SEMIACTIVE CONTROL OF SEISMIC RESPONSE BASED ON STORY DISPLACEMENT USING MAGNETORHEOLOGICAL FLUID DAMPER

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ABSTRACT :

This paper discusses the characteristics of the dynamic response of a structure with simple semiactive control system. The control system consists of magnetorheological fluid (MR) dampers which were set up in each inter-story level. MR damper whose damping force is variable according to applied electric current is one of the semiactive control devices. The proposed control method of the damper force was based on potential energy of inter-story and in addition controlled the hysteretic shape. Shaking table tests were performed on a one-story steel structure model. In the tests, three kinds of damper supporters were examined in order to clarify the influence of the support stiffness on the damping properties and control effectiveness. Effectiveness of the proposed method was examined by comparing the numerical results and the experimental results. In the case of using soft support member, the seismic response increases as damper force exceed a critical value. However, the proposed control method is found to be better than the conventional ones. For such control system, the hysteretic control and support member stiffness are significantly influential on effectiveness of the seismic control.

KEYWORDS: Structural control, Semiactive control, Magnetorheological fluid damper

1. INTRODUCTION

In recent years, vibration control systems have been adopted in many buildings in Japan, a lot of which utilize passive supplemental damping schemes. These passive device methods are unable to adapt to structural changes and to varying usage patterns and exciting condition. Active, semiactive structural control systems are evolution of passive control techniques. Especially, semiactive control systems, which need energy in order to alter damping characteristics, are different from active control, which needs more huge energy to suppress seismic response directly. Semiactive control is stable as compared with the active control. Thus, semiactive control schemes are expected to play a much more significant role in future stages of civil engineering and can enhance structural safety during severe earthquakes.

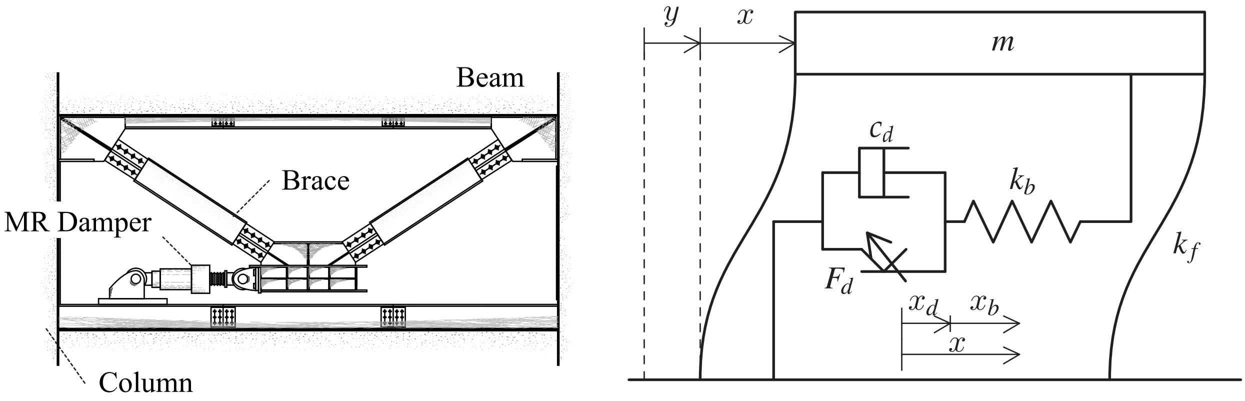
Various types of semiactive control methods have been proposed. A typical approach is to apply a modern control theory such as linear quadratic optimal control. However, the variable damper's highly nonlinear dynamics makes it difficult to determine the optimal control parameter in such an approach. On the other hands, simple control methods have been also proposed. On/off switching control using variable hydraulic damper is to optimize the force-displacement loops (Kurino et al. 1998). Using variable slip-force level damper, Nishitani et al. (2003) proposed a simple control method in such a way that the damper exhibits bilinear hysteresis with a ductility factor equal to two. Shiozaki et al. (2002) proposed EF control that controls damping force depending on vibration energy of a base isolated structure using magnetorheological fluid (MR) damper. MR damper whose damping force can be variable is one of the semiactive control devices.

