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Seismic Response Control of Bridge Structure using Fuzzy-based Semi-active Magneto-rheological Dampers

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Abstract : Seismic response control method of the bridge structures with semi-active control device, i.e., magneto-rheological (MR) damper, is studied in this paper. Design of various kinds of clipped optimal controller and fuzzy controller are suggested as a semi-active control algorithm. For determining the control force of MR damper, clipped optimal control method adopts bi-state approach, but the fuzzy control method continuously quantifies input currents through fuzzy inference mechanism to finely modulate the damper force. To investigate the performances of the suggested control techniques, numerical simulations of a multi-span continuous bridge system subjected to various earthquakes are performed, and their performances are compared with each other. From the comparison of results, it is shown that the fuzzy control system can provide well-balanced control force between girder and pier in the view point of structural safety and stability and be quite effective in reducing both girder and pier displacements over the existing control method.

Key words : Semi-active magneto-rheological damper, bridge, seismic response control, fuzzy

1. Introduction

Due to recent evidences of increasing seismic activities and lessons from the Northridge and Kobe earthquakes, there has been extensive research on structural control concepts and technologies to improve the seismic performance of civil structures. Structural control system can be classified as passive, semi-active, active and hybrid control systems. Each control strategy has its advantages and disadvantages depending on the nature of the problem, control purpose, structure, devices, etc. Among the various control systems, seismic isolation system such as lead rubber bearing and frictional bearing has been widely recognized as efficient design alternative and successfully applied for the safety of bridge structures during seismic events [1-3]. For example, conventional seismic reinforcement system strengthens the stiffness of the substructure, i.e. pier, so that the displacement of the superstructure, i.e. girder, can be reduced. However, restriction of the girder displacement concentrates relatively large forces on the pier which causes the failure of the pier and eventually leads to the bridge collapse. On the other hand, the isolation system that places horizontally-flexible bearing between the girder and the pier lengthens the period of the bridge to reflect a portion of the seismic input energy. Accordingly, the member force on the pier can be relieved significantly but the girder displacement is increased on the contrary, which might cause unseating of the girder during seismic events. In order to deal with the mutually conflicting behavioral characteristics of the bridges, semi-active control system has been positively considered as a promising alternative system to suppress the girder displacement and simultaneously limit the member force on the pier. The main advantage of the semi-active system is that it has both the adaptability of the active control system and the reliable stability of the passive control system.

In particular, recently developed magneto-rheological damper, abbreviated as MR damper, has become a subject of special interest for seismic protection of bridge structures. In order to utilize the essential features of MR fluid, a prototype MR damper has been fabricated and its mechanical behavior for structural applications

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has been studied theoretically and experimentally [4-6]. Thereafter, large-scale MR damper has also been demonstrated by many researchers [7-9] for practical applications. As semi-active control strategy of the MR damper, clipped optimal control method was suggested and its validity and applicability have been investigated extensively [10-12]. The clipped optimal control method adopts a two-stage control framework; the primary controller for ideal active control device is designed by optimal control theory in preliminary design stage and the secondary controller performs a real-time operation for the command in order that the device can track the optimal force computed from the primary controller. Therefore, the performance of the semi-active system is dependent on how well it can mimic the behavior of the primary controller. The semi-active damper, however, can only produce forces that dissipate energy from the system. While this property guarantees a reliable behavior of the system, the performance of the semi-active system is limited because the dissipative property provides sub-optimal control force instead of the global optimal control force computed from the primary controller. In a different way, the performance of semi-active controller is dependent on the design of primary controller. Hence, the design of a primary controller that well establishes the dissipative feature of the semi-active damper is an important problem in the control strategy of the semi-active damper. In the popular method, the input command, which may be current or voltage to operate the device, is just selected as either a maximum or zero in a bi-state approach [11] or as linearly-scaled value under the assumption that the input current or voltage has an approximately linear relationship with the damper force [13]. A decision on the input command is then made according to the dissipativeness and the scale of the optimum force determined by the pre-designed primary controller. Another approach is based on fuzzy logic control [14, 15] which utilizes the fuzzy inference and directly determines the damping force of the semi-active control device. However, they only considered an ideal semi-active control device without any specific dynamic model and its interaction effect with another dynamic system, i.e. structure. Since the actual semi-active control system such as MR damper shows strong nonlinearity, its practical operation such as modulating the input current or voltage rather than the direct damper force of the ideal device is another important issue. For practical implementation, the nonlinear dynamic model of the semi-active device such as MR damper should be taken into account.

In this paper, a fuzzy control technique is also adopted, but it uses the fuzzy logic to modulate the input command, i.e. input current or voltage that is entered into the MR damper and exerts the damper force. Unlike the previous method, this indirect fuzzy control method can consider the nonlinear dynamic model of MR damper and makes it possible to continuously vary the input command into the device. Such a continuous-varying input command can enable the fine tuning of the damper force so that the damper performance can be utilized more effectively as already verified by the same authors [16, 17]. In this study, we further extended its implementation of the fuzzy control technique to improve the performance of the semi-active MR damper system by more refining the fuzzy rules. We also investigated the parametric performance of the conventional bi-state clipped optimal control method. Numerical simulation of a multi-span continuous bridge subjected to various earthquakes has been carried out, and the validity and applicability of the semi-active control strategies are examined extensively.

