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Experimental Study on Semiactive Modal Neuro-Control Scheme

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ABSTRACT

In this paper, a semiactive modal neuro-control scheme which combines the modal neuro-control algorithm and semiactive control device (MR damper) is proposed. The efficacy and feasibility of the semiactive modal neuro-control scheme has been experimentally investigated through a shaking table experiment. In the experiment, a scaled three-story shear building model including an MR damper attached between ground and the first floor is considered as target structure. A Kalman filter is also adopted for estimating the modal coordinates from the measurements by various sensors. The clipped algorithm which induces the MR damper to generate approximately the desired control force is adopted in the proposed scheme. The cost function based neuro-controller produces the desired control force, then by using the clipped algorithm the appropriate command voltage for MR damper is selected in order to cause the MR damper to generate the desired control force. The performance of a semiactive modal neuro-control algorithm is compared with that of passively MR damper-based control systems.

INTRODUCTION

Semiactive control system appears to combine the best features of both passive and active control system. According to currently accepted definitions, a semiactive control device is one that can not inject mechanical energy into the controlled structural system, but has properties which can be controlled to optimally reduce the responses of the system. Consequently in contrast to active control devices, semiactive control device do not have the potential to destabilize the structural system. Previous studies indicate that appropriately implemented semiactive systems perform significantly better than passive devices and have the potential to achieve the majority of the performance of fully active systems. (Spencer and Sain 1997; Symans and Constantinou 1999) Among the semiactive control devices, magnetorheological fluid damper (MR damper) has gained distinguished attention from the researchers over two decades. MR damper requires only little-sized power such a small battery and have an inherent ability to provide a simple and robust interface between electronic controls and mechanical components.

Modal control is especially desirable for the vibration control of civil engineering structure, which is usually a large structural system but its vibration is usually dominated by the first few modes. That is the reason why the motion of the civil structural system can be effectively suppressed by only controlling these few modes. In this reason, Cho *et al.* proposed an implementation of modal control scheme for seismically excited structures using MR dampers (Cho *et al.* 2005) and Choi *et al.* showed that an fuzzy control scheme using modal states as the input variables is quite effective to reduce seismic responses (Choi *et al.* 2005). In this paper, a semiactive modal neuro-control scheme which combines the modal neuro-control algorithm and semiactive control device (MR damper) is developed and verified in experiments with scaled shear building model.

SEMIACTIVE MODAL NEURO-CONTROL SCHEME

Figure 1 shows the block diagram of the proposed semiactive modal neuro-control scheme using MR damper. The proposed control scheme consists of a clipped algorithm and modal neuro-controller. Since the force generated by MR damper cannot be commanded directly, in order to induce the MR damper to generate approximately the desired control force, the

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command voltage v is selected by the clipped algorithm (Dyke *et al.*, 1996). The modal neuro-controller in the proposed scheme is trained based on the cost function (Kim *et al.*, 2001, 2002).

The proposed control scheme consists of a Kalman filter and modal neuro-controller. Since real sensors may not estimate the full modal states directly or the system may be expensive to prepare the sensors for the full states, Kalman filter which can estimate specific modal coordinates or states well enough is used in order to generate modal coordinates for modal neuro-controller. Subsequently the modal neuro-controller produces appropriate desired force or command using the generated modal coordinates from Kalman filter so that the actuator could reduce the seismic response of the structural system.

The training of neural network for modal neuro-controller is based on the minimization of a type of new cost function. The cost function defined in discrete-time domain is expressed by

$$J = \frac{1}{2}\sum_{k=0}^{N-1}\left\{\eta_{k+1}^{T}\mathbf{Q}\,\eta_{k+1} + \mathbf{u}_{k+1}^{T}\mathbf{R}\mathbf{u}_{k+1}\right\} \tag{1}$$

where $\eta(2l\times 1)$ and $\mathbf{u}(m\times 1)$ are selected controlled modal coordinates and control signals; $\mathbf{Q}(2l\times 2l)$ and $\mathbf{R}(m\times m)$ are weighting matrices; k and N are sampling number and total number of sampling time.

