A STUDY AND DEVELOPMENT OF SEMI-ACTIVE CONTROL METHOD BY MAGNETORHEOLOGICAL FLUID DAMPER IN BASE ISOLATED STRUCTURES

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ABSTRACT:

The semi-active damping devices can vary their damping characteristics without large power source, and can improve seismic response of building. MR damper (magnetorheological fluid damper) is one of the suitable devices for semi-active seismic response control of structures. The purpose of this study is to develop a simple and effective semi-active control method to reduce seismic response of base isolated structures by MR damper. Proposed method is only based on the response displacement of isolated story, and attempt to reduce response displacement of isolated story and acceleration to superstructure. By applying this control method, the displacement and acceleration response can be reduced with relatively smaller damper force.

KEYWORDS: Semi-active control, MR damper, Base isolation, Control algorithm

1. INTRODUCTION

Base isolated structures can reduce seismic response acceleration by the effect of their long natural period and damping, but these structures demand large displacement clearance at the isolated story because of large response displacement. Furthermore, over predicted response displacement may occur by severe earthquake or ground motion including low frequency components. In case of usual passive damping devices, larger damping performance will be required to decrease larger predicted response displacement, but too much damping performance may prevent reduction of response acceleration.

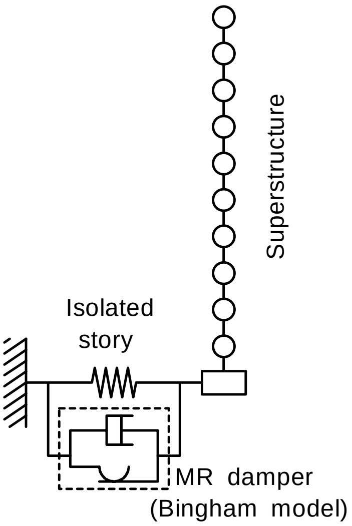
For effective reduction both of response displacement and acceleration, semi-active control, that varies damping performance (stiffness or damping coefficient of devices) corresponding to seismic response behavior of the structure, is developed. Relevant semi-active control is expected to reduce seismic response caused by various earthquakes, such as moderate or severe intensity, cyclic or pulse type, different frequency components, and devices can be used without large power source and complicated mechanism. MR damper (magnetorheological fluid damper), whose viscosity is varied as power of the magnetic field, is one of the suitable devices for semi-active seismic response control of structures.

The purpose of this study is to develop a simple and effective semi-active control method by MR damper on base isolated structures. MR damper is installed in isolated story and controlled. At first step, seismic response behavior of structures and control effect by the optimal control algorithm based on Linear Quadratic Regulator theory, are investigated. This algorithm can estimate optimal control force of devices with evaluating several response indices (in this study, top acceleration, displacement of the isolated story, and MR damper force), but it requires real time information of response displacement and velocity at all stories of the structure. Because practical inconvenience such as requirement of many sensors, increase of calculation time, time lag of damper force, and so on are expected, a simple control method only based on response displacement of the isolated story is attempted to develop in next step of this study.

2. ANALYTICAL METHOD

2.1. Model of structure and MR damper

Subjected structure is ten-story base isolated R/C building, and lumped mass model is shown in Figure 1. MR damper for semi-active control is in isolated story. Without magnetic field, MR damper provides only viscous damping force. When the magnetic field caused by electrical current exists around the orifice, variable damping force corresponding to the intensity of the magnetic field is provided besides viscous damping force.
For the analytical model of MR damper (Spencer, *et al*. 1997; Wen 1976), Bingham model that has dashpot for viscosity and friction slider for variable damping force is used in this study. The required control force is provided by friction slider, and therefore total damping force of MR damper is the sum of the control force by friction slider and the viscous damping force by dashpot. And when the electrical currents are provided, it takes some short time to start providing required control force generally. But in this study, this time lag is neglected because subjected base isolated structure has relatively long natural period.



