma_1 a_0 a_1 |\dot{x}| z v + (\sigma_1 + \sigma_2) s \ . \tag{6}$$

Define the following parameters

$$\theta_1 = \sigma_0 \ , \tag{7a}$$
$$\theta_2 = \sigma_0 \sigma_1 a_0 \ , \tag{7b}$$
$$\theta_3 = \sigma_0 \sigma_1 a_0 a_1 \ , \tag{7c}$$
$$\theta_4 = \sigma_1 + \sigma_2 \ . \tag{7d}$$

Using Eqs. (7), Eq. (6) can be rewritten as a form linear in the parameters

$$f = U\Theta \ , \tag{8}$$

with

$$U = [zv, -|\dot{x}|z, -|\dot{x}|zv, \dot{x}(t)]^{\mathrm{T}} \tag{9}$$

and

$$\Theta = [\theta_1, \theta_2, \theta_3, \theta_4]^{\mathrm{T}} \ . \tag{10}$$

3. REAL-TIME IDENTIFICATION OF MR-DAMPER PARAMETERS

Once the structure of the MR-damper is transformed to a linear in the parameters form, it is straightforward to apply conventional identification algorithms to adjust the parameters value. In this paper a recursive least squares identification algorithm (Ljung, 1987) is used as this method allows real-time implementation.

The adaptation law for $\hat{\theta}$, the estimated value of θ is

$$\hat{\theta}(t) = \hat{\theta}(t-1) + L(t)(f(t) - U(t)\hat{\theta}(t-1)) \ , \tag{11a}$$

$$L(t) = \frac{P(t-1)U(t)}{\lambda(t) + U(t)^{\mathrm{T}}P(t-1)U(t)} \ , \tag{11b}$$

$$P(t) = \frac{P(t-1)}{\lambda(t)}\left(I - \frac{U(t)U(t)^{\mathrm{T}}P(t-1)}{(\lambda(t) + U(t)^{\mathrm{T}}P(t-1)U)}\right) \ . \tag{11c}$$

The regressor U in Eq. (9) assumes that the internal state is known. This is not the case. For that reason an observer for this state is proposed of form

$$\dot{\hat{z}} = \dot{x} - \hat{\sigma}_0\hat{a}_0|\dot{x}|\hat{z}(1 + \hat{a}_1 v) \ , \tag{12}$$

where $\hat{\sigma}_0$, $\hat{a}_0$, $\hat{a}_1$ are the estimated values of the non-hat parameters calculated with base on Eqs. (7) and the current estimation of θ.

The regressor U in Eq. (11) is then substituted by $\hat{U}$

$$\hat{U} = [\hat{z}v, -|\dot{x}|\hat{z}, -|\dot{x}|\hat{z}v, \dot{x}(t)]^{\mathrm{T}} \ . \tag{13}$$

Substituting Eq. (13) into Eqs. (11) yields

$$\hat{\theta}(t) = \hat{\theta}(t-1) + L(t)(f(t) - \hat{U}(t)\hat{\theta}(t-1)) \tag{14a}$$

$$L(t) = \frac{P(t-1)\hat{U}(t)}{\lambda(t) + \hat{U}(t)^{\mathrm{T}}P(t-1)\hat{U}(t)} \tag{14b}$$

$$P(t) = \frac{P(t-1)}{\lambda(t)}\left(I - \frac{\hat{U}(t)\hat{U}(t)^{\mathrm{T}}P(t-1)}{(\lambda(t) + \hat{U}(t)^{\mathrm{T}}P(t-1)\hat{U})}\right) \tag{14c}$$

The join convergence of the parameter identification scheme and the observer for the internal state z follow similar lines to those presented in (Luis Alvarez and Luis Olmos, 2001). Consider the following Lyapunov function candidate

$$W = \frac{1}{2}\tilde{\theta}^T P^{-1}\tilde{\theta} + \frac{1}{2}\tilde{z}^2 \ , \tag{15}$$

where $\tilde{\theta} = \theta - \hat{\theta}$ and $\tilde{z} = z - \hat{z}$. Taking the time derivative of Eq. (15) yields, after some manipulation

$$\dot{W} \leq = -\begin{bmatrix}\tilde{\Theta} & \tilde{z}\end{bmatrix}\begin{bmatrix}\hat{U}^T\hat{U} & \hat{U}^T U_1 \Theta \\ U_2 & |\dot{x}|(\theta_2 + \theta_3 v)/\sigma_1\end{bmatrix}\begin{bmatrix}\tilde{\Theta} \\ \tilde{z}\end{bmatrix} \ , \tag{16}$$

Table 1. Parameters for the model in Eqs. (1)-(3).

