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EVENTUAL SLIDING MODE CONTROL FOR AN ISOLATED STRUCTURE USING MR DAMPER

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Abstract

This paper presents the effectiveness of a sliding mode control for a one-story isolated structure in E-Defense shaking table tests. A magnetorheological (MR) damper was employed as a semi-active control device, and controlled by an electric current, based on a control algorithm. The sliding mode control adopted herein is a robust non-linear control algorithm commonly used in robotics and automotive applications. It provides attractive features such as robustness for model parameter uncertainties and external disturbances. The eventual sliding mode control scheme, which comprised two independent terms, i.e., a linear control term and a non-linear control term, was employed for the tests. To reduce the chattering of the control signal, which is a harmful high frequency excitation, a smoothing function was used for the non-linear control term. The gains of the non-linear control term of 4000 and 8000 were adopted as test parameters.

Using the sliding mode control with the gain of the non-linear control term at 4000 (SMC 4000), the peak displacements were suppressed relative to the passive-off (0 A constant) for all ground motions. They were reduced by 64% for the El Centro 1940 NS and by 41% for the Sylmar 1994 NS. In addition, the sliding mode control accelerated the convergence of the response displacement, indicating that the state variable reached the swiching surface immediatly following occurrence of the large pulse. Compared with the passive-on (4 A constant), the displacement increased slightly for the Sylmar, however, it decreased for the El Centro and the JR Takatori 1995 NS. The peak acceleration with SMC 4000 increased for all ground motions compared with the passive-off, but they were smaller than those with the passive-on. The chattering of the control signal for the sliding mode control was not observed in the experiments. With the gain of the non-linear control term at 8000 (SMC 8000), both the displacement and acceleration increased by 9–36% compared with SMC 4000. The reason for this was that an excessive control force was exerted on the structure due to the twofold increase in the non-linear control force. By comparing the shaking table test results with simulation results, it is found that the displacement, acceleration and damper force showed good agreement between the experiments and simulations.

The eventual sliding mode control was confirmed effective for reducing the maximum displacement without a large increase in acceleration and for achieving rapid convergence of the response displacement using optimum control parameters.

Keywords: sliding mode control, semi-active control, E-Defense test, base-isolation, MR damper

1. Introduction

Seismic isolation is widely considered an effective technique for improving the safety and functionality of buildings. However, the isolation layer can excessively deform when the structure is subjected to long-period or strong impulsive ground motions. This study aims to decrease isolation layer deformation without increasing floor accelerations by introducing a semi-active control using a magnetorheological (MR) damper in the isolation layer. An eventual sliding mode control algorithm was adopted as a semi-active control. The algorithm is a robust non-linear control that is commonly used in robotics and automotive applications. It provides attractive features such as robustness for model parameter uncertainties and external disturbances. The effectiveness of the eventual sliding mode control in reducing the responses of a base-fixed structure was previously demonstrated [1]. In this study, a series of large-scale shaking table tests were conducted in E-Defense to verify the eventual sliding mode control of an MR damper for a one-story isolated structure.

2. Semi-active Control Algorithm

In sliding mode control, a switching hyperplane is set in the state space, and the trajectories always move toward a region adjacent to the hyperplane. As shown in Figure 1, by adopting the sliding mode control, motion is constrained to remain on the hyperplane, and the trajectories will slide along the surface to the origin [2-4].

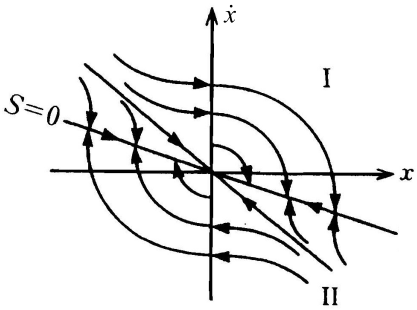


Fig. 1 Sliding mode.

The design procedure of the sliding mode control is as follows.

1) The switching hyperplane is designed in such a way that the trajectories slide along the surface to the origin.

2) The sliding mode controller is designed to ensure that motion is constrained to the hyperplane.

The state equation of the structure can be given as:

$$\dot{X} = AX + Bu \tag{1}$$

where $A = \begin{bmatrix} 0 & I \\ -M_f^{-1}K_f & -M_f^{-1}C_f \end{bmatrix}$, $B = \begin{bmatrix} O \\ M_f^{-1}F_f \end{bmatrix}$, $X = \begin{bmatrix} x^T & \dot{x}^T \end{bmatrix}^T$, M_f is a mass matrix, C is a damping matrix, K_f is a stiffness matrix, F_f is a control force position vector, and x is a displacement vector.

The switching function is given by:

$$\sigma = SX \tag{2}$$

where $\sigma = [\sigma_1(x), \sigma_2(x), \cdots \sigma_m(x)]^T$ and $S = \left[S_1^T, S_2^T, \cdots S_m^T\right]^T$.