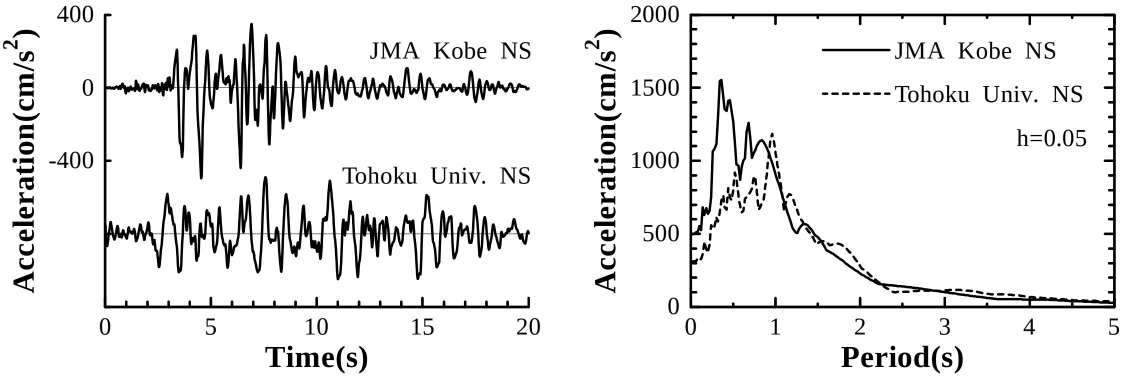
Superstructure
Story height : 4.0m
Floor mass : 388.8t=1.2t/m^2 × 18m × 18m
Elastic
Viscous damping factor : 0.03
Isolated story
Stiffness : K_I =10553kN/m (elastic)
First floor mass : 388.8t
No viscous damping
Viscous damping coefficient of MR damper : 403kNs/m
(Damping factor is 0.03)

Natural Period	1st mode	2nd mode
Superstructure	0.8sec.	0.3sec.
Base isolated structure system	4.1sec.	0.5sec.

Figure 1. Analytical model of subjected base isolated structure

2.2. Input Ground Motions

Characteristics of input ground motions are shown in Figure 2. JMA (Japan meteorological agency) Kobe NS record from 1995 Hyogo-ken nanbu earthquake that occurred in near fault of Kobe city, has pulse type property and short duration time. Tohoku University NS record from 1978 Miyagi-ken oki earthquake that occurred in ocean plate, has cyclic type property and long duration time. Normalized records by PGV=50cm/s are used in this paper.



(a) Time history of acceleration **(b) Acceleration response spectra**

Figure 2. Input ground motions normalized by PGV=50cm/s

3. OPTIMAL CONTROL BASED ON LINEAR QUADRATIC REGULATOR THEORY

3.1. Algorithm

For the control algorithm of buildings with AMD (Active Mass Damper) system, the optimal feedback control based on such as LQR (Linear Quadratic Regulator) theory is applied generally. And application to base isolated system is investigated as well (Ramallo, *et al*. 2002; Yang 1975). This control algorithm provides optimal control force with evaluating several response indices. In this chapter, seismic response behavior and reduction effect of MR damper controlled by LQR theory to reduce both response displacement of isolated story and response acceleration of superstructure is shown.

By evaluating top acceleration $\ddot{x}_{11} + \ddot{x}_0$ of superstructure ($\ddot{x}_0$ is ground acceleration) and control force F by MR damper, a performance index J in this study is determined by Eqn. 3.1.

$$J = \int \alpha (\ddot{x}_{11} + \ddot{x}_0)^2 dt + \int \gamma F^2 dt \tag{3.1}$$

in which α and γ are control factor of top acceleration and control force respectively. Response displacement of isolated story increases as control force F decreases, and decreases as F increases. Because the value of response displacement depends on the value of F, response displacement is not included in J for the simplification.