2. Damper-controlled Bridge System

The example structure is as shown in Fig. 1. It illustrates the bridge model with semi-active dampers that are installed between pier and girder and play a part in reducing the displacement of girder and transmitting the load from girder to pier. As denoted by shaded area, it can be modeled as a 2-DOF equivalent system and its equation of motion can be expressed as

$$M\ddot{q} + C\dot{q} + Kq = E_w\ddot{x}_g + E_uF \tag{1}$$

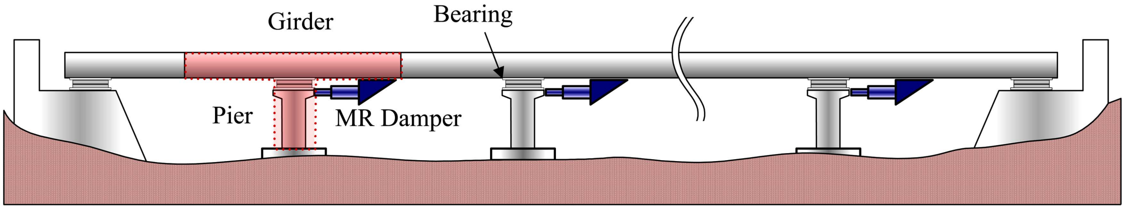


Fig. 1. Bridge model connected by dampers at the connection between girder and pier.

where q, $\dot{q}$ and $\ddot{q}$ are displacement, velocity and acceleration vectors of the system, M, C and K are mass, damping, stiffness matrices of the system, F is force vector of MR damper, $\ddot{x}_g$ is external excitation or seismic ground acceleration, and E_w and E_u are position vectors of external excitation and damper force, respectively.

MR fluids are the magnetic analogs of electro-rheological (ER) fluids and typically consist of micron-sized, magnetically polarizable particles dispersed in a carrier medium such as mineral or silicone oil. The discovery and development of MR fluids can be dated back to the 1940s [18]. The attractive characteristics of MR fluid can be briefly summarized as high dynamic yielding strength, stable hysteretic behavior over a wide range of operation temperature, high viscosity at no magnetic field and short response time [4-9]. When a magnetic field is applied to the fluids, particle chains form, and the fluid becomes a semi-solid and exhibits visco-plastic behavior with controllable yield strength. Yield strength of the damper that induces the damping force depends on the input current or voltage. Therefore, the damping force of the MR damper can be controlled by varying input current, which changes strength of induced magnetic field. Modified Bouc-Wen model suggested by Yang *et al.* [9] is used as a numerical model of 200 kN MR damper and its simple mechanical idealization and the corresponding parameter values are provided in Fig. 2 and Table 1.

The applied force predicted by this model is given by

$$\begin{aligned} F &= \alpha z_v + c_0(\dot{x} - \dot{y}_v) + k_0(x - y_v) + k_1(x - x_0) \\ &= c_1 \dot{y}_v + k_1(x - x_0) \end{aligned} \tag{2}$$

where x is relative displacement of the damper, y_v is inelastic displacement and evolutionary variable z_v is governed by

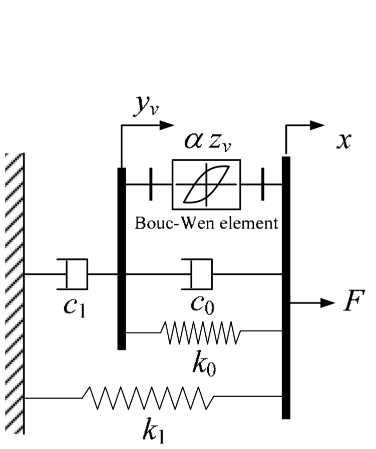


Fig. 2. MR damper model.

Table 1. Parameters of MR damper model.

Parameter	Value
k_0	137810 *N/m*
k_1	617.31 *N/m*
x_0	0.18 *m*
g	647.46 m^{-1}
n	10
b	647.46 m^{-1}
A	2679 m^{-1}

$$\dot{z}_v = -\gamma|\dot{x} - \dot{y}_v| z_v |z_v|^{n-1} - \beta(\dot{x} - \dot{y}_v)|z_v|^n + A(\dot{x} - \dot{y}_v) \tag{3}$$

$$\dot{y}_v = \frac{1}{c_0 + c_1}\{\alpha z_v + c_0 \dot{x} + k_0(x - y_v)\} \tag{4}$$

where x_0 is initial displacement of the damper, c_0 and k_0 are viscous damping and stiffness at high velocity, c_1 is viscous damping at low velocity, and k_1 is stiffness of accumulator, respectively.