Each scalar switching function $\sigma_i(x)$ has a linear plane, $\sigma_i(x) = 0$. This is defined as the switching hyperplane.

For the first procedure, the slope of hyperplane S was selected as the feedback gain of the optimal control, as shown in the following equation:

$$S = R^{-1}B^{T}P \tag{3}$$

where P is the solution of the Riccati equation in Eq. (4).

$$PA_{\varepsilon} + A_{\varepsilon}^{T}P - PBR^{-1}B^{T}P + Q = 0 \tag{4}$$
$$A_{\varepsilon} = A + \varepsilon I \qquad \varepsilon \geq 0$$

For the second procedure, an eventual sliding mode control scheme was used for the controller. Motion is constrained to the eventual switching surface and slide along the surface without sliding on other surfaces. The control force comprises linear control term u_l and non-linear control term u_{nl}, as shown in the following equation:

$$u = u_l + u_{nl} = -(SB)^{-1}SAX - \eta\frac{\sigma}{\|\sigma\|} \tag{5}$$

where η is the switching gain of non-linear inputs. The function of the linear control term is to adjust speed of convergence to the switching surface.

When sliding along the surface, the trajectories are confined to the vicinity of the hyperplane with high frequency oscillations in practice. This may have been the result of small time constants of sensors and actuators. This phenomenon, referred to as *chattering*, is an obstacle in the use of sliding modes in control systems. Therefore, a chattering suppression method was used in this study. The non-linear control term in Eq. (5) contributes to chattering in the vicinity of $\sigma = 0$. Smoothing function δ is thus adopted to the non-linear control term u_{nl}.

$$u = u_l + u_{nl} = -(SB)^{-1}SAX - \eta\frac{\sigma}{\|\sigma\| + \delta} \tag{6}$$

3. Shaking Table Tests

3.1 Test specimen

A series of large-scale E-Defense shaking table tests were conducted to verify the eventual sliding mode control of an MR damper for a one-story isolated structure. The test specimen is shown in Figure 2. The mass of the superstructure is 14.9 tons. Between the superstructure and the shaking table, there are four linear guides at the corners, a natural rubber bearing, and an MR damper. The stiffness of the rubber bearing is 42.3 kN/m, and the damping factor is 3.6%. The natural period of the isolation structure is 3.73 seconds.

Fig. 2 Specimen.

3.2 MR damper

The damper force of MR damper can be adjusted by changing the strength of the magnetic field induced within the MR fluid by the damper electromagnet. The maximum force of the MR damper used in E-Defense tests is 10 kN by application of electric current of 5.0 A. The stroke of the damper is 300mm.

The damper was modeled using the Bingham plastic model based on sinusoidal excitation tests of the damper only. Obtained damper force F_{MR} (kN) is expressed as:

$$F_{MR} = (-0.226I^2 + 2.867I - 0.203)\,\mathrm{sgn}(v) + 2.11v \tag{7}$$

where I (A) is electric current and v (m/s) is the piston velocity of the damper. It was confirmed that the modeled force showed good agreement with experiment results. In experiments, the electric current was calculated using Eq. (7) from the target damper force obtained from the control algorithm shown in Section 2. The limit value of the electric current induced in the damper was set to 4 A in the experiments.

3.3 Experimental outline

The effectiveness of the eventual sliding mode control was evaluated and confirmed through shaking table tests of the isolated structure using the MR damper. In these tests, the coefficient ε in Eq. (4) was set to 1, and the smoothing function δ in Eq. (6) was set to 100. The switching gains of the non-linear control term η were set to 4000 and 8000 as test perameters; these were labeled SMC 4000 and SMC 8000, respectively. The performance of the sliding mode control was compared with two passive strategies: passive-off and passive-on. These strategies set the electric current command in the MR damper to $I = 0$ or a constant electric current $I = 4$ A, respectively.