The optimal control force F for feedback control to minimize the value of J is given in the formulation of Eqn. 3.2.

$$F = \{G\} \begin{Bmatrix} \{\dot{x}\} \\ \{x\} \end{Bmatrix} \tag{3.2}$$

in which $\{x\}$ is relative displacement of each floor from the ground. The feedback gain $\{G\}$ is given by solving Riccati equation (Laub 1979), and is constant vector determined by structural properties (i.e. mass, damping coefficient and stiffness of structure) and control performance (i.e. α and γ). The relation diagram of response values and required control force is shown in Figure 3. Observed data of response velocity $\dot{x}_i$ and response displacement x_i of all floors are required in this control algorithm. Because MR damper is semi-active device that causes only passive resisting force, MR damper provides control force only in case that the direction of required control force F is opposite to the movement, that is, velocity $\dot{x}_1$ of isolated story. In case that these directions are same, control force should be zero.

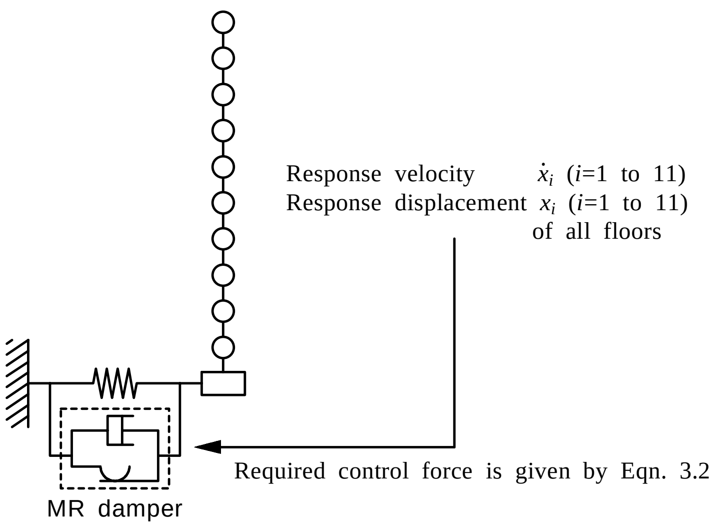
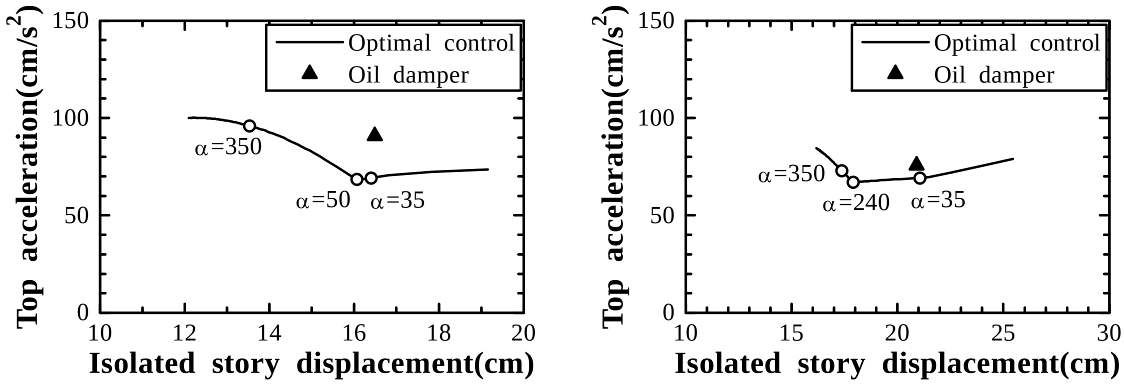