This paper proposes a simple semiactive control method utilizing MR dampers which were set up in each inter-story level of building structure. The proposed control method of the damper force based on potential energy of inter-story and controls the hysteretic shape. The basic concept of this semiactive control method is first explained in the following. The control effectiveness of this scheme is then discussed through shaking table tests on a one-story steel structure model. In the shaking table tests, three kinds of damper supporters were examined in order to focus on damper support stiffness impact on the control effectiveness.

2. OUTLINE OF THE CONTROL METHOD

2.1 Structural Model with MR Damper

Structural frame with MR dampers which were set up in each inter-story of building is showing in Figure 1. A simplified analytical model to represent it is shown in Figure 1b, where m is the mass of the frame, k_f is the stiffness of the original frame. MR damper is represented as a Bingham model which consists of a variable frictional element F_d and dashpot c_d in parallel. The Bingham model is in series with a spring element which represents the damper support members (k_b indicates the stiffness of the brace). It was assumed that k_f and k_b are linear, and only F_d can only be variable while c_d is constant.



(a) Installation of MR damper at inter story

(b) Analytical model

Figure 1 Analytical model of the structure with MR Damper

Here, a parameter α represents the stiffness ratio of damper support members to the frame stiffness defined as:

$$\alpha = \frac{k_b}{k_f} \tag{2.1}$$

2.2 Semiactive Control Algorithm

The frictional force of the MR damper was controlled according to the following law.

$$|F_d| = \begin{cases} \lambda\sqrt{\dfrac{1}{2}k_f x_p^2} = \Lambda|x_p| & \mathrm{sgn}(x) \neq \mathrm{sgn}(\dot{x}) \\ \Lambda|x_p|\left(1 - \dfrac{|x|}{|x_{\max}|}\right) & \mathrm{sgn}(x) = \mathrm{sgn}(\dot{x}) \ \ \& \ \ |x| \leq |x_{\max}| \\ 0 & \mathrm{sgn}(x) = \mathrm{sgn}(\dot{x}) \ \ \& \ \ |x| > |x_{\max}| \end{cases} \tag{2.2}$$

where x is the displacement of the frame and $\dot{x}$ is the velocity of the frame. A parameter x_p indicates peak displacement which occurs at the time of zero velocity. At the time of zero velocity ($\dot{x} = 0$), controlled frictional force of the MR damper is determined based on a potential energy of the structure. The control force can be calculated as follows: the square root of the potential energy multiplied by a control gain λ. In addition, if equation (2.2) is rearranged using $\Lambda = \sqrt{\frac{1}{2}}k_f$, the control force at the time of peak displacement is simply evaluated as $F_d = \Lambda|x|$. When the sign of displacement of the frame (x) is not same as the velocity ($\dot{x}$), the control force F_d, which was evaluated just at the peak displacement, was kept fixed. When x and $\dot{x}$ have the same sign, F_d is reduced proportionally in such way that F_d becomes zero when x reaches its maximum value. The hysteresis loop of this semiactive control, when subjected to sinusoidal excitation, is shown in Figure 2.

