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# MULTIPLE GAIN-SCHEDULED FUZZY-CONTROLLED MAGNETORHEOLOGICAL DAMPERS FOR VIBRATION REDUCTION OF MULTI-DEGREE-OF-FREEDOM STRUCTURES

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## ABSTRACT

Due to their mechanical simplicity and low power requirements, magnetorheological (MR) dampers have been proposed for reducing vibrations of seismically excited structures. Among the control algorithms proposed to regulate the damping properties of these control devices and reduce structural responses, is fuzzy logic control. This strategy uses simple "IF-THEN" statements developed based on expert knowledge of the structure's behavior. It is therefore an attractive alternative for complex and/or nonlinear systems. Tuning of these controllers is however a complex task due to the large number of parameters used to define membership functions and inference mechanisms. The objective of this research is to determine the effects of using multiple fuzzy-controlled MR dampers, tuned individually with gain-scheduling strategies, in reducing responses of a multi-degree-of-freedom structure. Different damper placement configurations are also considered. Structural response parameters evaluated include maximum and root mean square floor displacements, accelerations, and interstory drifts. Results obtained with the proposed gain-scheduling fuzzy control strategy are compared to those resulting from passive control strategies.

## Introduction

Magnetorheological (MR) dampers have been considered to reduce structural vibrations. These semi-active devices are formed by a hydraulic cylinder filled with a fluid whose viscosity can be varied through the application of a magnetic field. Because MR fluid is a suspension of magnetically polarizable iron particles that form chains in the presence of a magnetic field, hence increasing the fluid's viscosity, it can reversibly change from free-flowing to semi-solid. The relationship between the current supplied to the damper and the resulting damping force is highly non-linear, making challenging the development of effective and practical controllers.

Fuzzy algorithms have been considered an attractive alternative for controlling MR dampers because they are simple, intrinsically robust, and not based on a model of the damper, which can be computationally intensive and often impractical for control applications. Instead of

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differential equations, these algorithms use a basic understanding of the structure's behavior to develop simple "IF-THEN" rules that relate the controller inputs to the desired outputs. Tuning of these algorithms is often a complex task due to the large number of parameters that define the membership functions and inference mechanisms (Zheng 1992, Yager and Filev 1994, Li and Gatland 1996). Some of the strategies proposed for their tuning involve the adjustment of the scaling factors responsible for mapping the inputs and outputs to their respective universes of discourse (Daugherity *et al.* 1992, Nishimori *et al.* 1994, Yager and Filev 1994, Faravelli and Yao 1996, Li and Gatland 1996, Arslan and Kaya 2001). Of the several approaches available, gain scheduling of these parameters, is of particular interest. It consists in varying one or more of the scaling factors according to changes in the input variables to the fuzzy controller or the excitation to the system (Jang and Gulley 1994, Zhao 2001). This technique was successfully used by the author to control MR dampers and reduce vibrations of single degree-of-freedom (DOF) systems (Wilson 2005, Wilson and Abdullah 2005).

Because, as mentioned by Park *et al.* (2002), it may be more economical to use multiple small control devices than a single large one, the objective of this research is to determine the effects of using multiple fuzzy-controlled MR dampers, tuned individually with gain-scheduling strategies, in reducing responses of a multi-degree-of-freedom structure. A 3 DOF structure was therefore selected and different damper placement configurations considered.

## System Description

The structure selected for this study was the three-story model building presented in Park et al. (2002), where the mass of each floor was 345,600 kg, the stiffness 120,000 kN/m, and 1% of the modal damping ratios were assumed for all modes. The mass (**M**), damping (**C**), and stiffness (**K**) matrices are presented as follows:

$$\mathbf{M} = 10^5\, x \begin{bmatrix} 3.456 & 0 & 0 \\ 0 & 3.456 & 0 \\ 0 & 0 & 3.456 \end{bmatrix} \text{kg} \tag{1}$$

$$\mathbf{C} = 10^5\, x \begin{bmatrix} 1.745 & -0.512 & -0.111 \\ -0.512 & 1.634 & -0.623 \\ -0.111 & -0.623 & 1.122 \end{bmatrix} \text{N s/m} \tag{2}$$

$$\mathbf{K} = 10^8\, x \begin{bmatrix} 2.4 & -1.2 & 0 \\ -1.2 & 2.4 & -1.2 \\ 0 & -1.2 & 1.2 \end{bmatrix} \text{N/m} \tag{3}$$