Figure 3. Optimal control by linear quadratic regulator theory

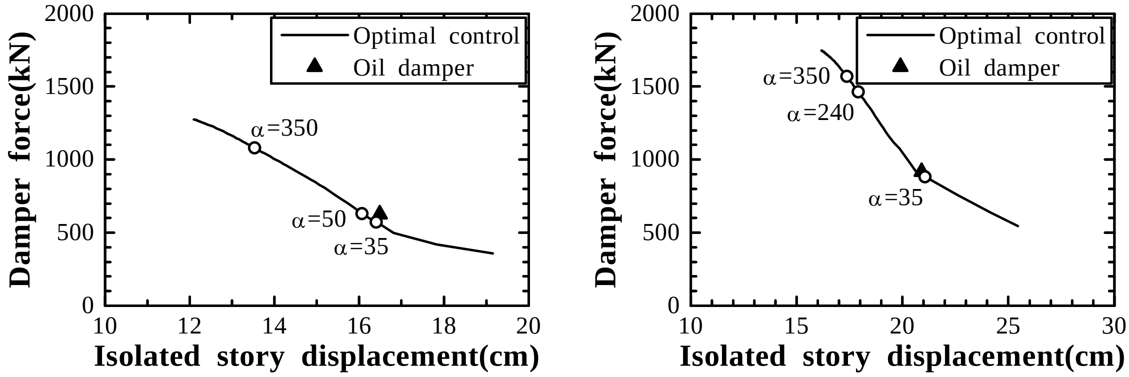
3.2. Control factor and control effect

To investigate the effect of control factor α and γ in Eqn. 3.1, maximum response values in case of optimal control with constant $\gamma=10^{-4}$ and various α are shown. In Eqn. 3.1, cm/s^2 for top acceleration and kN for control force are used as units. Figure 4 shows top acceleration and isolated story displacement, Figure 5 shows damper force and isolated story displacement, and maximum response values by oil damper with damping factor 0.10 are also shown.



(a) JMA Kobe NS **(b) Tohoku Univ. NS**

Figure 4. Maximum response values of top acceleration and isolated story displacement with various α



(a) JMA Kobe NS **(b) Tohoku Univ. NS**

Figure 5. Maximum response values of damper force and isolated story displacement with various α

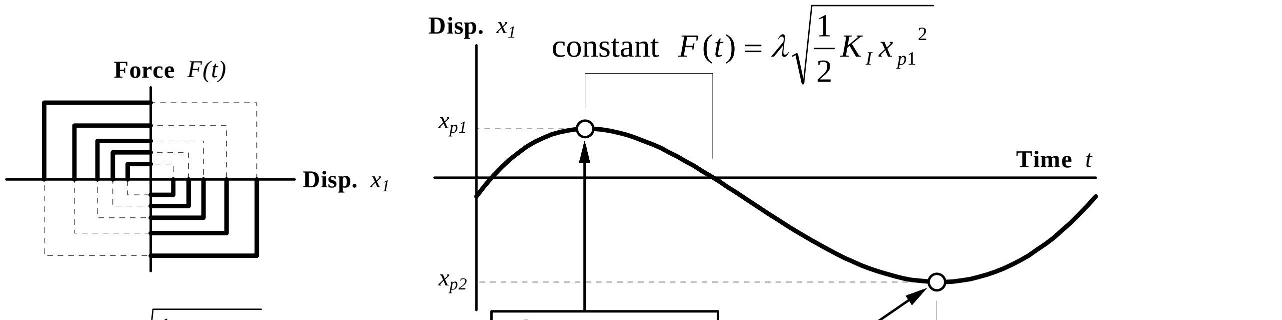
Though displacement is reduced as α increases, top acceleration increases in the range of large α (larger than 50 in Kobe case, larger than 240 in Tohoku case). In Kobe case, top acceleration and damper force increases as α increases. In Tohoku case, damper force is larger than that in Kobe case, however, top acceleration does not increase largely. It is necessary to select suitable α in the range that top acceleration and damper force are not too large.