Parameter	Value
c_{0_a}	$20.2N\ s/cm$
c_{0_b}	$2.68N\ s/V\ cm$
k_0	$15.0N\ cm$
c_{1_a}	$350N\ s/cm$
c_{1_b}	$70.7N\ s/V\ cm$
k_1	$5.37N/cm$
α_a	44.9
α_b	$6381/V$
γ	$39.31/cm^2$
β	$39.31/cm^2$
A	47.2
n	2
η	$2511/s$

where $U_1 = [v \quad -|\dot{x}| \quad -|\dot{x}|v \ \ 0]$ and $U_2 = [0 \ c_1|\dot{x}|\hat{z} \ c_2|\dot{x}|\hat{z}v \ c_3|\dot{x}| + c_4|\dot{x}|v]$ with c_1, c_2, c_3, c_4 depending on σ_1, $\hat{\sigma}_1$, $\hat{\theta}_2$ and $\hat{\theta}_3$. It is direct to show that Eq. (16) is a negative semidefinite form. Stability of $\tilde{f} = 0$ and $\tilde{z} = 0$ follows. Seismic excitation forces are normally rich enough to guarantee persistence of excitation, therefore in most practical cases $\tilde{\theta} = 0$.

It is important to remark that only four parameters are identified with θ although Eqs. (5) require five. To uniquely determine the parameters, it is assumed that the value of σ_2 is known and the others are obtained from

$$\sigma_1 = \theta_4 - \sigma_2 \tag{17a}$$

$$\sigma_0 a_0 = \frac{\theta_2}{\sigma_1} \tag{17b}$$

$$\sigma_0 a_0 a_1 = \frac{\theta_3}{\sigma_1} \tag{17c}$$

4. SIMULATION RESULTS

To evaluate the performance of the proposed model for the MR-dampers, the model in (Spencer *et al.*, 1997) was used as a reference to generate forces. The values in Table 1 for the parameters in Eqs. (1) to (3) were also taken also from (Spencer *et al.*, 1997).

The first simulation result corresponds to an input signal in which displacement x $[cm]$ and excitation voltage v $[V]$ satisfy

$$x = 1.15\ sin(8.6\pi\ t)$$
$$v = 1.25 + 1.25\ sin(10.2\pi\ t)$$

Using this signal, a force is generated using Eqs. (1)-(3) and then the identification-observation scheme is applied. The results, in Fig. 2, shows very good agreement between the reference force and the force obtained by the identification procedure suggested in this paper.

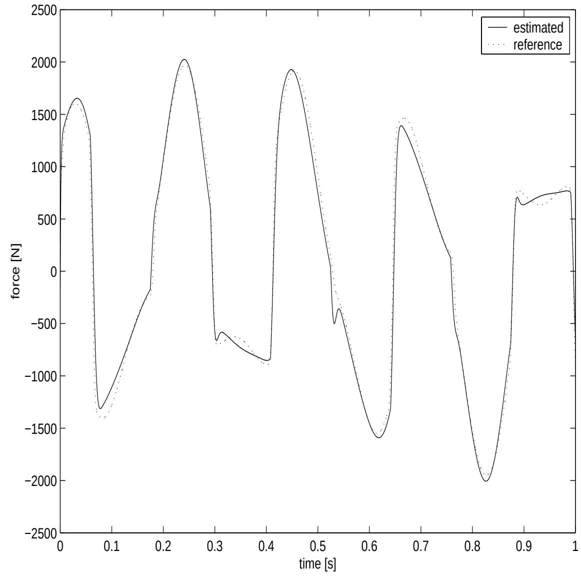

Fig. 2. Response of MR-damper model for time varying excitation signal.

The vector of adapted parameters, obtained after 36 s of simulation is

$$\hat{\theta} = 10^4 \times [1.059\ 0.181\ \text{-}0.026\ 0.008]^{\mathrm{T}}\ . \qquad (18)$$

The parameter evolution curves in time are shown in Fig. 3. It can be noticed that response time is about 1.5 s.

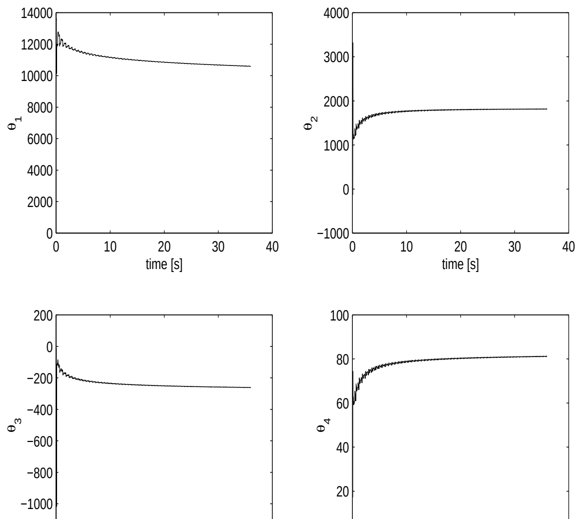

Fig. 3. Evolution of adapted parameters vs. time.