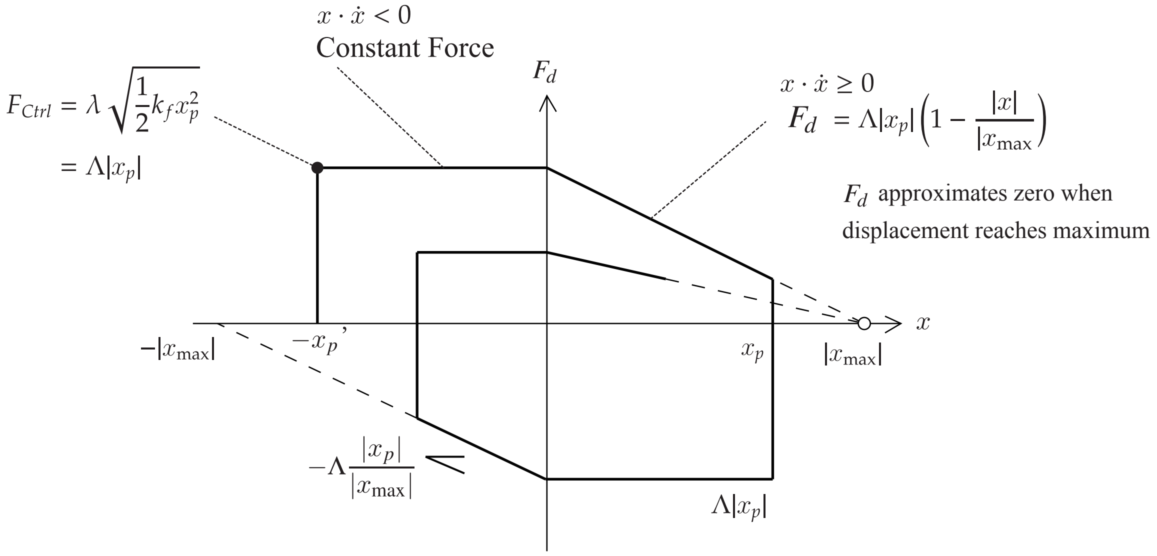


Figure 2 Hysteresis loop with the semiactive control

3. METHOD OF SHAKING TABLE TESTS

3.1 Configuration of the testing system

A one-story steel structure model with MR damper was tested at Laboratories of Architecture and Building Science of Tohoku University, Japan. The size of the frame was 1,645 mm high, 2,540 mm long and 1,440 mm wide as illustrated in Figure 3. The mass of the structure was 2,200 kg. The frame without any damper added had a minimal damping (damping ratio was 0.06 %). The natural frequency of the structure without any damper added was 1.8 Hz and the stiffness was 280.6 kN/m. Three kinds of damper support members were used to attach the MR damper to the frame. Support member section properties are shown in Table 1. T3 and T9 were fabricated from two plate sections and HH consists of 148x100x6x9 H-section steel. Stiffness ratio α of them follows: T3 and T9 was 0.3 and 0.9 respectively. HH was stiff enough compared to the frame stiffness.