4. SIMPLE CONTROL BY RESPONSE DISPLACEMENT OF ISOLATED STORY

4.1. Purpose and control force of proposed control method

A simple control method only based on response displacement of isolated story is proposed in this chapter.
When the absolute value of displacement x_1 of isolated story decreases, namely, in the second and fourth quadrant of damper force-displacement diagram, control force $F(t)$ is determined as Eqn. 4.1 in Figure 6 to have suitable capacity of energy dissipation corresponded to response level. λ is a factor for the intensity of control. In this study, the time history is divided into each interval time of peak displacement, that is, half cycle.

In each half cycle, elastic vibration energy (kinematic energy + potential energy) is assumed to be constant in this study. And accordingly control force $F(t)$ can be assumed as constant value given by potential energy at the start of each half cycle as shown in Figure 6. Because the capacity of energy dissipation changes according as response amplitude, various response levels from small to large, can be controlled relevantly.



$$F(t)=\lambda\sqrt{\frac{1}{2}K_I x_p{}^2} \tag{4.1}$$

Figure 6. Determination of control force in the second and fourth quadrant

$$F(t)=Fa=\lambda\sqrt{\frac{1}{2}K\,x_p{}^2} \qquad F(t)=Fa\left(1-\frac{|x_1|}{x_{max}}\right) \tag{4.2}$$

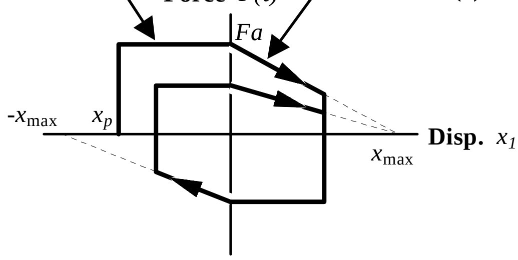


Figure 7. Control force of proposed control method

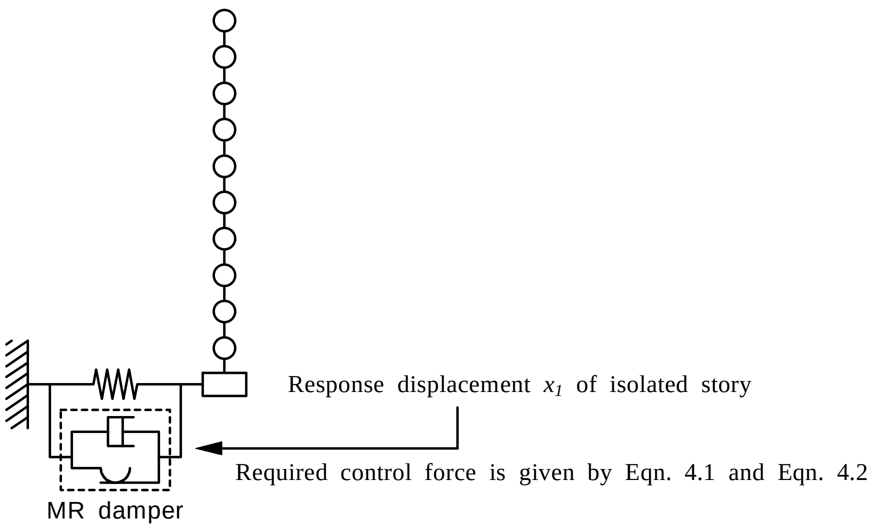


Figure 8. Proposed control by response displacement of isolated story

When the absolute value of displacement x_1 of isolated story increases, namely, in the first and third quadrant of damper force-displacement diagram, control force $F(t)$ is determined as Eqn. 4.2 in Figure 7. Because large damper force will cause large inertia force or large acceleration, $F(t)$ is decreased to be zero at tentative maximum displacement x_{max} until then.

The relation diagram of response value and required control force is shown in Figure 8. Proposed control method needs only response displacement of isolated story, and can provide relevant control force for reduction of response displacement and acceleration.