Of the coefficients used in the above equations, a, c_0 and c_1 are variables to account for the dependence of the damper force on applied current, and was identified [9] by a function of input current i such that

$$\alpha(i) = 16566i^3 - 87071i^2 + 168326i + 15114 \tag{5a}$$

$$c_0(i) = 437097i^3 - 1545407i^2 + 1641376i + 457741 \tag{5b}$$

$$\begin{aligned} c_1(i) = &-9363108i^3 + 5334183i^2 + 48788640i \\ &- 2791630 \end{aligned} \tag{5c}$$

Transition to rheological equilibrium can be achieved in a few milliseconds, but there exists a time lag between command input and generated damper force. A first-order filter in Eq. (6) is thus used to accommodate the dynamics involved in the MR fluid reaching rheological equilibrium.

$$H(s) = \frac{31.4}{s + 31.4} \tag{6}$$

3. Semi-active Control Algorithms

3.1 Clipped optimal controller design

Clipped optimal control is composed of two steps: one that designs an ideal active controller to determine the *desired optimal force*, and the other that determines the input current to the MR damper at every time step as maximum or minimum values by comparing the *desired optimal force* with the *actual damper force* produced by the damper. Ideal active controller can be designed by using LQR or LQG strategies based on conventional optimal control theory. Classical LQR method [19] is used in this study, which requires a constitution of state space equation. The state vector is defined as the Eq. (7) with the displacement and velocity vectors of the system.

$$z = \begin{bmatrix} q \\ \dot{q} \end{bmatrix} \tag{7}$$

Then, Eq. (1) is transformed into the state space equation as the first order differential equation such that

$$\begin{aligned}\dot{z}(t) &= Az(t) + B_w \ddot{x}_g + B_u F \\ &= \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \begin{bmatrix} q \\ \dot{q} \end{bmatrix} + \begin{bmatrix} 0 \\ M^{-1}E_w \end{bmatrix} \ddot{x}_g + \begin{bmatrix} 0 \\ M^{-1}E_u \end{bmatrix} F \end{aligned} \tag{8}$$

where A, B_w and B_u respectively represent the system and position matrices of external excitation and control force.

Performance index J is defined as Eq. (9), and the LQR controller is designed such that the performance index subjected to the constraint of the state equation of the system in Eq. (8) is minimized

$$J = \int_0^\infty \left\{ z^T Q z + F^T R F \right\} dt = \int_0^\infty \left\{ z^T C^{*T} q C^* z + F^T R F \right\} dt \tag{9}$$

where, Q is a weighting matrix to the state variables as in Eq. (9), C^* is an output matrix of the displacements and velocities, q is a weighting parameter matrix of the output vector C^*z, and R is a weighting matrix to control force F (set to I in this study).

The output matrix C^* is expressed by Eq. (10a) to represent the pier displacement/velocity and relative displacement/velocity between the pier and girder (e.g., C^*z), and the weighting parameter matrix q can be expressed by Eq. (10b). In Eq. (10b), weightings to the pier displacement and velocity are denoted as w_{pu} and w_{pv}, and weightings to the relative responses of pier and girder are denoted as w_{ru}, w_{rv}, respectively.

$$C^* = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -1 & 1 \end{bmatrix} \tag{10a}$$

$$q = \begin{bmatrix} w_{pu} & 0 & 0 & 0 \\ 0 & w_{ru} & 0 & 0 \\ 0 & 0 & w_{pv} & 0 \\ 0 & 0 & 0 & w_{rv} \end{bmatrix} \tag{10b}$$

To simplify the weighting parameter matrix, it is assumed that the ratio of the weighting parameters to pier and girder displacements ($=w_{pu}/w_{ru}$) is equal to that of the velocity weighting parameters ($=w_{pv}/w_{rv}$), which is denoted as λ. Then, let w_{pv}/w_{ru} as μ. Substituting λ and m into Eq. (10b), q matrix can be rewritten as

$$q = w_{ru} \times \begin{bmatrix} \lambda & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & \mu/\lambda \end{bmatrix} \tag{11}$$

The optimal control force that minimizes the performance index J is calculated by solving Eq. (12), so-called Riccati equation, and substituting its solution, P matrix, into Eq. (13)

$$A^T P + PA - PB_u R^{-1} B_u^T P + Q = 0 \tag{12}$$

$$F_d(t) = -R^{-1} B_u^T P z(t) \tag{13}$$

Note that the optimal control force is denoted as F_d.

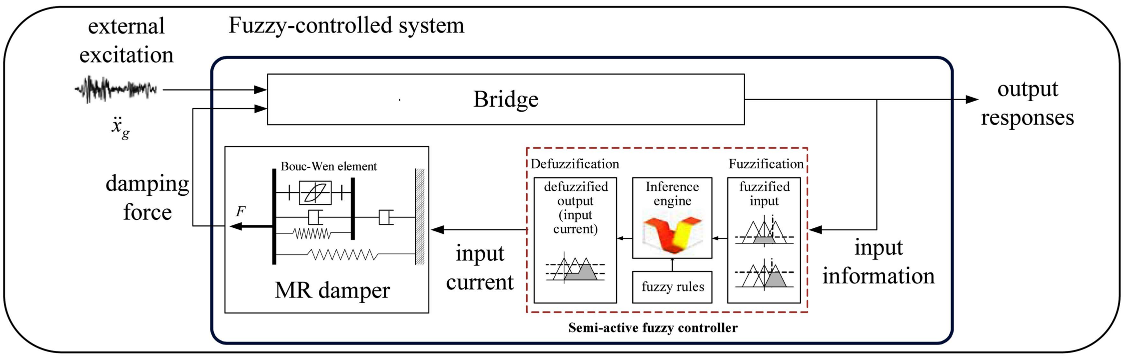


Fig. 3. Conceptual diagram of fuzzy control system for the bridge subjected to earthquakes.