Experimental Setup

A schematic of the experimental setup used in this study is shown in Figure 3.7. Experiments were conducted with the shaking table which is driven by a servo-controlled hydraulic actuator uni-axially. Note that totally five measurements are needed in setting up the semiactive modal neuro-controller as shown in Eq. (6). The measurements consist of three measurements of any kind of states (e.g. displacement, velocity, or acceleration) for y in Eq. (6) and two measurements of control force and ground acceleration for u. In experiment, relative displacements of the first and second floor, absolute acceleration of the third floor are chosen as the three measurements of states. In order to measure the relative displacements of the first and second floor, three laser displacement sensors are required for measuring absolute displacements of ground, the first floor, and the second floor, respectively. The test structure model used in the experiment is a scaled three-story shear building model. The frame is constructed of steel and has a height of 105 cm and the floor masses of the model weigh a total of 48.27 kg, which is distributed evenly between the three floors. The first three natural frequencies for the test structure model are 2.05 Hz, 5.57 Hz, and 8.41 Hz. Choi (2005) conducted system identification for the test structure model using natural frequency matching method and Hilbert transform-based identification method. The shaking table (Model: DY-HV-2000) has a testing platform with 110 cm by 96 cm, a maximum payload of 600 kg, a maximum acceleration of ±0.4 g, and a maximum velocity of 21 cm/sec. The actuator was built by Dong-yang system manufacturing. The actuator with a maximum dynamic force of 2 ton and stroke length ±5 cm was controlled by a servo-hydraulic controller in displacement or acceleration feedback mode. The displacement feedback mode is used in experiments. The control device used in the experiment is a controllable friction MR fluid damper (Model: RD-1097-01) from Lord Corporation. Maximum force level is approximately ±100 N, and the maximum allowable voltage is 10 Volt because of heat damage at the current more than 0.5 ampere. The resistance of the MR damper is 20 ohms at 25°C. The digital controller is constructed by the MATLAB real-time workshop executed in real-time using MS Visual C++. The measurements of responses are acquired from the laser displacement sensor, accelerometer, and load cell and converted into the digital data by the NI DAQCard-6062E. Then the controller computes the desired control force with those measurements and finally output signal (in voltage) is sent to wonder box for the MR damper through the output port. Three types of sensor are used; laser displacement sensor, accelerometer, and load cell. Keyence LK-081, LB-301, CD4-350 series laser displacement sensors measure the displacement of ground, the first and second floor, respectively. Moreover, two accelerometers for acceleration of the ground and the third floor are PCB 393A03 ±5 g measurement range. PCB 442B104 is used as an amplifier for accelerometers. Finally the damper force is measured by Kyowa UR-A-100NSA1 load cell with a ±100 N measurement range and Kyowa DPM-751A amplifier.

To evaluate the performance of the semiactive control systems for different levels and types of seismic events, five historical earthquake records are considered as ground excitations for experiments. Because the structure under consideration is a scaled model, the earthquakes must be reproduced at the peak ground acceleration and at times the recorded rate. The test building structure is subjected to: (1) El Centro earthquake scaled to 40% amplitude and 2 times the recorded rate (PGA: 0.14 g), (2) El Centro earthquake scaled to 20% amplitude and 2 times the recorded rate (PGA: 0.07 g) (3) Hachinohe earthquake scaled to 30% amplitude and 2 times the recorded rate (PGA: 0.08 g) (4) Kobe earthquake scaled to 20% amplitude and 2 times the recorded rate (PGA: 0.16 g) (5) Northridge earthquake scaled to 10% amplitude and 2 times the recorded rate (PGA: 0.08 g).

Kalman filter design

Let's assume the equations of motion of given structure Eq. (2) and the first mode is dominant in the structural dynamics like general building structure in civil engineering. Then the steady-state equation for the first modal state and the measurement output can be expressed as

$$\begin{aligned} \dot{x} &= Ax + Bu + Gw \\ y &= Cx + Du + Hw + v \end{aligned} \tag{2}$$

$$\begin{Bmatrix} \dot{\eta}_1 \\ \ddot{\eta}_1 \end{Bmatrix} = \begin{bmatrix} 0 & 1 \\ -k_1/m_1 & -c_1/m_1 \end{bmatrix}\begin{Bmatrix} \eta_1 \\ \dot{\eta}_1 \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ \phi_1^{T}\Gamma & -\phi_1^{T}M\Lambda \end{bmatrix}\begin{Bmatrix} f \\ \ddot{x}_g \end{Bmatrix}, \tag{3}$$

$$y = \ddot{x} \cong \phi_1 \ddot{\eta}_1 = \phi_1 \begin{bmatrix} -k_1/m_1 & -c_1/m_1 \end{bmatrix} \begin{Bmatrix} \eta_1 \\ \dot{\eta}_1 \end{Bmatrix} + \phi_1 \begin{bmatrix} \phi_1^T \Gamma & -\phi_1^T M \Lambda \end{bmatrix} \begin{Bmatrix} f \\ \ddot{x}_g \end{Bmatrix} \quad (4)$$