4.2. Response control effect of control methods

Comparison of response behavior with various dampers and control methods, (a) Oil damper (h=0.10); (b) Optimal control by MR damper; (c) Proposed control by MR damper, is shown.

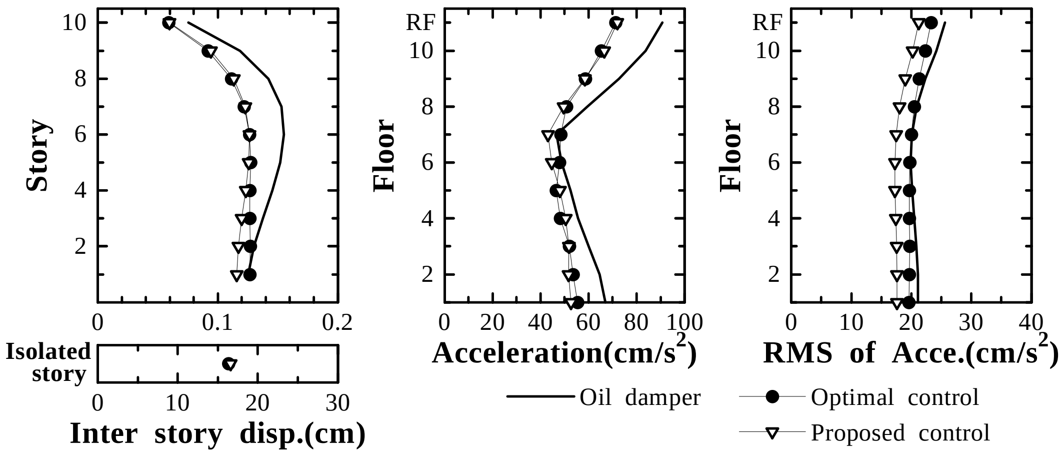
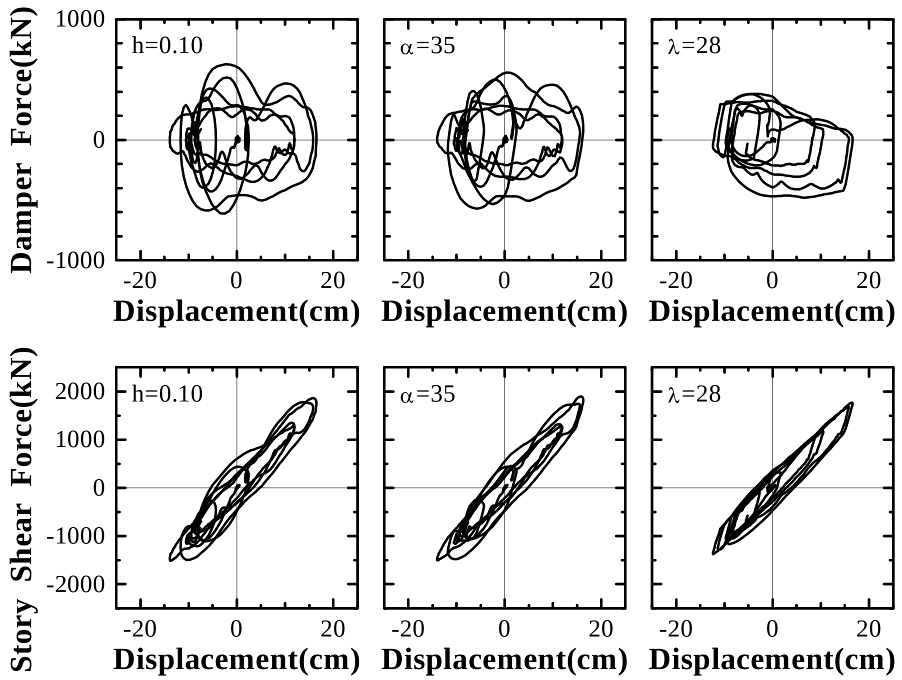


Figure 9. Maximum response values with various dampers (JMA Kobe NS)