The equation of motion for the seismically excited 3 DOF structure equipped with dampers can be written as:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = -\mathbf{\Gamma f} - \mathbf{M}_{\mathbf{v}}\ddot{x}_g \tag{4}$$

where $\mathbf{x}$, $\dot{\mathbf{x}}$, and $\ddot{\mathbf{x}}$ are the structural displacement, velocity, and acceleration vectors, respectively, $\mathbf{\Gamma}$ is a 3x3 matrix denoting the location of the dampers in the structure (1st floor only, 1st and 2nd floors, and all 3 floors), **f** is the 3x1 vector of control forces, $\mathbf{M_v}$ is a 3x1 vector of floor masses, and $\ddot{x}_g$ is the ground acceleration, in this paper, the 1940 El Centro earthquake.

The MR damper model selected for the numerical simulations was the phenomenological model proposed by Spencer *et al.* (1997), a modification of the commonly used Bouc-Wen model. Eqs. 5-7 express the force produced by each MR damper (Spencer *et al.* 1997):

$$f = \alpha z + c_o(\dot{x} - \dot{y}) + k_o(x - y) + k_1(x - x_o) = c_1\dot{y} + k_1(x - x_o) \tag{5}$$

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \tag{6}$$

$$\dot{y} = \frac{1}{c_o + c_1}\{\alpha z + c_o\dot{x} + k_o(x - y)\} \tag{7}$$

where $f$ represents the control force of the MR damper, $x$, the damper displacement, $y$, an internal displacement of the damper, $\alpha$ is the Bouc-Wen parameter describing the MR fluid yield stress, $c_o$ the viscous damping at large velocities, $k_o$ the stiffness at large velocities, $k_1$ the damper force due to the accumulator, and $c_1$ reproduces the roll-off observed in the experimental data when velocities are close to zero. Parameters for a 20-ton MR damper were obtained experimentally (Yang 2001, Yang *et al.* 2002): $A = 2679.0$ m$^{-1}$, $\gamma = \beta = 647.46$ m$^{-1}$, $k_o = 137{,}810$ N/m, $N = 10$, $x_o = 0.18$ m, $k_1 = 617.31$ N/m, and variables $\alpha$, $c_o$, $c_1$ are functions of the current to the damper ($i$):

$$\alpha(i) = 16566\, i^3 - 87071\, i^2 + 168326\, i + 15114 \tag{8}$$

$$c_o(i) = 437097\, i^3 - 1545407\, i^2 + 1641376\, i + 457741 \tag{9}$$

$$c_1(i) = -\,9363108\, i^3 + 5334183\, i^2 + 48788640\, i - 2791630 \tag{10}$$

To accommodate the dynamics of the MR fluid reaching rheological equilibrium, the following first order filter is also provided by Yang (2001) and Yang *et al.* (2002):

$$H(s) = \frac{31.4}{s + 31.4} \tag{11}$$

It is important to note that a model for the MR damper was required in this study only to numerically simulate the structural responses, not to design or run the gain-scheduled fuzzy controller developed.

## Gain-Scheduled Fuzzy Controller

A block diagram of the gain-scheduled fuzzy controlled system is presented in Fig. 1 to illustrate the process employed in the numerical simulations conducted in Matlab and Simulink.

Three configurations were considered in this study: dampers only on the first floor, dampers on the first and second floors, and dampers on all three floors. For each MR damper, the variables selected as input to the fuzzy controller are the displacement and velocity of the floor to which the damper is connected, while the output is the current applied to the device.