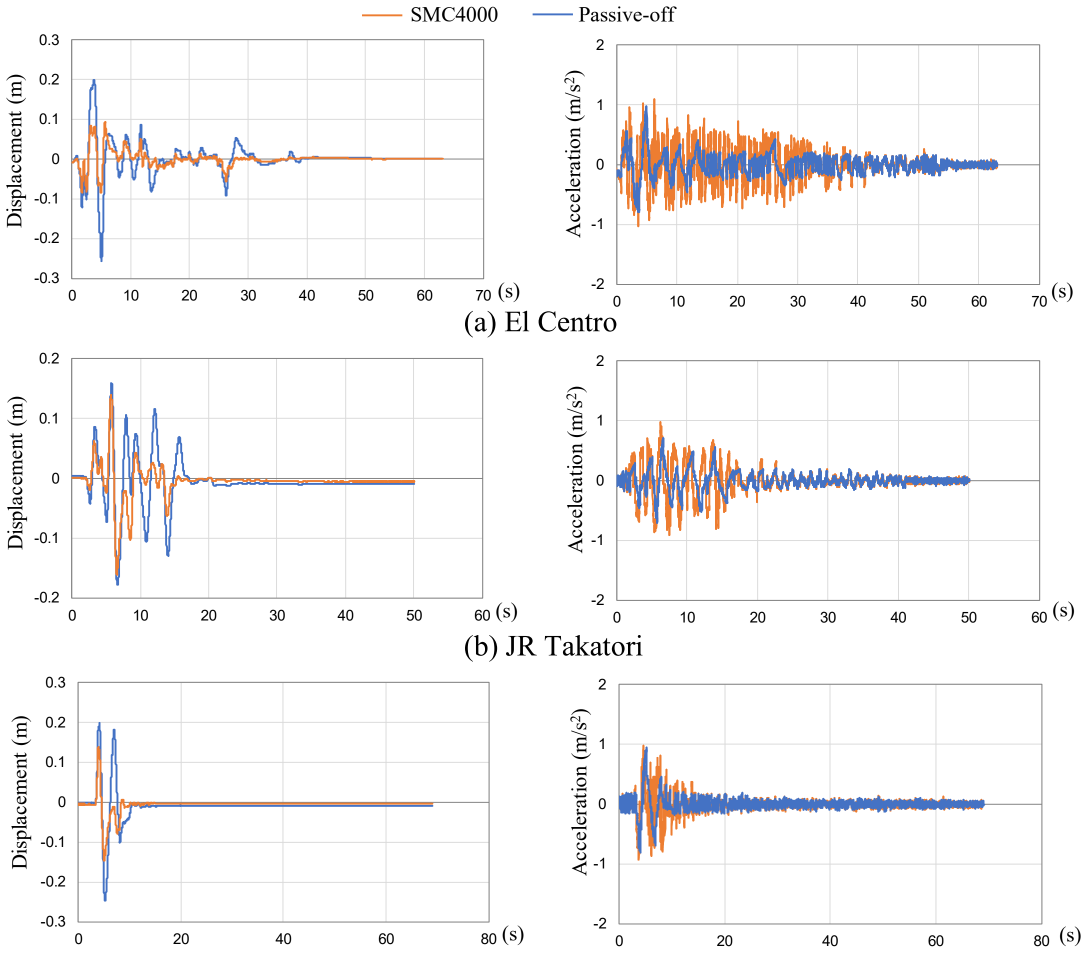
The input ground motions used for the tests were the El Centro 1940 NS record multiplied by 1.5, the JR Takatori 1995 NS record multiplied by 0.4, and the Sylmar 1994 NS record multiplied by 0.5 with consideration for the stroke of the MR damper.

3.4 Experiment results

The time histories of the response displacement and acceleration with SMC 4000 and the passive-off (0 A) for all ground motions are shown in Figure 3. Experiment acceleration data had noise with a high frequency, therefore, the moving average of three successive values was used for evaluation (corresponding to a 15 Hz low-pass filter). The peak displacement of SMC 4000 was drastically reduced, particularly for El Centro and Sylmar, whereas the acceleration was larger than the passive-off for all ground motions.

Table 1 lists the peak displacements, peak accelerations, and root-mean-square accelerations for all cases. For SMC 4000, the peak displacements were suppressed relative to the passive-off for all ground motions. They were reduced by 64% for the El Centro, by 41% for the Sylmar, and by 10% for the JR Takatori. Additionally, the sliding mode control accelerated the convergence of response displacement. This indicated that, as a feature of the sliding mode control, the state variable reached the switching surface immediately after occurrence of the large pulse. Compared with the passive-on (4 A constant), the displacement with SMC 4000 was slightly larger for the Sylmar, whereas they decreased for the El Centro and JR Takatori. The peak accelerations and root-mean-square accelerations with SMC 4000 increased for all ground motions compared with the passive-off, however they were smaller than those for the passive-on. The chattering of the control signal for the sliding mode control was not observed in the experiments due to the effect of the smoothing function mounted in the non-linear control term of the sliding mode control, as shown in Eq. (6).

With the SMC 8000, the accelerations increased by 9–36% compared with the SMC 4000 because an excessive control force was exerted on the structure due to the twofold increase in the non-linear control term. Since the peak value of the target damper force of SMC 8000 was not achieved due to the limitation of the electric current (4A), the displacements with SMC 8000 were slightly larger than those with SMC 4000. The



(a) El Centro

(b) JR Takatori

(c) Sylmar

Fig. 3 Comparison between SMC 4000 and the passive-off.

Table 1 Comparison of responses for four control strategies.