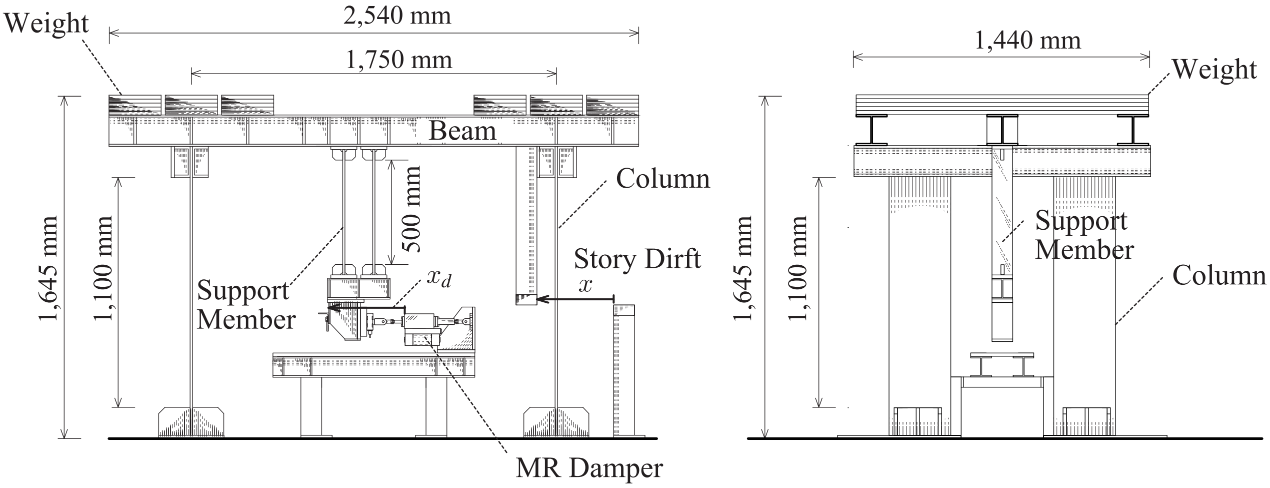


Figure 3 Configuration of tested structural model

3.2 Properties of the MR damper

Sodeyama et al, (2004) have proposed MR dampers, which have a bypass-flow type magnetizing mechanism. The MR dampers developed by them have a bypass portion in which the electromagnets are installed. The MR fluid passing through the narrow orifice in the bypass portion is applied the magnetic field by electromagnets.

Table 1 Section properties of three kinds of damper support members

	T3	T9	HH
Section shape	plate section	plate section	H-section
Section size	7x75 mm	10.5x75 mm	148x100x6x9
Area	525 mm^2	787.5 mm^2	2,635 mm^2
Second moment of area	2.14x10^3 mm^4	7.24x10^3 mm^4	1.00x10^7 mm^4
Section Modulus	6.13x10^2 mm^3	1.38x10^3 mm^3	1.35x10^5 mm^3
Stiffness	89.1 kN/m	259.2 kN/m	stiff enough
Stiffness ratio α	0.32	0.92	

In this paper, the bypass-type MR damper which has a capacity of 2 kN was used. The schematic structure of the MR damper is shown in Figure 4. Table 2 shows the design specifications of the MR damper. The piston stroke is 73 mm. MR fluid was enclosed in the cylinder and the bypass portion.

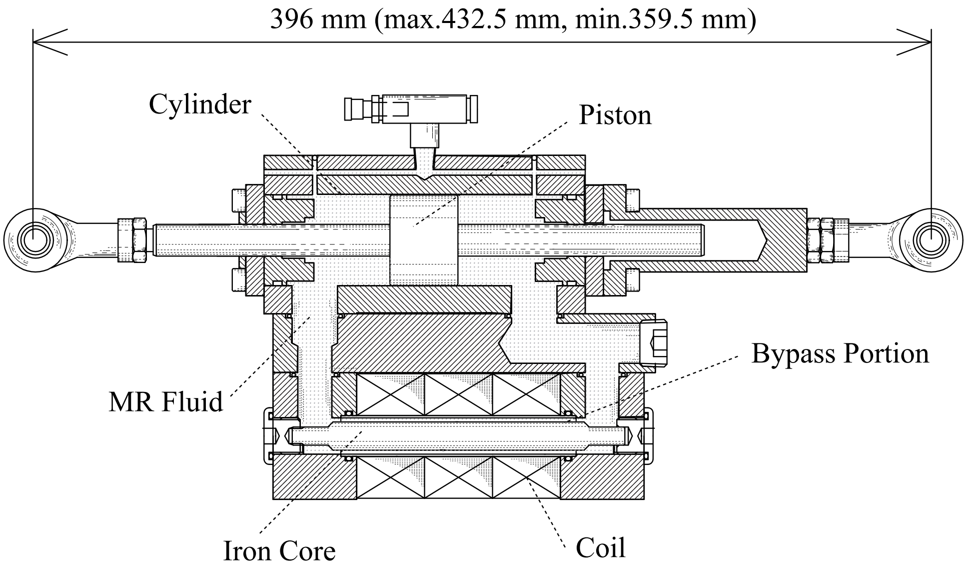
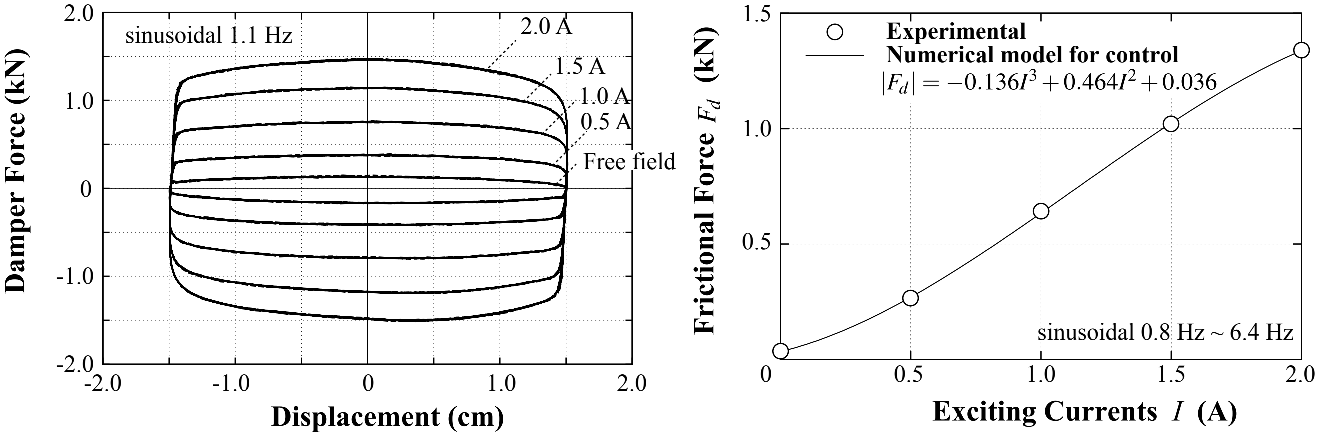