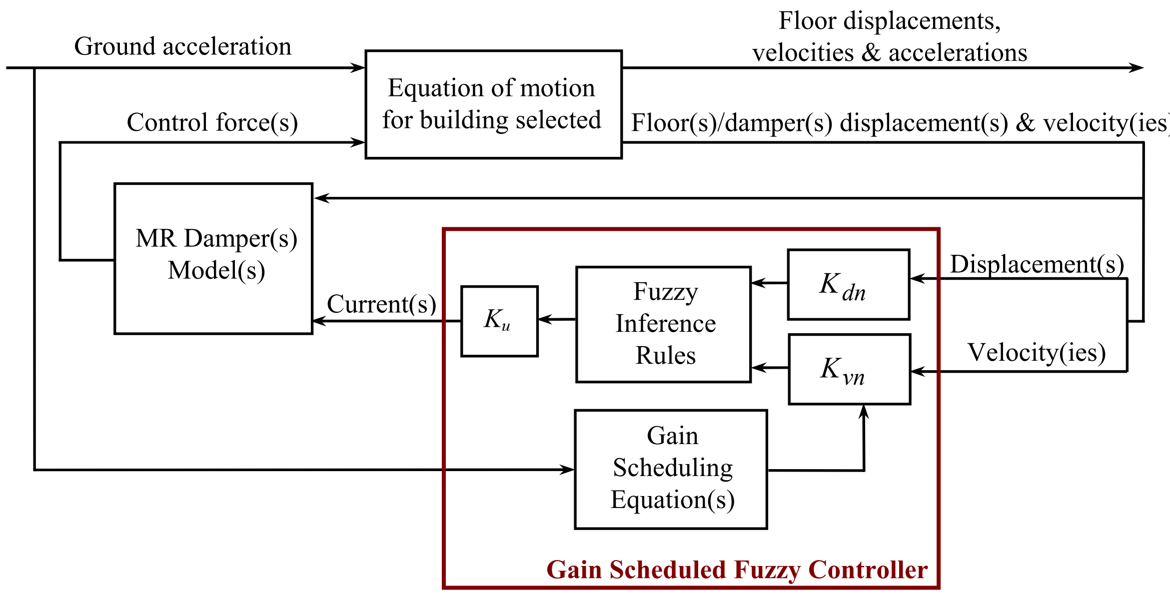


Figure 1. Block diagram of gain-scheduled fuzzy control system.

Membership functions required to fuzzify the input variables (Fig. 2a) were defined on the normalized universe of discourse [-1,1]. They are composed of 7 identical triangles with 50% overlap. To defuzzify the output, 4 membership functions were defined on the universe of discourse [0,1] (Fig. 2b). Labels NL, NM, NS, ZO, PS, PM, and PL refer to negative large, medium, and small, zero, positive small, medium, and large, respectively.

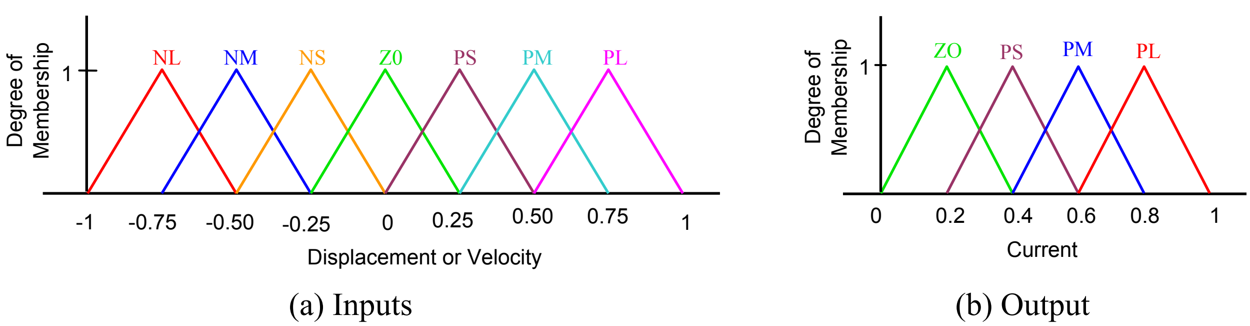


Figure 2. Membership functions of gain-scheduled fuzzy control system.