Now, the maximum or minimum value of input current to the MR damper is determined as

$$[\text{Input Current}] = IC_{\max} H\{(F_d - F)F\} \tag{14}$$

where F_d is the desired optimal force computed by LQR controller, F is the control force generated by MR damper. $IC_{\max}$ is the maximum current limit to the MR damper; here the MR damper model is set to 2A(ampere). $H(\cdot)$ is the heaviside step function which has only two values, 0 or 1. It represents whether input current is a maximum or zero by comparing the desired optimal control force with the control force produced by the damper model. For more details, see [5].

3.2 Fuzzy controller design

Fuzzy controller allows a convenient way of representing input-output mapping by using human reasoning with verbose statements rather than mathematical equation. The given information is in the form of crisp value with the physical meaning, e.g. bridge responses. Through fuzzification, the crisp inputs are converted into some linguistic values that can be easily understood and manipulated. In the combination process of the linguistic values, often called inference mechanism where expert's decision can be included, outputs are determined in the form of linguistic values. Thereafter, defuzzification converts again outputs into the form of crisp values with physical meaning. In this study, the fuzzy logic determines the input current to the MR damper from response information such as relative displacement between pier and girder. Fig. 3 shows the conceptual diagram of fuzzy control system for the earthquake-excited bridge.

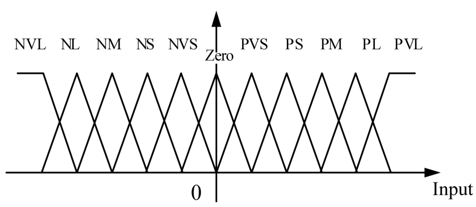


Fig. 4. Input membership functions.

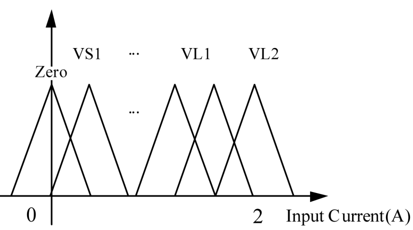


Fig. 5. Output membership functions.

In the fuzzification or defuzzification process, certain interface is required to relate the infinite number of crisp inputs to finite number of linguistic values or fuzzy variables. This is done by membership function. Input membership function is defined by a number of fuzzy sets, which have physical values about given information. A reasonable number of input membership functions must be selected since, if the number is large,

Table 2. Fuzzy rule tables.

Rule Table 1	u (Relative displacement of pier and girder)										
	NVL	NL	NM	NS	NVS	Zero	PVS	PS	PM	PL	PVL
Output (α)	VL2	L2	M2	S2	VS2	Zero	VS2	S2	M2	L2	VL2

Rule Table 2	$\dot{u}$ (Relative velocity of pier and girder)										
	NVL	NL	NM	NS	NVS	Zero	PVS	PS	PM	PL	PVL
Output (α)	VL2	L2	M2	S2	VS2	Zero	VS2	S2	M2	L2	VL2

Rule Table 3		u (Relative displacement of pier and girder)										
Output (α)		NVL	NL	NM	NS	NVS	Zero	PVS	PS	PM	PL	PVL
$\dot{u}$ (Relative velocity of pier and girder)	NVL	VL2	VL1	L2	L1	M2	M1	M2	L1	L2	VL1	VL2
	NL	VL1	L2	L1	M2	M1	S2	M1	M2	L1	L2	VL1
	NM	L2	L1	M2	M1	S2	S1	S2	M1	M2	L1	L2
	NS	L1	M2	M1	S2	S1	VS2	S1	S2	M1	M2	L1
	NVS	M2	M1	S2	S1	VS2	VS1	VS2	S1	S2	M1	M2
	Zero	M1	S2	S1	VS2	VS1	Zero	VS1	VS2	S1	S2	M1
	PVS	M2	M1	S2	S1	VS2	VS1	VS2	S1	S2	M1	M2
	PS	L1	M2	M1	S2	S1	VS2	S1	S2	M1	M2	L1
	PM	L2	L1	M2	M1	S2	S1	S2	M1	M2	L1	L2
	PL	VL1	L2	L1	M2	M1	S2	M1	M2	L1	L2	VL1
	PVL	VL2	VL1	L2	L1	M2	M1	M2	L1	L2	VL1	VL2