Figure 4 Schematic of 2 kN MR damper

Table 2 Specifications of the MR damper

Rated Load		2 kN
Stroke		73 mm (±36.5 mm)
Cylinder bore		40 mm
Piston rod dia.		14 mm
Bypass orifice	Outer dia.	16 mm
	Inner dia.	12.5 mm (Iron core dia.)
	Length	90 mm
MR fluid		#230 of Bando Chemical Industries, Ltd.,
Electromagnet	Coil	ϕ0.6/2PEW 460 turns × 3
	Inductance	26.9 mH
	Resistance	10.7 Ω

The cyclic loading tests were carried out to clarify the fundamental dynamic characteristics of the MR damper. Figure 5 shows displacement-force hysteresis loops and the relationship between input electric currents and frictional force generated by the MR damper. These are measured under the sinusoidal loading conditions as following: amplitude 15 mm; piston velocity 10 cm/s. In Figure 5b, the rigid line indicates the predicted performance at the semiactive control in this research.



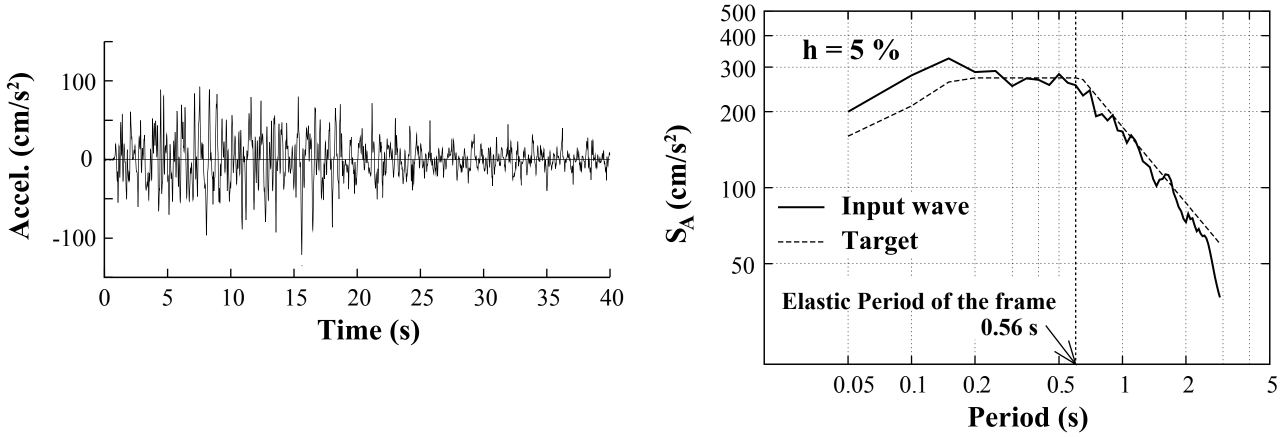
(a)displacment-force hysteresis loop **(b)exciting currents-frictional force relationship**