As shown in Fig. 1, the scaling factors used to map the input and output variables to their respective universes of discourse were labeled $K_{dn}$, $K_{vn}$, $K_u$, for displacement, velocity, and current, respectively (subscript $n$ refers to the $n^{th}$ floor). Several values were considered for scaling factors $K_{dn}$, the ones yielding the best responses and thus selected for this study were obtained with the following equation (Yager and Filev 1994):

$$K_{d\,n} = \frac{1}{d_{max\,n}} \tag{12}$$

where $d_{max_n}$ is the maximum structural displacement of the $n^{th}$ floor, which, in this paper, was estimated as the largest uncontrolled response of the structure to the following four earthquakes: El Centro, Hachinohe, Northridge, and Kobe. The value of $K_u$ selected for all control algorithms was obtained with the equation suggested by Liu *et al.* (2001):

$$K_u = \frac{i_{max} - i_{min}}{3} \tag{13}$$

where $i_{min}$ is the minimum current to the dampers (0A), and $i_{max}$, the maximum: 6A (Yang 2001).

To determine the relationships between scaling factors $K_{vn}$ and ground motion and determine the equations required for gain-scheduling these variables, a parametric analysis was conducted where the 3 DOF structure was subjected to the following scaled versions of the El Centro earthquake: 25%, 50%, 100%, 150%, and 200%. Several values were selected for $K_{vn}$, including the ones obtained with (Yager and Filev 1994, Liu *et al.* 2001, respectively):

$$K_{vn} = \frac{1}{v_{max\,n}} \tag{14}$$

$$K_{vn} = \frac{3}{v_{max_n}} \tag{15}$$

where $v_{max_n}$ is the maximum structural velocity of the $n^{th}$ floor, estimated as the largest uncontrolled velocity of the structure to the four earthquakes previously mentioned. Table 1 presents the values selected for scaling factors $K_u$ and $K_{dn}$, as well as the equations relating the ground acceleration ($\ddot{x}_g$) to scaling factors $K_{vn}$.

Table 1. Values and equations selected for the different scaling factors.

| **Location of dampers** | $K_{un}$ | $K_{dn}$ | $K_{vn}$ | $R^{2\,*}$ |
|---|---|---|---|---|
| **First floor** | $K_{u1} = 2$ | $K_{d1} = 5$ | $K_{v1} = 14.80\ddot{x}_g^2 - 22.49\ddot{x}_g + 9.18$ | 0.9377 |
| **Second floor** | $K_{u2} = 2$ | $K_{d2} = 3$ | $K_{v2} = 9.98\ddot{x}_g^2 - 15.16\ddot{x}_g + 6.19$ | 0.9378 |
| **Third floor** | $K_{u3} = 2$ | $K_{d3} = 2$ | $K_{v3} = 8.96\ddot{x}_g^2 - 13.60\ddot{x}_g + 5.54$ | 0.9382 |

* coefficient of determination

Because the standard rule-base developed by MacVicar-Whelan (1976) and the modified version of these rules proposed by Liu *et al.* (2001) appeared to satisfactorily represent the relationship between the inputs and the output of the fuzzy controller, they were selected as a starting point for these algorithms. Some of these rules were then varied and their effect on the structural responses observed. Since there are no systematic methods for creating rule-bases, this is a common approach in the design of fuzzy control algorithms (Yager and Filev 1994). And because variations to these standard rules did not noticeably change the structural responses obtained, the rule-base proposed by Liu *et al.* (2001) and presented in Table 2 was adopted.