(a) (b) (c)

Figure 10. Hysteresis loop of damper and isolated story with various dampers (JMA Kobe NS): (a) Oil damper; (b) Optimal control by MR damper; (c) Proposed control by MR damper

As for JMA Kobe NS, Figure 9 shows maximum response values and Figure 10 shows hysteresis loop of damper and isolated story. RMS (root of mean of squares) values in Figure 9 are applied to estimate equivalent acceleration in duration time. Story shear force in Figure 10 consists of damper force and restoring force of isolated story. The values of control factors (α of optimal control, λ of proposed control) are given to cause almost same maximum isolated story displacement with oil damper case.

And then, response behavior subjected to Tohoku University NS is shown in Figure 11 and Figure 12. In this case, values of h, α and λ are same as JMA Kobe NS case.

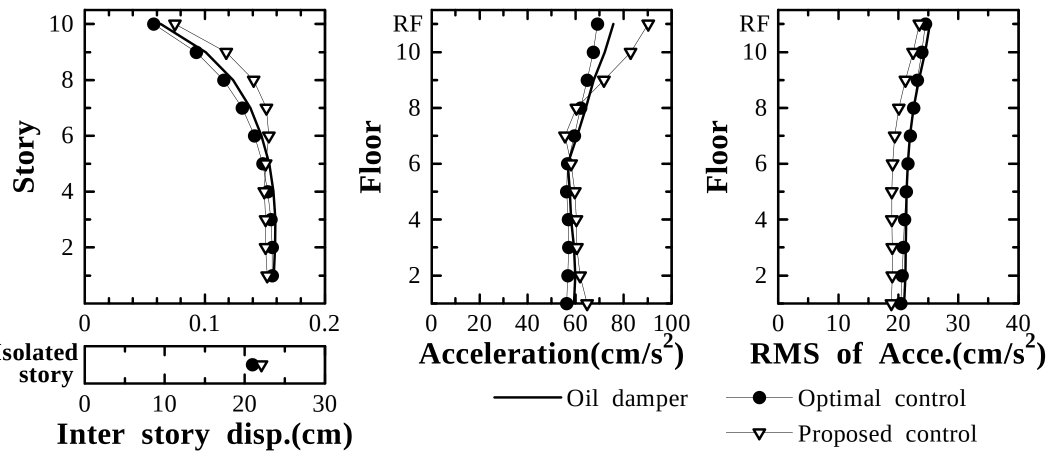


Figure 11. Maximum response values with various dampers (Tohoku Univ. NS)