Figure 5 Displacement-force hysteresis loops and exciting currents-frictional force relationship

3.3 Experimental Method

Shaking table tests also have been carried out using a simulated earthquake ground motion. The simulated ground motion (Figure 6a) was obtained using the phase characteristics of the 1978 Miyagi-ken Oki Earthquake. The peak ground acceleration (PGA) was 0.12G. From the input wave, the spectral characteristics were calculated (Figure 6b) based on the design spectrum stipulated in the Japanese design code.

These tests aim to confirm a seismic response mitigation effectiveness of the semiactive control scheme and to clarify an influence of the support stiffness on the damping properties and control effectiveness. Constant exciting current inputting to the MR damper (i.e. passive control) were also examined during the tests.

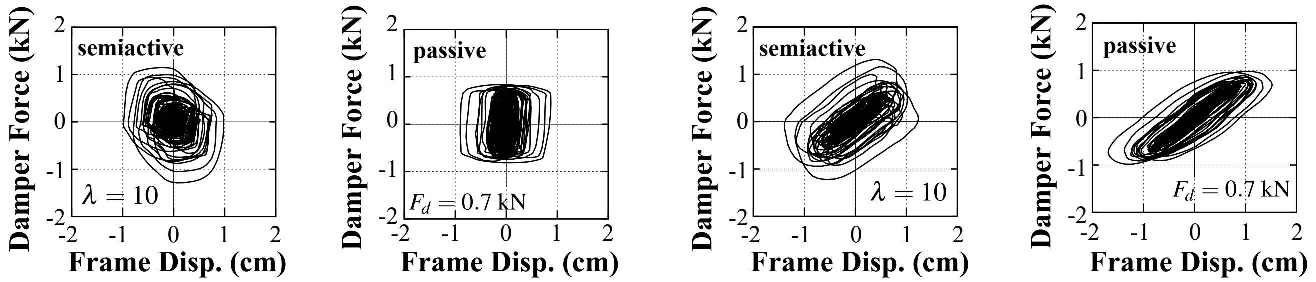


a) Input Wave **b) Response Spectrum**

Figure 6 Simulated seismic wave used in shaking table tests

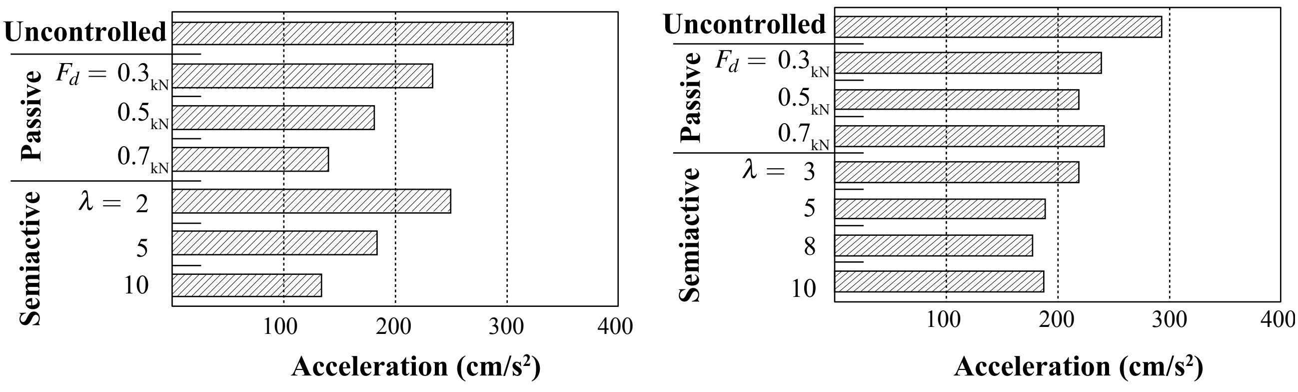
4. RESULTS OF SHAKING TABLE TESTS

Figure 7 gives damper force - frame displacement hysteresis loops at the maximum damping force for the damper support member HH and T3, in the case of semiactive control and passive control. These loop shapes are well controlled by the proposed algorithm. However, in the case of T3, shapes of loops perform like a linear spring k_b because damper force is so large that support member is deformable under such large force. Thus, it is clear that α is a major parameter in both the semiactive control and the passive control. The maximum response acceleration values are shown in Figure 8. Form this figure, it can be seen that when the support member HH is used, large damping force exhibits higher mitigation of the response acceleration. In the case of T3 (i.e. minimum α in these tests), if the damper force (control gain λ) becomes very large, the acceleration response will become large. The response acceleration for $\lambda = 8$ is the smallest of all the cases. Considering the above results, it can be said that as in the passive control case, optimal value of λ seems to exist in the case of the proposed semiactive control method.