		SMC 4000	SMC 8000	Passive-off	Passive-on
El Centro	Peak displ. (mm)	93.1	108	257	109
	Peak acc. (m/s^2)	1.09	1.33	0.97	1.18
	R.M.S. acc. (m/s^2)	0.25	0.31	0.16	0.32
JR Takatori	Peak displ. (mm)	161	176	179	182
	Peak acc. (m/s^2)	0.98	1.07	0.72	1.15
	R.M.S. acc. (m/s^2)	0.21	0.26	0.14	0.27
Sylmar	Peak displ. (mm)	146	152	247	130
	Peak acc. (m/s^2)	0.98	1.34	0.95	1.07
	R.M.S. acc. (m/s^2)	0.14	0.17	0.12	0.17

peak displacements and root-mean-square accelerations with SMC 8000 were almost identical to those in the passive-on because the damper force of the two controls were similar.

Using the optimum parameters of the control, the eventual sliding mode control employing the MR damper reduced response displacement for the isolated structure without a large increase in acceleration.

3.5 Comparison between experiments and simulations

The shaking table test results were compared with simulation results. In the simulation, friction force was set to 2 kN, which was measured in the experiments. The time histories of the displacement, acceleration, and the damper force of SMC 4000 for El Centro are shown in Figure 4. The simulation responses agreed well with those of the test results within an error of peak values up to 15%. Similar good agreement was also observed for other controls and ground motions.

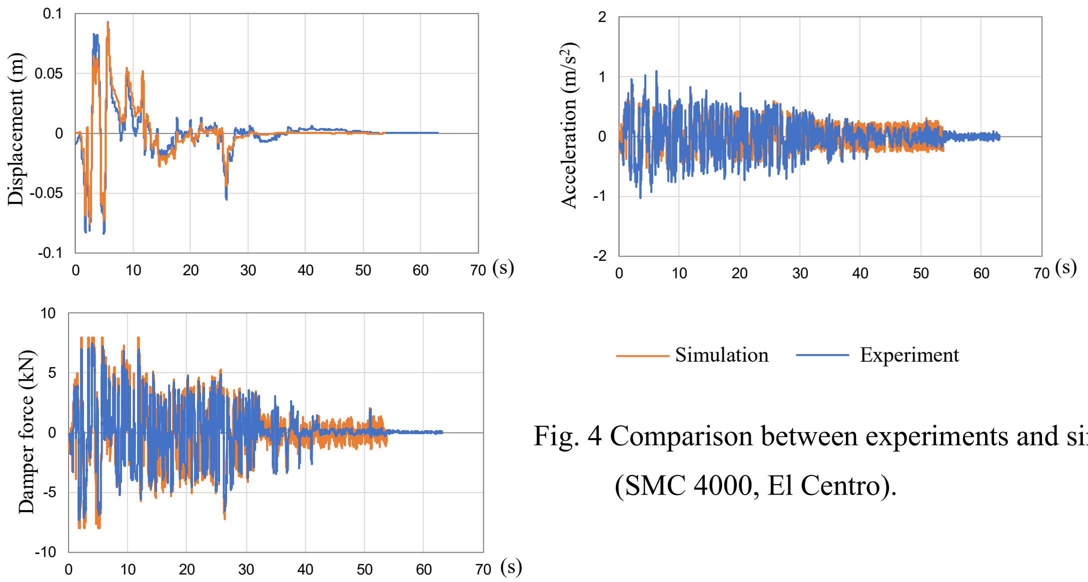


Fig. 4 Comparison between experiments and simulations (SMC 4000, El Centro).

4. Conclusions

A series of E-Defense shaking table tests were conducted to validate the effectiveness of a semi-active control for an MR damper. The eventual sliding mode control algorithm was applied to a one-story isotated structure.

1) The sliding mode control was confirmed effective for reducing the maximum displacement without a large increase in the acceleration and for achieving rapid convergence of the response displacement.

2) By comparing the shaking table test results with simulation results, it was found that the displacement, acceleration, and damper force showed good agreement between the experiments and simulations.

5. Acknowledgements

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6. References

[1] Mai Ito, Hideo Fujitani (2008): *Semi-active vibration control with MR damper utilizing sliding mode control theory*. Summaries of technical papers of annual meeting, Architectural Institute of Japan, 481-482. (in Japanese)

[2] J.N. Yang, J.C. Wu, A.K. Agrawal, Z. Li (1995): *Sliding mode control for seismically excited linear structures*. Journal of Engineering Mechanics, 121(12), 1386-1390.

[3] Christopher Edwards, Sarah K. Spurgeon (1998): *Sliding Mode Control: Theory and Applications*. Taylor & Francis.

[4] Vadim Utkin, Jurgen Guldner, Jingxin Shi (2009): *Sliding Mode Control in Electro-Mechanical Systems*. CRC Press.

