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Performance Evaluation of Passive and Semi-Active Magnetorheological Dampers

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Abstract

Seismic control performance of the magnetorheological (MR) damper, which has strong nonlinearity, varies with the dynamic characteristics of the structure and ground motion such as natural period, peak ground acceleration. The MR damper has a property of the friction damper so that the relative magnitude of the friction force over excitation intensity affects the control performance. In this study, through numerical analyses of single-degree-of-freedom (SDOF) structures, design spectra for the passive MR damper and optimal non-dimensional friction forces are suggested. Additionally, simple semi-active control algorithms modulating the friction force of the MR damper in accordance with structural responses are proposed and compared with each other and the passive MR damper. Finally, the condition that the semi-active control is more appropriate than the passive one is identified for reasonable selection of the control strategy.

Keywords: Magnetorheological damper; Semi-active control

1. Introduction

The magnetorheological (MR) damper has been increasingly applied to the control of civil structures subjected to earthquake or wind loads (Dyke et al., 1996). The MR damper has a property of the friction damper with additional viscousity, and the friction force can be modulated by changing the magnetic field passing the MR fluid. In particular, the property of the variable friction force has lead to the development and application of many semi-active control algorithms for the MR damper. Many researches show the superiority of the semi-active control algorithm over passive one, but the verification was confined to a limited number of structures and dynamic loads (Jansen and Dyke, 2000 ; Cho et al., 2005). However, the nonlinearity of the MR damper due to its friction component makes its control performance affected by the magnitude of the excitation. Also, damping effect obtained by the same MR damper varies with the vibration frequency. Therefore the determination of the friction force considering the magnitude and frequency characteristics of both the structure and excitation is essential in the design of the MR damper. In this study, passive and semi-active MR dampers are evaluated and compared through extensive nonlinear time history analysis of single-degree-of-freedom (SDOF) structures for various natural periods and ground motions. For passive MR dampers, empirical design spectra and optimal design parameters are proposed. For semi-active MR dampers, simple control algorithms of the MR damper are proposed and their performances are compared with each other and the passive controls. Finally, the

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condition that the semi-active MR damper gives better performance than passive one is identified for reasonable selection of the MR damper control strategy

2. Passive MR damper

To investigate the performance of the passive MR damper, nonlinear time history analyses of the mass-normalized SDOF structure is conducted for 20 ground motion data recorded on rock site (Applied Technology Council, 1996). The structural responses with the MR damper are normalized with those without the MR damper and represented in the form of spectrum. To represent the magnitude of the friction force, a non-dimensional friction force is defined as follows

$$\rho = f_f / f_s \tag{1}$$

where f_f is the friction force of the MR damper and f_s is the base shear of the structure without the MR damper. Normalized response spectra of the relative displacement and absolute acceleration and their variation with respect to ρ are represented in Fig. 1. The normalized response spectra converge to 1.0 as the natural period, T_n, approaches to 0. It is observed that response reduction efficiency decreases as ρ increases. In particular, increasing ρ over a critical value causes the absolute acceleration of the long period structure to increase.

3. Design spectrum of the passive MR damper

The shape of the normalized response spectrum can be approximated by three straight lines corresponding to three ranges of the natural period as shown in Fig. 1. Each line is expressed by the following equation.

$$J(\rho, T_N) = \begin{bmatrix} 1 + \dfrac{J_S(\rho) - 1}{0.25} & T_n < T_a \\ J_S(\rho) & 0.25 \le T_n \le 0.65 \\ \dfrac{J_L(\rho) - J_S(\rho)}{1.35}(T_n - 0.65) + J_S(\rho) & T_S > T_N \end{bmatrix} \tag{2}$$

where $J_S(\rho)$ and $J_L(\rho)$ denote representative normalized spectrum values correspondding to the short and long period, respectively, and are the functions of the non-dimensional friction force, ρ. Curve fitting equations for $J_S(\rho)$ and $J_L(\rho)$ have different forms, depending on which response is concerned. The relative displacement and its derivative decrease monotonically with respect to ρ, but the absolute acceleration has an extremal point. As a result, curve fitting equations for $J_S(\rho)$ and $J_L(\rho)$ are given as

For relative displacement : $$J_d = \frac{c_{d2}\rho + 1}{c_{d1}\rho + 1} \tag{3}$$

For absolute acceleration: $$J_a = c_{a1}\rho + \frac{1}{c_{a2}\rho + 1} \tag{4}$$

where c_{d1}, c_{d2}, c_{a1} and c_{a2} is the coefficient to be determined by curve fitting. Table 1 represents