Table 2. Control rule-base (Liu *et al.* 2001).

| $x$ \ $\dot{x}$ | **NL** | **NM** | **NS** | **ZO** | **PS** | **PM** | **PL** |
|---|---|---|---|---|---|---|---|
| **NL** | PL | PL | PL | PM | ZO | ZO | ZO |
| **NM** | PL | PL | PL | PS | ZO | ZO | PS |
| **NS** | PL | PL | PL | ZO | ZO | PS | PM |
| **ZO** | PM | PL | PS | ZO | PS | PM | PL |
| **PS** | PS | PM | ZO | ZO | PL | PL | PL |
| **PM** | ZO | PS | ZO | PS | PL | PL | PL |
| **PL** | ZO | ZO | ZO | PM | PL | PL | PL |

## Results and Discussion

Numerical simulations were conducted in Matlab and Simulink, and responses were obtained for the 3 DOF structure equipped with gain-scheduled fuzzy controlled MR dampers and subjected to the El Centro earthquake. Three main configurations were considered: dampers only on the first floor, dampers on the first and second floors, and dampers on all three floors (dampers placed on multiple floors were equally distributed among the floors). The six criteria used to evaluate the effectiveness of the control system were obtained by dividing the controlled responses by the respective uncontrolled responses. They considered root mean square (RMS) and maximum displacements, accelerations, and interstory drifts (Eqs. 16-21).

$$J_{1n} = \frac{\mathrm{RMS}\,(x_n(t))}{\mathrm{RMS}\,(x_{unc\,n}(t))} \tag{16}$$

$$J_{2n} = \frac{\mathrm{RMS}\,(\ddot{x}_n(t))}{\mathrm{RMS}\,(\ddot{x}_{unc_n}(t))} \tag{17}$$

$$J_{3n} = \frac{max\left|x_n(t)\right|}{max\left|x_{unc_n}(t)\right|} \tag{18}$$

$$J_{4n} = \frac{max\left|\ddot{x}_n(t)\right|}{max\left|\ddot{x}_{unc_n}(t)\right|} \tag{19}$$

$$J_{5n} = \frac{\mathrm{RMS}\,(x_n(t) - x_{n-1}(t))}{\mathrm{RMS}\,(x_{unc\,n}(t) - x_{unc\,n-1}(t))} \tag{20}$$

$$J_{6n} = \frac{\max\left|(x_n(t) - x_{n-1}(t))\right|}{\max\left|x_{unc\,n}(t) - x_{unc\,n-1}(t)\right|} \tag{21}$$

where $x_n$ and $\ddot{x}_n$ are the controlled $n^{th}$ floor displacement and acceleration, respectively, whereas $x_{unc_n}$ and $\ddot{x}_{unc_n}$ are the uncontrolled $n^{th}$ floor displacement and acceleration, also respectively.

For succinctness, only the average of the evaluation criteria calculated over the three floors is presented in Fig. 3. This figure also presents results obtained with a more traditional fuzzy controller that maintained constant all scaling factors. For simplicity, this strategy will be referred in this paper as "fuzzy control". Values for the scaling factors used in this traditional fuzzy controller were obtained with Eqs. 12-14 and are presented in Table 3. Results in Fig. 3 also compare these responses to those obtained with the use of two passive control strategies: "passive on", where the current to the MR dampers was kept constant and equal to its maximum value (6 A), and "passive off", where the current was kept at 0 A.

Table 3. Scaling factors used with the more traditional fuzzy controller.

| **Location of dampers** | $K_{un}$ | $K_{dn}$ | $K_{vn}$ |
|---|---|---|---|
| **First floor** | $K_{u1} = 2$ | $K_{d1} = 5$ | $K_{v1} = 0.66$ |
| **Second floor** | $K_{u2} = 2$ | $K_{d2} = 3$ | $K_{v2} = 0.36$ |
| **Third floor** | $K_{u3} = 2$ | $K_{d3} = 2$ | $K_{v3} = 0.29$ |