Rule Table 4		u (Relative displacement of pier and girder)										
Output (α)		NVL	NL	NM	NS	NVS	Zero	PVS	PS	PM	PL	PVL
$\dot{u}$ (Relative velocity of pier and girder)	NVL	VL2	VL1	L2	L1	M2	M1	S1	S1	S2	S2	M1
	NL	VL1	L2	L1	M2	M1	S2	VS2	S1	S1	S2	S2
	NM	L2	L1	M2	M1	S2	S1	VS1	VS2	S1	S1	S2
	NS	L1	M2	M1	S2	S1	VS2	VS1	VS1	VS2	S1	S1
	NVS	M2	M1	S2	S1	VS2	VS1	Zero	VS1	VS1	VS2	S1
	Zero	M1	S2	S1	VS2	VS1	Zero	VS1	VS2	S1	S2	M1
	PVS	S1	VS2	VS2	VS1	VS1	VS1	VS2	S1	S2	M1	M2
	PS	S1	S1	VS2	VS2	VS1	VS2	S1	S2	M1	M2	L1
	PM	S2	S1	S1	VS2	VS2	S1	S2	M1	M2	L1	L2
	PL	S2	S2	S1	S1	VS2	S2	M1	M2	L1	L2	VL1
	PVL	M1	S2	S2	S1	S1	M1	M2	L1	L2	VL1	VL2

Rule Table 5		u (Relative displacement of pier and girder)										
Output (α)		NVL	NL	NM	NS	NVS	Zero	PVS	PS	PM	PL	PVL
$\dot{u}$ (Relative velocity of pier and girder)	NVL	VL2	VL1	L2	L1	M2	M1	S2	S1	VS2	VS1	Zero
	NL	VL1	L2	L1	M2	M1	S2	S1	VS2	VS1	Zero	VS1
	NM	L2	L1	M2	M1	S2	S1	VS2	VS1	Zero	VS1	VS2
	NS	L1	M2	M1	S2	S1	VS2	VS1	Zero	VS1	VS2	S1
	NVS	M2	M1	S2	S1	VS2	VS1	Zero	VS1	VS2	S1	S2
	Zero	M1	S2	S1	VS2	VS1	Zero	VS1	VS2	S1	S2	M1
	PVS	S2	S1	VS2	VS1	Zero	VS1	VS2	S1	S2	M1	M2
	PS	S1	VS2	VS1	Zero	VS1	VS2	S1	S2	M1	M2	L1
	PM	VS2	VS1	Zero	VS1	VS2	S1	S2	M1	M2	L1	L2
	PL	VS1	Zero	VS1	VS2	S1	S2	M1	M2	L1	L2	VL1
	PVL	Zero	VS1	VS2	S1	S2	M1	M2	L1	L2	VL1	VL2

input to the fuzzy system will be subdivided into larger number with small ranges and thus control system can be finely tuned for the given input, but much longer computation time is need. In this study, 11 triangular input and output membership functions are used as shown in Figs. 4 and 5, where N(negative), P(positive), S(small), M(medium), L(large), V(very) and Zero are used as an abbreviation to represent each physical meaning.

To reflect the reasonable operation, input membership functions are defined according to the scale and sign of input response, and the range of output value is set as 0~2A, considering the maximum input current.

In the inference engine, combinations of linguistic values have the form of rule table. We developed a total of 5 rule tables for controlling the MR damper-bridge system. The first 2 designs use only one response of the bridge; one is relative displacement and the other is relative velocity. As shown above, rule tables 1 and 2 have the same form of rule, whose output varies in proportion to its corresponding input. The next 3 designs use both relative displacement and velocity for fuzzy input. Rule table 3 has a similar form to the rule tables 1 and 2, but it uses two inputs such as relative displacement and velocity and its output value is proportional to the summation of the two inputs. The rule tables 4 and 5 are devised to reflect a dissipative feature of semi-active damper. The dissipativeness of the damper, e.g., whether or not the semi-active damper is producing dissipative force, can be checked by the sign of damper displacement and velocity. It is natural that the differently modified damping forces in that situation could achieve better performance. Accordingly, rule tables 4, and 5 use different rules in the region with opposite sign of displacement and velocity. In that region, damper force prohibits the bridge from going back to its original equilibrium position. Therefore, it would be better to reduce the equilibrium-prohibitive damper force. Rule table 4 reduces the output in the opposite sign region by half, compared with that in rule table 3. Note that the largest value in the opposite sign region of rule table 4 is M1, which was VL2 in case of rule table 3. In rule table 5, output value is fully proportional to the magnitude of the input values in a same sign region where the damper force help return its original equilibrium position but further reduced from that of rule table 4 in the opposite sign region. For readers' understanding, rule surfaces of the rule tables 3~5 are shown in Fig. 6.

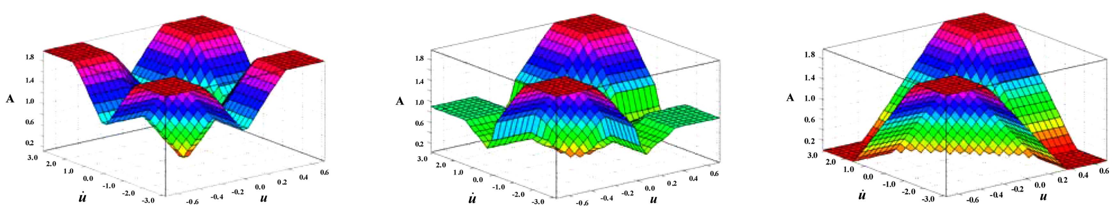
4. Analysis Results

4.1 Passive system vs. semi-active system

The masses of girder and pier are 609,612 kg and 121,922 kg respectively, and the stiffness of pier is 95,257 kN/m. Its damping ratio is assumed to have 5%. As for the semi-active MR damper system, elastomeric bearing with 4,763 kN/m of stiffness and 2% of damping ratio is used.