where, ϕ_1 is the first eigenvector, $m_1 = \phi_1^T M \phi_1$, $c_1 = \phi_1^T C \phi_1$, and $k_1 = \phi_1^T K \phi_1$. If a modal steady-state matrices are defined as

$$A_m = \begin{bmatrix} 0 & 1 \\ -k_1/m_1 & -c_1/m_1 \end{bmatrix}, \quad B_m = \begin{bmatrix} 0 & 0 \\ \phi_1^T \Gamma & -\phi_1^T M \Lambda \end{bmatrix}, \quad C_m = \phi_1 \begin{bmatrix} -k_1/m_1 & -c_1/m_1 \end{bmatrix}, \quad D_m = \phi_1 \begin{bmatrix} \phi_1^T \Gamma & -\phi_1^T M \Lambda \end{bmatrix} \quad (5)$$

Finally the Kalman filter for modal state estimation can be expressed as

$$\dot{\hat{\eta}} = (A_m - LC_m)\hat{\eta} + \begin{bmatrix} L & B_m - LD_m \end{bmatrix} \begin{Bmatrix} y \\ u \end{Bmatrix}, \quad \begin{bmatrix} \hat{y} \\ \hat{\eta} \end{bmatrix} = \begin{bmatrix} C_m \\ I \end{bmatrix} \hat{\eta} + \begin{bmatrix} 0 & D_m \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} y \\ u \end{Bmatrix} \quad (6)$$

The available measurements in the experimental setup are relative displacements of the first floor and second floor, accelerations of the ground and the third floor, and control force. Using Eq. from (3) to (6), a Kalman filter for the experiment is designed with the available measurements. In designing the Kalman filter, each of the measured responses is assumed that it contains an RMS noise of 3% of the full span of the A/D converters. Through the numerical example the estimation of the Kalman filter for modal state under the scaled El Centro earthquake (0.4 times PGA and 2 times recorded rate) is accurate enough to be used in experimental study. Since the assumption about noise (3% of the full span) can be regarded as severely bad environment for measurement, the estimation error of the designed Kalman filter, 1.93% and 1.95% in maximum, is small enough for the experiment.

Control Systems

In designing the modal neuro-controller, two kinds of controller are considered. The modal neuro-controller type A is designed for reducing the overall responses (both inter-story drift and acceleration), and type B is designed for focusing on reducing the inter-story drift mainly. One can design the modal neuro-controller along ones own purpose by varying the weighting matrices of modal states. For the cost function, the first modal state and its derivatives are included as in Eq. (1). This is because the first mode is dominant in structural response. That is, the structural response becomes small, if the first modal state and its derivatives are controlled.

The passive-off, passive-on, and optimal passive control case is investigated by using the conventional MR damper-based control system. In these cases, the MR damper is only passively operated. Choi (2005) conducted an experiment for finding the optimal passive voltage for the controllable friction MR fluid damper. In order to change damping characteristics of the MR damper, the input voltage to the damper was changed from 0 V to 8 V and the N-S component of the El Centro earthquake with two intensities is considered in the experiment. It was shown that a constant voltage 2 V is optimal for reducing both the maximum acceleration and maximum displacement of the structure simultaneously and efficiently. This design case (passive-2V) is adopted as the optimal passive control case in this paper.

Experimental Results

The values of the peak inter-story drift of the controlled structure (among the first and second inter-story drift) are compared to those of an uncontrolled system, the passive-off (0 V), passive-on (8 V), optimal passive case (2 V), and two semiactive modal neuro-controllers (i.e., Type A based on reducing overall responses and Type B focusing on inter-story drift only) as shown in Table 1 and Figure 3. The values of the peak acceleration are also compared each other as shown in Table 2 and Figure 4. As seen in those tables and figures, the passive-off case and passive-on case cannot show good performance. Although those control cases are very simple (no algorithm, no analysis, and no measurement), the adaptability or serviceability of those control cases are not sufficiently good enough. Especially note that the performance of the passive-on case under the Kobe and Northridge earthquakes is worse than that of the uncontrolled case.

The semiactive modal neuro-controller type A trained with the purpose of reducing overall responses shows comparative performance to that of the passive optimal case. Generally speaking, however, the proposed semiactive modal neuro-controller needs a lot of tasks for design, such as the system identification, training, measurement from sensors. Therefore one can say that the passive optimal case is better than the proposed neuro-controller, because of simplicity. But the passive optimal case also needs troublesome tasks such as system identification, mathematical modeling of the MR damper used in the real world for determination of the optimal voltage. Moreover, the passive optimal case has inherent disadvantages as a passive control system, the adaptability. If the passive control system is set up once for specific purpose, it is very difficult to adapt itself to the excitation which has different characteristic. (e.g., frequency distribution etc.) The proposed semiactive modal neuro-controller can be designed for specific purpose which fulfills the designer's requirement. The semiactive modal neuro-controller type B was trained with the purpose of mainly reducing the inter-story drift responses. As seen in tables and figures, the neuro-controller type B shows the best performance in the inter-story drift along with slightly worse performance in the acceleration. These show the ability to wide application of the proposed modal neuro-controller.