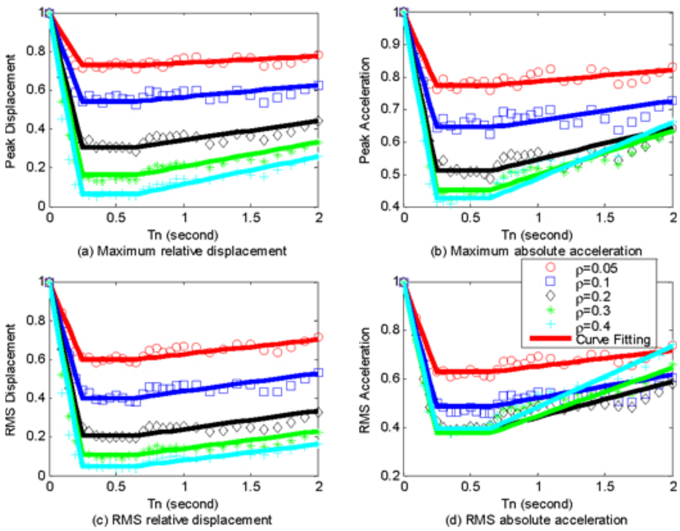

Fig. 1. Normalized response spectra of the passive MR damper.

Table 1. Curve Fitting Coefficients.

		J_s		J_L	
		c_{d1}	c_{d2}	c_{d1}	c_{d2}
J_d	Peak	4.67	-2.03	5.09	-0.535
	RMS	10.2	-1.86	7.16	-0.928
J_a	Peak	0.367	6.43	0.884	5.67
	RMS	0.590	13.4	1.37	10.8

Table 2. Optimal ρ.

γ	Displacement				Absolute Acceleration			
	J_s		J_L		J_s		J_L	
	Peak	RMS	Peak	RMS	Peak	RMS	Peak	RMS
0.0	-	-	-	-	0.50	0.28	0.27	0.17
0.1	0.46	0.21	0.43	0.30	0.24	0.13	0.18	0.11
0.2	0.27	0.12	0.24	0.17	0.16	0.08	0.13	0.08

coefficient of Eqs. (3) and (4) obtained from curve fitting

4. Optimal non-dimensional friction force

Generally, optimal ρ should make the derivative of the Eqs. (3) or (4) equal to zero. However, the derivative of the normalized relative displacement is always minus for the coefficients listed on Table 1. Therefore, the optimal ρ for the relative displacement response is defined as one achieving a specific derivative value of the normalized response. This means that the efficiency of the MR damper is introduced to the optimality concept, because the derivative, that is, the decrement of the normalized relative displacement by unit ρ, is the highest right after installation and decreases monotonically as ρ increases. Optimal ρ s for the relative displacement and the absolute acceleration are represented in Table 2, where γ is given as

$$\gamma = \frac{|\partial J / \partial \rho|}{|\partial J / \partial \rho|_{\rho=0}} \tag{5}$$

5. Semi-active MR damper

A semi-active MR damper has variable friction force modulated by a suitable control algorithm. However, the direction of the damper force cannot be changed by the controller artificially, and is dominated by the sign of the relative velocity between both ends of the damper. Therefore, considering variable friction property of the MR damper directly, simple semi-active control algorithms are proposed rather than existing active control algorithms are applied in this study.

5.1 Magnitude-dependent semi-active control

Magnitude-dependent semi-active control modulates the friction force of the MR damper based on the magnitude of the representative structural response defined by

$$V(x,\dot{x}) = \alpha_D\,|x|^n + \alpha_V\,|\dot{x}|^m \tag{6}$$

where α_D and α_V determine relative weightings between the relative displacement and velocity, and n and m determine the shape of friction force variation. The friction force is modulated between its upper and lower bound using the following equation.

$$f_f = \begin{cases} f_{\min} & V < V_1 \\ \dfrac{f_{\max} - f_{\min}}{V_2 - V_1}(V - V_1) + f_{\min} & V_1 \le V \le V_2 \\ f_{\max} & V > V_2 \end{cases} \tag{7}$$

where $f_{\max}$ and $f_{\min}$ are the maximum and minimum friction force corresponding to the passive-on and passive-off state, and V_1 and V_2 are important design factors defining the range of V corresponding to the transition of the friction force.