For the purpose of comparison, passive control system is also considered as two-DOF system with seismic isolation bearing. The bearing is designed using the single-mode spectral analysis method of the AASHTO *Guide Specifications for Seismic Isolation Design* [20]. The isolated bridge has a natural period of 2.0 sec in the fundamental mode and a design displacement of 8.32 cm. As a result, the isolator bearing turned out to have stiffness of 6,422 kN/m and a damping ratio of 40%. For realistic simulation of the seismic bridge responses, the bi-linear model corresponding to the designed isolator bearing is used. The yielding displacement of the bi-linear model is assumed to be 2.0 cm. The initial and second stiffness is thus determined as 23,215 kN/m and 1,111 kN/m, which has equivalent stiffness and damping ratio of the designed isolator bearing.

Given the bridge model, semi-active damper system is designed using clipped optimal control method. A total of 4 MR dampers are installed at each connection to the girder and pier. As previously stated in section 3, design of clipped optimal controller can be realized by determining the weighting parameters. For comparison



(a) Rule surface of rule table 3 (b) Rule surface of rule table 4 (c) Rule surface of rule table 5

Fig. 6. Rule surfaces of two-input-one-output fuzzy controllers.

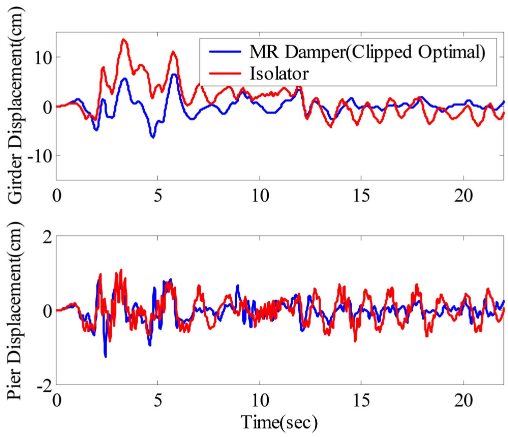


Fig. 7. Time histories of passive and semi-active systems.

with the passive system, the clipped optimal controller is designed using weighting parameters λ and μ as 10.0 and 10.0, respectively. Details of the design of clipped optimal controller are given next.

For the performance comparison of the two designed systems, numerical analysis is performed for El Centro earthquake (1940). The time histories of the pier and girder displacement are plotted in Fig. 7. The isolation system shows a clear reduction effect on the pier displacement, which means a reduction of shear force of the pier. However, the girder displacement is increased considerably. On the other hand, the MR damper-bridge system reveals better performance for the girder displacement while maintaining similar reduction effect on the pier displacement to that of the passive isolation system. The semi-active control system is shown to exhibit successful seismic performance for both pier and girder displacement. Similar results are observed for different earthquakes, i.e. Kobe and Mexico earthquakes.

4.2 LQR-based active system vs. semi-active clipped optimal control system

It is previously stated that the semi-active control system can show a successful performance by mimicking optimal control force from primary controller. Thus, the performance of the clipped optimal control is dependent on the primary controller and the performance of the primary controller is problem-dependent. To investigate the applicability of clipped optimal method, various kinds of numerical simulations are carried out by varying weighting parameters λ and μ. Three different types of ground motions, i.e. El Centro (1940), Kobe (1995) and Mexico (1985) earthquakes with different frequency components and peak ground acceleration are considered for design. LQR controller as an active system is

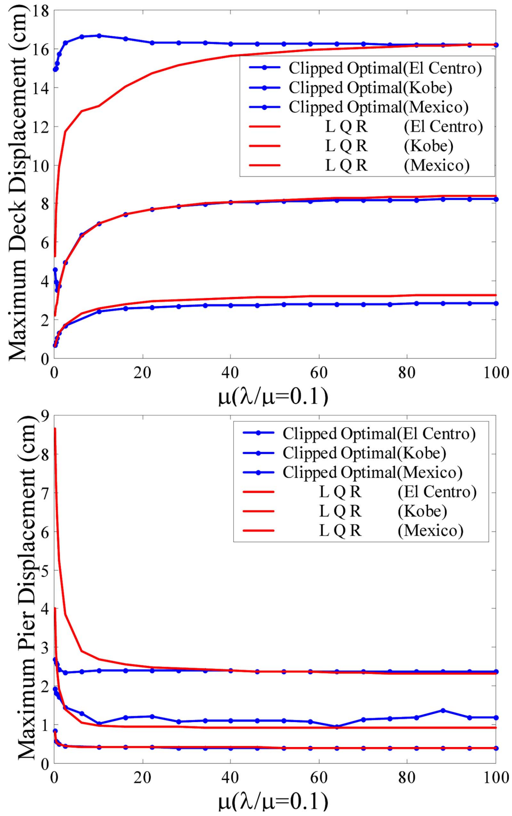


Fig. 8. Comparative results between clipped optimal control and LQR control.

also simulated for comparison. The simulation results are illustrated in Fig. 8.