(a) support memeber HH (stiff enough) **(b) support memeber T3** ($\alpha = 0.3$)

Figure 7 Damper force - frame displacement hysteresis loops



(a) support memeber HH (stiff enough) **(b) support memeber T3** ($\alpha = 0.3$)

Figure 8 Maximum response acceleration values

5. NUMERICAL ANALYSIS USING EQUIVALENT LINEARIZATION METHOD

5.1 Analytical Method

To examine the performance of the proposed control scheme under seismic excitations, numerical analysis based on equivalent linearization method were conducted. This method, which has been first introduced by T.K.Caughey (1960) is very useful and practical because of the simplicity of its theory.

For this proposed semiactive method, a parameter η, which represents the ratio of loss stiffness of damping force to the frame stiffness, is defined as

$$\eta = \frac{\lambda\sqrt{\frac{1}{2}k_f}}{kf} = \frac{\Lambda}{k_f} \tag{5.1}$$

For the semiactive controlled structure vibrating in resonance with steady state sinusoidal excitation, equivalent elastic period T_{eq} and equivalent damping ratio h_{eq} are given by

$$T_{eq} = \frac{1}{\sqrt{1+C(\alpha,\eta)}} \cdot T_f \tag{5.2}$$

$$h_{eq} = \frac{-S(\alpha,\eta)}{2\,(1+C(\alpha,\eta))} + \frac{h_f}{\sqrt{1+C(\alpha,\eta)}} \tag{5.3}$$

where T_f is elastic period and h_f is damping ratio of the frame without the damper added. In the case of this semiactive control algorithm, C and S are functions of α and η as following

$$C(\alpha,\eta) = \begin{cases} \dfrac{1}{\pi}\left\{\alpha\theta^* - (\alpha-\eta)\sin\theta^* - \dfrac{\pi}{2}\eta\right\} & \alpha \ge \eta \\[2ex] \dfrac{1}{\pi}\{(\alpha+\eta)\theta^* - (\alpha-\eta)\sin\theta^* - \pi\eta\} & \alpha < \eta \end{cases} \tag{5.4}$$

$$S(\alpha,\eta) = \begin{cases} \dfrac{1}{\pi}\left\{\alpha\sin^2\theta^* + \dfrac{2}{\alpha}(\alpha-\eta)^2 - 2\alpha - \eta\right\} & \alpha \ge \eta \\[2ex] \dfrac{1}{\pi}\{-(\alpha+\eta)\sin^2\theta^*\} & \alpha < \eta \end{cases} \tag{5.5}$$

where θ^* is given by

$$\cos\theta^* = \begin{cases} 1 - \dfrac{\eta}{\alpha} & \alpha \ge \eta \\[2ex] \dfrac{\alpha-\eta}{\alpha+\eta} & \alpha < \eta \end{cases} \tag{5.6}$$