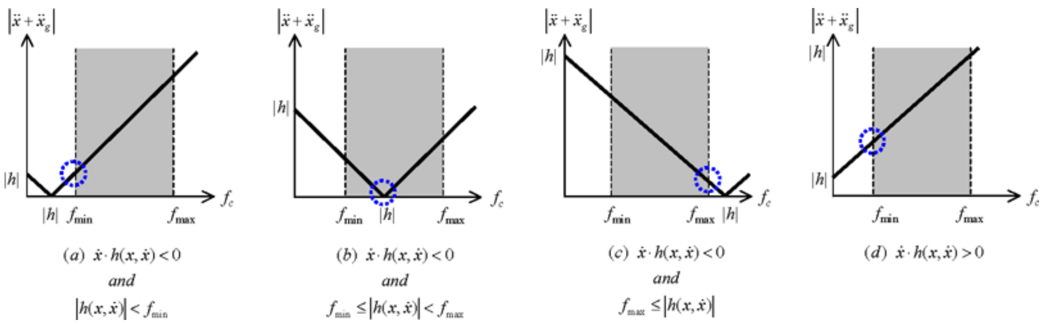

Fig. 2. Optimal friction force of the phase-dependent semi-active control.

5.2 Phase-dependent semi-active control

The phase-dependent semi-active control algorithm selects a control law considering which zone on the phase plane the structural response state belongs to. Unlike the magnitude-dependent semi-active control, structural states equal in respect of their components' magnitude may result in different control signal if they disagree in respect of their components' sign. In this study, a phase-dependent semi-active control algorithm is proposed to minimize the absolute acceleration, an important response related to human comfort, high-precision equipment protection and base shear reduction. The magnitude of the abs olute acceleration of a SDOF structure with an MR damper is expressed by the following equation employing Bingham model with the damper's viscousity neglected

$$|\ddot{x}+\ddot{x}_g| = \frac{1}{m}|h(x,\dot{x}) + f_f \,\mathrm{sgn}(\dot{x})| \tag{8}$$

where

$$h(x,\dot{x}) = c\dot{x} + kx \tag{9}$$

The magnitude of the absolute acceleration is the absolute value of a linear function with respect to friction force, f_c in Eq. (8). Figure 2 illustrates the absolute acceleration and the optimal f_c s, which are indicated by a circle for each case. The shaded areas in Fig. 2 represent the feasible range of the friction force. If the damping force in Eq. (9) is negligible, Fig. 2 can be interpreted in the following way. That is, the minimum friction force is used if the magnitude of the relative displacement is increasing, but the friction force is proportional to $h(x,\dot{x})$, in essence, otherwise.

6. Performance evaluation of the semi-active control algorithms

For the performance evaluation of the semi-active control algorithms, nonlinear time history analyses are conducted. The structures and ground motions are the same as those applied to the analysis of the passive MR damper. The maximum ρ is increased from 0.1 to 0.6 by 0.1 and corresponding minimum ρ's are assumed to be 10 % of the maximum values. Three magnitude-dependent semi-active controls denoted by 'Semiactive-M1,' 'Semiactive-M2' and 'Semiactive-M3' have (α_D, α_V) equal to (0, $1/\omega_n$), (1, 0) and (1, $1/\omega_n$), respectively, where ω_n is the natural circular frequency of the structure. Also, m= n=1, V_1=0.05V_2, V_2=$\alpha_D(\sigma_D)^n$+$\alpha_V(\sigma_V)^m$, where σ_D and σ_V are the RMS displacement and velocity without the MR damper. 'Semiactive-P' denotes the phase-dependent semi-active control.

The normalized response spectra of the relative displacement are represented in Fig. 3. It is observed that, for the relative displacement control, 'Passive-on' control is superior to all the semi-active control algorithms used in the analysis. Among four semi-active control algorithms, 'Semiactive-M1' and 'Semiactive-M3,' of which representative responses include the velocity response in common, are better

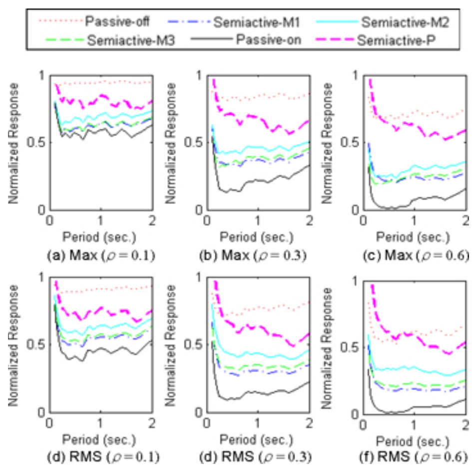

Fig. 3. Normalized response spectra of the relative displacement.