The average values of the evaluation criteria obtained with the gain-scheduled controllers were smaller than 1 for the configurations considered, indicating that the use of multiple dampers controlled by this strategy effectively reduced peak and RMS displacements, accelerations and interstory drifts. The only exception was observed for maximum accelerations ($J_4$) obtained with six dampers placed on the first floor. For this case, the average $J_4$ was 1.06, while the values obtained for the individual floors were: 0.92, 1.35, and 0.90, for the first, second, and third floors, respectively. Still considering the gain-scheduling strategy, it can be observed that, in general, distributing the dampers over the floors of the structure proved to be a more effective strategy with respect to all six criteria. In fact, not only were better responses obtained when the same number of dampers were distributed among the floors of the building, but similar responses were obtained with four dampers on the first floor as with two dampers equally distributed between floors 1 and 2. Similarly, comparable results were observed with six dampers on the first floor and with three dampers, one on each of the three floors.

Generally, results obtained with the more traditional fuzzy controller were close to those obtained with the gain scheduling fuzzy control scheme. However, the latter was more effective when a larger number of dampers were used. This may be due to the fact that greater control over this larger damping force could be obtained by varying the value of scaling factors $K_{vn}$ than by keeping them constant. This improvement of the gain-scheduled controller over its fuzzy


Figure 3. Average values of evaluation criteria obtained with different damper configurations.

counterpart is particularly evident for reductions in displacements and interstory drifts, but it can also be observed for maximum accelerations when dampers are placed on more than one floor.

As anticipated, the passive on strategy was more effective in reducing RMS and peak displacements than the passive off controller, while the passive off scheme outperformed its passive counterpart with respect to reductions in RMS accelerations. Passive off also performed better than passive on in reducing peak accelerations when all dampers were placed on the first floor or when a smaller number of dampers were used in multiple floors. The aim of the two fuzzy control strategies considered was to vary the current supplied to the dampers and hence the amount of damping provided to the structure in an attempt to reduce displacements more effectively than the passive off strategy and, if possible, as much as the passive on scheme, while preventing the increases in peak and RMS accelerations so often associated with this control setting. Results presented above indicate that this objective was achieved. With the exception of criteria $J_4$ (maximum accelerations), both the fuzzy and the gain-scheduled controllers performed better than the passive off strategy, and although not as effective in reducing displacements as the passive on scheme, these controllers successfully reduced these responses without causing the large increases in accelerations commonly observed with the passive on setting.

## Conclusions

The objective of this study was to investigate the effects of multiple fuzzy-controlled MR dampers, tuned individually with gain-scheduling strategies, in reducing responses of a seismically excited multi-degree-of-freedom structure. After considering different damper placement configurations on a 3 DOF structure, it was concluded that: (1) Multiple dampers controlled by the gain-scheduling strategy effectively reduced peak and RMS displacements, accelerations, and interstory drifts for all placement configurations. The only exception was the slight increase in maximum acceleration with the placement of 6 dampers on the 1$^{st}$ floor. However, this was not observed when the 6 dampers were distributed among the floors. (2) Although MR dampers placed on the 1$^{st}$ floor and controlled by the gain-scheduled fuzzy strategy effectively reduced structural responses, better results were obtained by equally distributing the dampers over the 1$^{st}$ and 2$^{nd}$ floors or even better, over the 3 floors of the structure. In fact, similar responses were obtained with 4 dampers on the 1$^{st}$ floor as with 2 dampers (1 on the 1$^{st}$ floor, 1 on the 2$^{nd}$). Similarly, results obtained by placing 6 dampers on the 1$^{st}$ floor were comparable to those obtained with 3 dampers, 1 on each floor. (3) While responses obtained with the more traditional fuzzy controller were close to those of the gain-scheduled strategy, the latter was more effective when a larger number of dampers were used. (4) In general, gain-scheduled fuzzy controllers outperformed the passive off control strategy. (5) The effectiveness of the gain-scheduled controllers in reducing displacements was comparable to that of the passive on scheme, with the advantage of not increasing structural accelerations as this passive strategy.

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