In most cases, two control systems show a similar seismic performance against the three earthquakes. As the weighting to pier μ increases, the corresponding displacement of pier is reduced and the girder displacement is increased. The performances of both systems on the pier and girder displacements are mutually conflicting to each other. A clear trade-off tendency is seen for given weightings, but semi-active controller shows a little degradation of performance in some regions.

4.3 Clipped optimal control vs. fuzzy control

At first, four types of clipped optimal controllers are selected with respect to the change of λ and μ, fixing

Table 3. Weightings for clipped optimal controllers.

Controllers	λ (=μ)
Clipped 1	0.1
Clipped 2	0.5
Clipped 3	2.5
Clipped 4	10

the λ/μ = 1.0 and the parameter values of the 4 cases are presented in Table 3.

The simulation results of clipped optimal control and fuzzy control for the three earthquakes are summarized in Tables 4~6. In each table, minimum values of pier and girder displacement are in boldface with respect to each control method.

"Clipped 1" and "Clipped 2" controllers are designed by putting smaller weighting to pier responses than girder responses, and "Clipped 3" and "Clipped 4" vice versa. It is clearly observed in Tables 4~6 that if pier displacement is more weighted than girder displacement, pier displacement can be reduced but the girder displacement is increased on the contrary.

In the fuzzy control system, the fuzzy rule plays a similar role to the weighting parameters. When the rule is made to generate larger output, larger damper force will be applied to the connection between the girder and the pier. It will lead to relatively smaller displacement of girder and larger displacement of pier. The overall performances of the fuzzy controllers show similar tendency to those of the clipped optimal controller. The trade-off relationship between the girder and pier responses holds the same for the fuzzy controller. In addition, when one fuzzy controller shows better performance on pier displacement than one clipped optimal controller, the performance on girder displacement by the fuzzy controller is overall poorer than that of the clipped optimal controller. For example, under the El Centro earthquake, the "Clipped 2" system shows the most balanced performance between the girder and pier responses over the other clipped optimal systems such as "Clipped 1, 3 and 4". More specifically, compared with the responses controlled by the fuzzy systems, "Clipped 1" system shows poorer performance on both responses and the "Clipped 3 and 4" systems put excessive weightings on the pier response. As a result, the "Clipped 3 and 4" reduce the pier response more than the fuzzy systems, but their girder displacements become too excessive. However, the "Clipped 2" system exhibits competent performance with the fuzzy system in terms of the girder and pier displacements. Now, let us focus on the results of the Kobe earthquake where the largest bridge responses occur due to the largest peak ground acceleration. The relative displacements between the girder and pier of the clipped optimal systems are slightly larger than those of the fuzzy control systems except for "Clipped 1", while their pier displacements are smaller than those of the fuzzy systems. On the other hand, "Clipped 1" exhibits the girder-pier displacement as 14.9161 cm and the pier displacement as 2.6615 cm respectively, but the "Fuzzy 5" still produces smaller responses such as 14.8041 cm of girder-pier displacement and 2.64 cm of pier displacement, as listed in Table 5. The performance of the "Fuzzy 5" system is superior to that of the "Clipped 1" system in terms of both displacements. This holds the same for the case where "Clipped 2" and "Fuzzy 2" are compared to each other when subjected to Mexico earthquake. The girder-pier displacements of "Clipped 2" and "Fuzzy 2" are 1.0170 cm and 1.0139 cm, whereas the pier displacements of both systems are 0.4918 cm and 0.4904 cm, as shown in Table 6. The fuzzy control system achieves more enhanced performance over the clipped optimal control system. These results demonstrate that the fuzzy controller could reduce the pier and girder displacement more efficiently than clipped optimal controller. However, it does not necessarily mean that the superior performance of the fuzzy control system is always guaranteed over the clipped optimal control system. As shown in Tables 4~6, both systems can be designed to have competent performance with each other by assigning appropriate weighting factors to the target responses of the structure or well-organized fuzzy rules.

Nonetheless, it should be mentioned that the fuzzy control system has the following merits; (1) it can deal with the dissipative feature of the semi-active MR damper by constructing the fuzzy rules in a convenient way, (2) it enables direct modulation of the input voltage of the MR damper without primary controller so that it provides simple design procedure and can be easily implemented, (3) it also enables us to consider the nonlinear dynamic model of the MR damper and its interaction with the structure, (4) it provides well-balanced performance on the mutually conflicting responses through the simple reasoning on the responses, (5) it is well known [21] that fuzzy control is inherently robust since it does not require precise, noise-free inputs, (6)

Table 4. Peak responses of bridge structure subjected to El Centro earthquake.