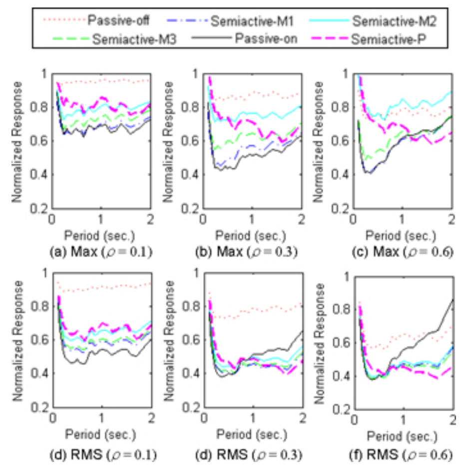

Fig. 4. Normalized response spectra of the absolute acceleration.

than the other two algorithms. The normalized response spectra of the absolute acceleration are represented in Fig. 4. Absolute acceleration control performance of the 'Passive-on' control is improved by increasing by increasing ρ from 0.1 to 0.3, however, ρ = 0.6 deteriorate control performance for long natural periods. This is because there exists an optimal ρ, given in Table 2, for which the normalized absolute acceleration response reaches to the extremum. For ρ = 0.6, most semi-active controls have performance equal to or better than passive ones in the range of the long natural period. In particular, phase-dependent semi-active control has the best performance since it is developed in order to minimize the absolute acceleration response.

Finally, the minimum normalized response spectrum obtained from the comparison of spectra corresponding to six values of ρ is plotted for each control laws and response type in Fig. 5. These plots provide useful information for the selection of the control law to obtain the best performance. For the control of the relative displacement, 'Passive-on' shows the best performance and has additional benefit of requiring no sensor and no data processing. For the control of the maximum absolute acceleration, 'Passive-on' is the most excellent for overall natural period. For the long period structures, 'Passive-on,' 'Semiactive-M1' and 'Semiactive-P' show similar performance level, but the advantage in installation makes 'Passive-on' best choice again. For the control of the RMS acceleration, 'Passive-on' is the best only for $T_n < 0.7$ sec. On the other hand, 'Semiactive-P1' is the best for $T_n > 0.7$ sec. However, it should be taken into account that 'Passive-on' consumes friction force less than 'Semiactive-P' and has benefit in installation mentioned above.

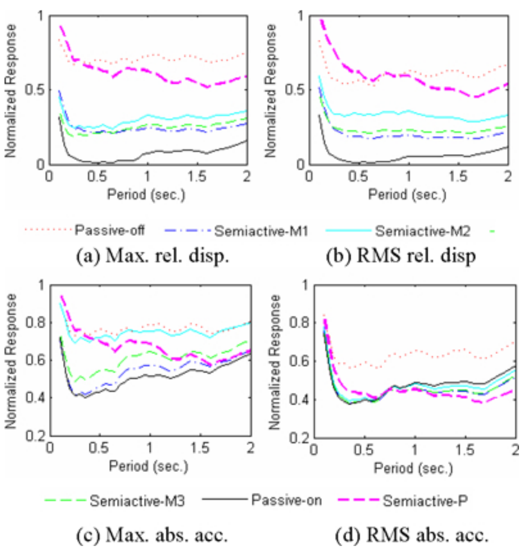

Fig. 5. Minimum normalized response spectra.

7. Concluding remarks

The performances of the passive and semi-active MR dampers are evaluated and compared through extensive nonlinear time history analyses of the SDOF structures with various natural frequencies for 20 ground motions. The design spectra of the passive MR damper are obtained from curve fitting of the normalized response spectra. Optimal non-dimensional friction forces are proposed based on the control efficiency represented by the derivative of the design spectrum. For the comparison with the passive MR damper, two types of semi-active control laws are proposed. The magnitude-dependent semi-active control depends on only the magnitude of the representative response such as the displacement, the velocity or the combination of those responses. The phase-dependent semi-active control modulates the friction force, considering which zone on the phase plane the structural state belongs to, so that the absolute acceleration is minimized in real time. The comparison of the passive and semi-active control laws reveal that the passive-on MR damper has the best performance except for the control of the RMS absolute acceleration, for which the phase-dependent semi-active control achieves the most excellent performance.

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