In the second simulation results, the parameters in Eq. (18) were kept constant and then used to match a different input signal. The excitation signal for both the model in Eqs. (1)-(3) and in Eq. (6) was a sinusoidal displacement x $[cm]$

$$x = 1.5\ sin(5\pi\ t)$$

with input constant voltages of $0.75, 1.5, 2.25\ V$. Figs. 4-6 show the results obtained in this case. Fig. 4 contains the force vs. time responses, Fig. 5 the force vs. displacement curves and, finally, Fig. 6 shows the force vs. velocity curves.

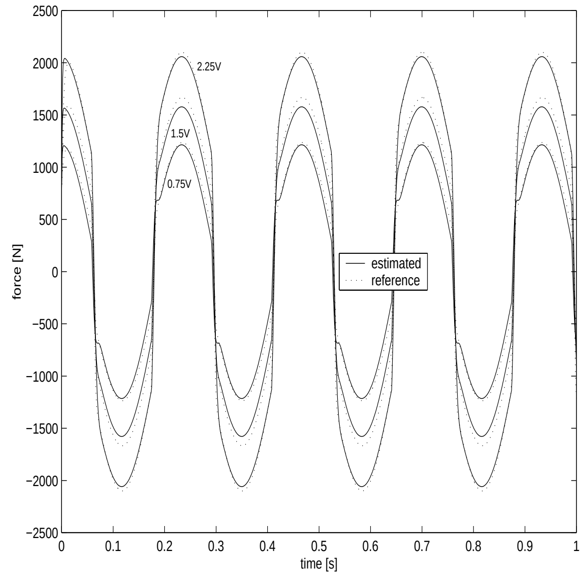

Fig. 4. Force vs. time response with constant voltage inputs.

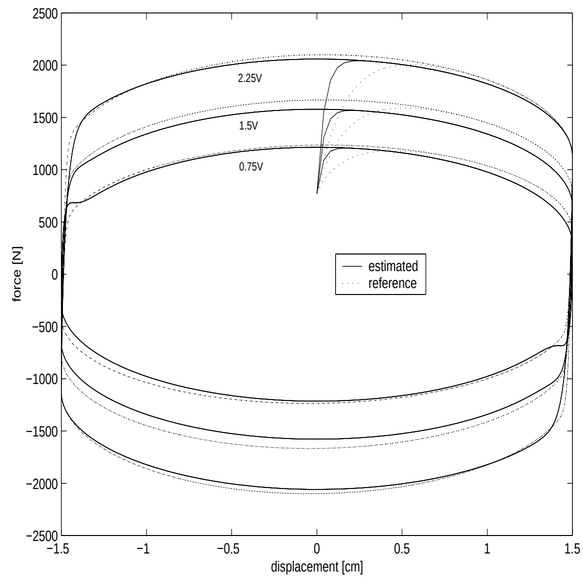

Fig. 5. Force vs. displacement curve with constant voltage inputs.

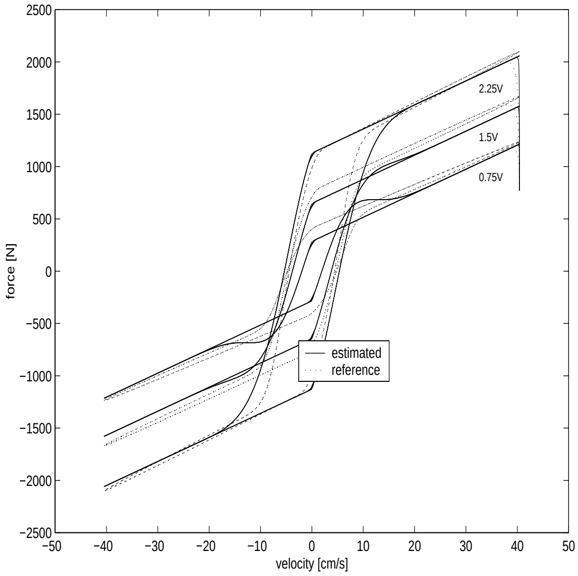

Fig. 6. Force vs. velocity curve with constant voltage inputs.

In summary, the results presented in Figs. 2-6 show good agreement with the reference force generated with the Bouc-Wen model. Parameter convergence, as shown in Fig. 3, is also very good.

5. CONCLUSIONS

A new model approach for MR-dampers based on a first order Lugre dynamic friction model was presented. The proposed structure can be transformed to render a linear in the parameters model that is used in combination with a nonlinear observer for the internal state of the friction model. The model proposed has a simpler analytical structure than the one introduced in (Spencer *et al.*, 1997) but it is still capable of reproducing the force responses for different kinds of excitation signals. One important feature of this modeling structure is that it allows real-time identification of the MR-damper model parameters. Experimental verification of these results is ongoing work.

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