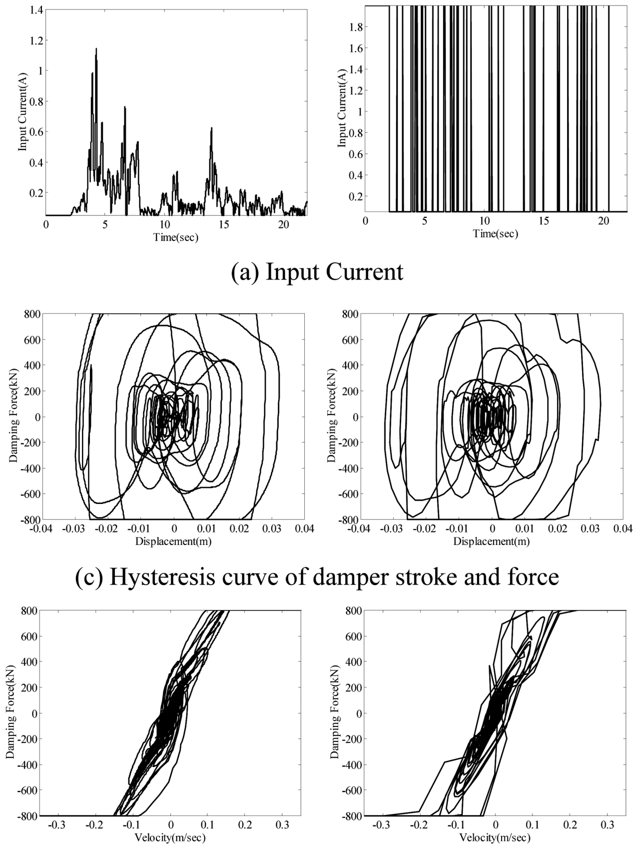
Control method	Peak displacement	
	Girder-Pier (cm)	Pier (cm)
Clipped 1	4.6922	1.8817
Clipped 2	**3.3139**	1.6659
Clipped 3	5.2440	1.4232
Clipped 4	6.5104	**1.2953**
Fuzzy 1	3.8163	1.7720
Fuzzy 2	3.6252	1.6939
Fuzzy 3	**3.2262**	1.7507
Fuzzy 4	3.5148	1.5964
Fuzzy 5	3.5103	**1.5945**

Table 5. Peak responses of bridge structure subjected to Kobe earthquake.

Control method	Peak displacement	
	Girder-Pier (cm)	Pier (cm)
Clipped 1	**14.9161**	2.6615
Clipped 2	15.3002	2.4555
Clipped 3	15.4844	2.2663
Clipped 4	15.6944	**2.2656**
Fuzzy 1	**14.3292**	2.7036
Fuzzy 2	14.9676	**2.4881**
Fuzzy 3	14.5764	2.6696
Fuzzy 4	15.0062	2.6176
Fuzzy 5	14.8041	2.6400

Table 6. Peak responses of bridge structure subjected to Mexico ground motion record.

Control method	Peak displacement	
	Girder-Pier (cm)	Pier (cm)
Clipped 1	**0.7317**	0.7749
Clipped 2	1.0170	0.4918
Clipped 3	1.7334	0.4116
Clipped 4	2.2931	**0.3998**
Fuzzy 1	1.5708	0.4859
Fuzzy 2	**1.0139**	0.4904
Fuzzy 3	1.1013	**0.4649**
Fuzzy 4	1.2975	0.4954
Fuzzy 5	1.2975	0.4954



(a) Input Current

(c) Hysteresis curve of damper stroke and force

(e) Hysteresis curve of damper velocity and force

Fig. 9. Analysis results of Fuzzy 3(left) and Clipped 2(right).

fuzzy logic is not limited to a few feedback inputs. Any sensor data that provide some indication of system's conditions can be implemented easily.

Fig. 9 shows the variation of input currents and the hysteresis curves of damper forces for “Fuzzy 3” and “Clipped 2” when the bridge is subjected to El Centro earthquake. As expected, input current of fuzzy controller varies continuously, whereas the clipped optimal controller adopts only two values for the input current, as shown in Fig. 9(a). It was reported [22] that abrupt changes in forces due to the bi-state control of the input voltage may cause high local acceleration in case of base isolation bridge system. Fig. 9(b) and 9(c) show hysteresis curves of relative displacement and velocity versus damper force.

5. Conclusion

Recently developed MR damper model is applied for the seismic vibration control of the bridge, and semi-active fuzzy control technique is employed to continuously quantify the input current to the MR damper at each time step rather than the damper force itself. While clipped optimal control based on the conventional linear optimal control theory determines the input current as bi-state, the suggested method enables the fine-tuning of the input current through the fuzzy inference engine.

To investigate the efficiency of the control strategies, four types of clipped optimal controllers depending on the weighting ratio of pier and girder responses and five fuzzy controllers with respect to the various rule-bases are designed. Then, numerical simulations of the seismically excited bridge with differently operated semi-active MR damper are carried out, and their seismic performances are compared with each other. It is observed from the results that fuzzy controllers generally exhibit similar performance to clipped optimal controller in reducing pier and girder displacement. However, the fuzzy system shows slightly improved performance over the clipped optimal controllers under the Kobe and Mexico earthquakes. Especially in case of Kobe earthquake, the clipped optimal controller cannot reduce the girder displacement below certain limit, whereas the fuzzy controllers further reduce the girder displacement below the limit without significant increase of pier displacement. Therefore, it can be concluded that fuzzy control system can provide well-balanced performance on bridge responses and be quite effective in reducing both girder and pier displacements simultaneously.

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