Under constant spectral acceleration, response reduction ratio of acceleration R_a and that of displacement R_d are given by

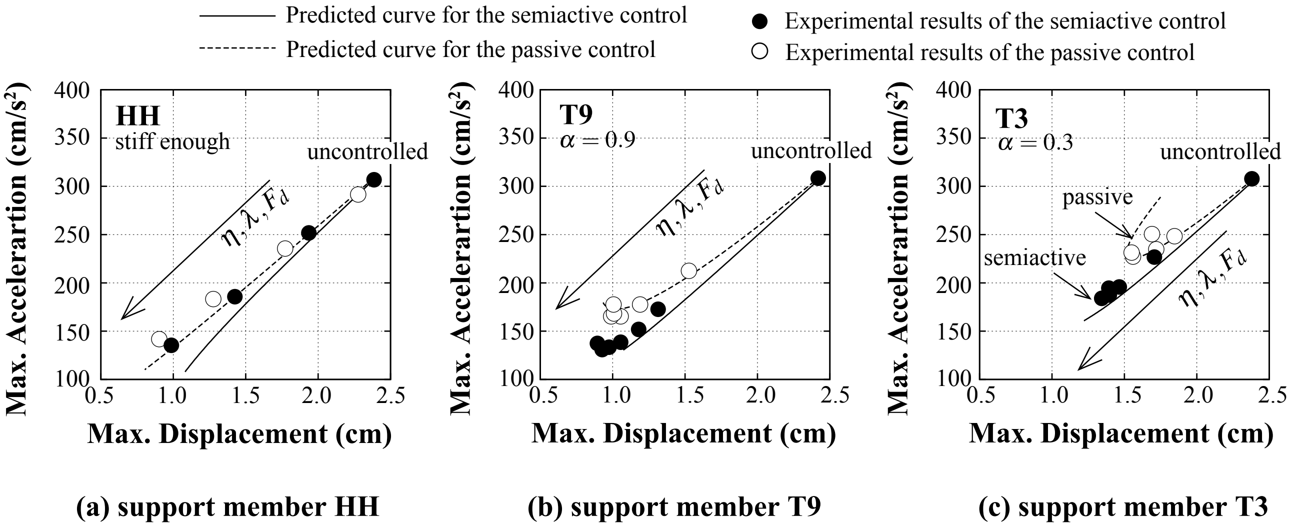
$$R_d = D_h\left(T_{eq}\middle/T_f\right)^2 \qquad R_a = R_d\left(T_f\middle/T_{eq}\right)^2 \tag{5.7}$$

where D_h indicates a damping effect factor, which is introduced by Kasai et al. (2003). For simulated seismic excitation, D_h is given by

$$D_h = \sqrt{\frac{1+75h_f}{1+75h_{eq}}} \tag{5.8}$$

5.2 Analytical Results using Equivalent Linearization Method

Figure 9 shows predicted maximum displacement and acceleration curves and their comparison with the experimental results. The predicted values using equivalent linearization method agree well with the experimental values. The result suggests that parameter α and η are significantly influential on the seismic control effectiveness. In the case of using rigid support member (HH), this proposed control scheme appears to be more effective in reducing the acceleration than the displacement. Moreover, using soft support member (T9 and T3), in the case of passive control, the seismic response increases as the damper force crosses a certain value. However, the semiactive proposed control method does not show such tendency.



(a) support member HH **(b) support member T9** **(c) support member T3**

Figure 9 Predictions of Maximum Displacement and Acceleration

6. CONCLUSION

A simple semiactive control based on energy response of the structure utilizing MR dampers has been presented. The response reduction of this scheme was confirmed though the shaking table tests performed on a one-story steel structure model. The control performance could be predicted by equivalent linearization method discussed here. It was found that the parameters α and η are significantly influential on effectiveness of the seismic control for structures.

ACKNOWLEDGEMENTS

This research was partially supported by the Ministry of Education, Culture, Sports, Science and Technology, Japan, under the Grant-in-Aid for Young Scientists (A), (Grant No. 18686046).

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