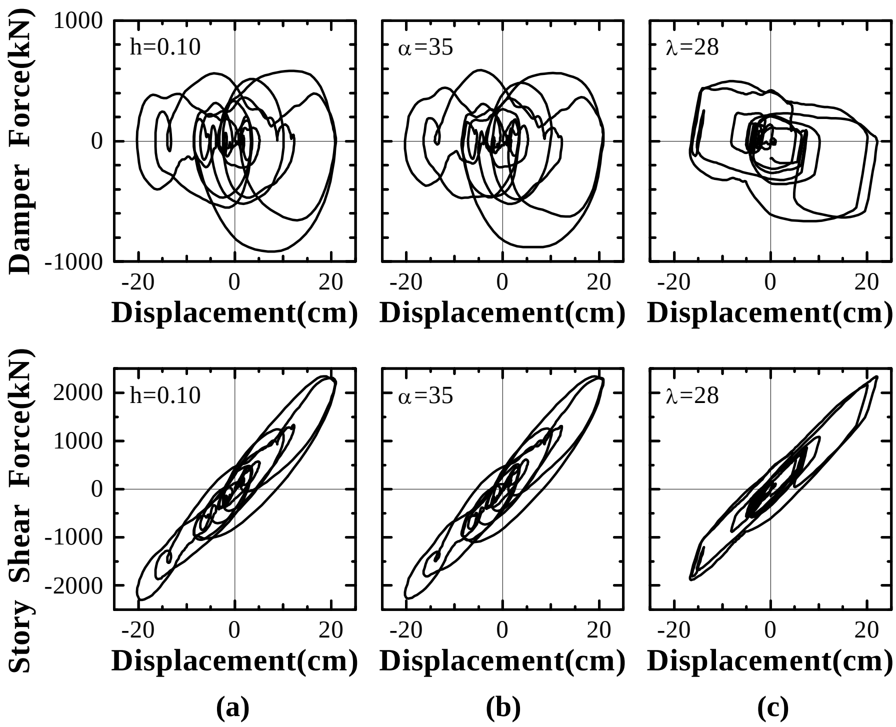
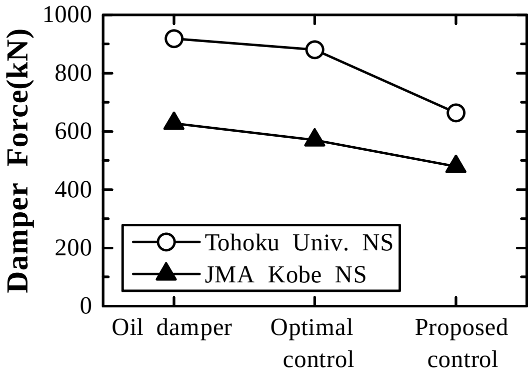


Figure 12. Hysteresis loop of damper and isolated story with various dampers (Tohoku Univ. NS): (a) Oil damper; (b) Optimal control by MR damper; (c) Proposed control by MR damper

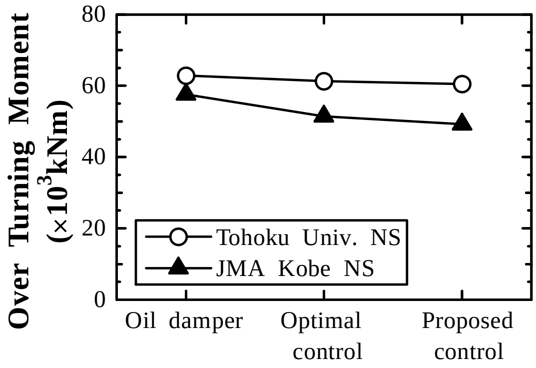
Maximum response displacement of isolated story is controlled to be almost same in all cases, and the differences in inter story displacement of superstructure by different control method are not noticeable. As shown in Figure 9, response displacement and acceleration of oil damper case are large. Large response velocity and sequential large damper force by impulsive ground motion of JMA Kobe NS would cause relatively large inertia force and acceleration.

In this study, top acceleration and control force of MR damper are evaluated in the performance index of

optimal control, and then hysteresis loop of damper with optimal control is found to be similar to that with oil damper as shown in Figure 10 and Figure 12. As for proposed control, damper force varies with the value of response displacement, and decreases in the first and third quadrant.
Maximum response values with proposed control are almost same with other cases except higher floors of Tohoku University NS case. When response displacement and acceleration are almost same with that of other cases, RMS of acceleration and damper force are smaller, and accordingly proposed control method is found to be effective to reduce seismic response.
Damper force and over turning moment are compared in Figure 13. Damper force by proposed control is about 70 to 80% of that by optimal control. Over turning moment by proposed control is a little smaller.



(a) Maximum damper force



(b) Maximum over turning moment

Figure 13. Maximum response values with various dampers

5. CONCLUSIONS

In this study, seismic response behavior of base isolated structure with MR damper controlled by semi-active control algorithm to reduce displacement of isolated story and acceleration of superstructure is investigated. And a simple control method only based on response displacement of the isolated story is proposed. By the proposed method, response displacement of isolated story can be controlled with relatively smaller damper force than optimal control, and it is found to be effective to reduce response acceleration.

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