The experimental results subjected to all of the scaled earthquakes finally indicate the effectiveness of the proposed semiactive modal neuro-control system in reducing the inter-story drift and acceleration responses.

CONCLUSIONS

The semiactive modal neuro-control system employing an MR damper for structural vibration suppression of the test building structure subjected to scaled historical earthquakes has been experimentally investigated by using a shaking table test. Two types of semiactive modal neuro-controller (i.e., Type A based on reducing overall responses and Type B focusing on inter-story drift mainly) are designed and investigated through the experiment. The control performance of the semiactive modal neuro-control systems is compared with that of the passive-off (0 V), passive-on (8 V), and the optimal passive case (2 V) operated in constant voltage mode. As compared to the optimal passive system, the semiactive modal neuro-control systems achieved satisfactory vibration reductions over the entire range of earthquake intensities considered. Moreover the proposed semiactive modal neuro-controllers show the good adaptability and ability to wide application subjected to specific purpose. These results indicate that the semiactive modal neuro-control systems can be effectively used over a wide range of ground motion intensities and characteristics.

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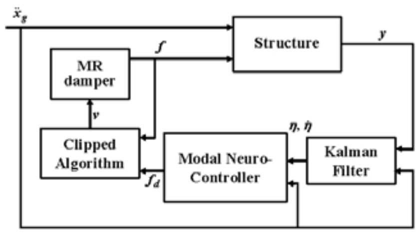

Fig. 1. Block diagram of semiactive modal neuro-control

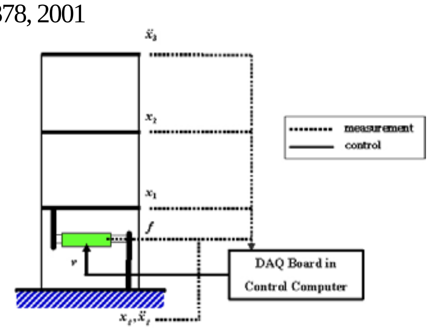

Fig. 2. Schematic of experimental setup

Table 1. Normalized controlled peak inter-story drift responses

	El Centro (0.14g)	El Centro (0.07g)	Hachinohe (0.08g)	Kobe (0.16g)	Northridge (0.08g)
Passive-off	0.75	0.49	0.45	0.73	0.72
Passive-on	0.46	0.68	0.41	0.38	0.76
Optimal passive	0.40	0.59	0.40	0.55	0.52
MNC (Type A)	0.41	0.55	0.38	0.42	0.54
MNC (Type B)	0.35	0.48	0.28	0.37	0.47

Table 2. Normalized controlled peak acceleration responses

	El Centro (0.14g)	El Centro (0.07g)	Hachinohe (0.08g)	Kobe (0.16g)	Northridge (0.08g)
Passive-off	0.79	0.62	0.51	0.68	0.64
Passive-on	0.77	0.96	0.54	**1.08**	**1.00**
Optimal passive	0.47	0.61	0.40	0.41	0.65
MNC (Type A)	0.50	0.43	0.36	0.41	0.45
MNC (Type B)	0.59	0.68	0.51	0.53	0.63

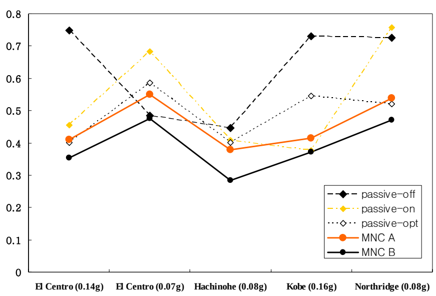

Fig. 3. Normalized controlled peak inter-story drift responses

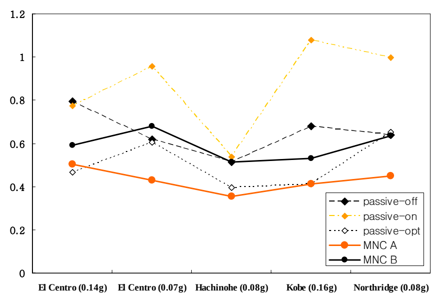

Fig. 4. Normalized controlled peak acceleration responses