Sādhanā Vol. 34, Part 3, June 2009, pp. 421–437. © Printed in India

A model for signal processing and predictive control of semi-active structural control system

M-H SHIH[1], W-P SUNG[2]* and CHING-JONG WANG[1]

[1]Department of Construction Engineering, National Kaohsiung First University of Science and Technology, Kaohsiung, 824, Taiwan
[2]Department of Landscape Architecture, National Chin-Yi University of Technology, Taichung, 411, Taiwan
e-mail: wps@ncut.edu.tw; drwpsung@yahoo.com.tw

MS received 11 January 2008; revised 1 April 2009

Abstract. The theory for structural control has been well developed and applied to perform excellent energy dissipation using dampers. Both active and semi-active control systems may be used to decide on the optimal switch point of the damper based on the current and past structural responses to the excitation of external forces. However, numerous noises may occur when the control signals are accessed and transported thus causing a delay of the damper. Therefore, a predictive control technique that integrates an improved method of detecting the control signal based on the direction of the structural motion, and a calculator for detecting the velocity using the least-square polynomial regression is proposed in this research. Comparisons of the analytical data and experimental results show that this predictor is effective in switching the moving direction of the semi-active damper. This conclusion is further verified using the component and shaking table test with constant amplitude but various frequencies, and the El Centro earthquake test. All tests confirm that this predictive control technique is effective to alleviate the time delay problem of semi-active dampers. This predictive control technique promotes about 30% to 40% reduction of the structural displacement response and about 35% to 45% reduction of the structural acceleration response.

Keywords. Predictive control; noise reduction; time delay; time compensate; component test; shaking table test.

1. Introduction

Structural control systems using vibration isolation and seismic isolation techniques have been extensively applied in many industries such as: mechanical, vehicle, motorcycle, military and civil engineering to avoid disastrous structural damages caused by internal impact forces or external forces. Particularly, a strong vibration caused by external forces on high-rise buildings

*For correspondence

with large displacement usually threatens the safety of the structures. Currently, the structural control methods may be classified as active, semi-active, and passive controls (Housner *et al* 1997; Yao 1972; Meirovitch 1990; Song & Spencer 2002; Song & Cimellaro 2008; Lin 2008). The active and semi-active controls depend on the system response to vibrations that have been converted to control signals with a core unit. The controls precisely organize the sequence of signals as querying dynamic response of structure, and properly adjust active or semi-active components. The electromagnetic valve of these dampers will select a correct signal to decide on the optimal switching moment of the semi-active damper according to dynamic response data (Qin *et al* 2008; Xu & Li 2008; Loh *et al* 2007). Signals with good quality are definitely of great importance to the performance of semi-active dampers. But, some noise may be generated when signals are queried and transported to deteriorate the signal quality. A low pass filter is usually installed in the measuring circuit to filter out noises when signals are gathered and transmitted (Maheshwari 2007; Hayano *et al* 2007; Kawachi *et al* 2007). Nevertheless, the low pass filter causes additional time delay problem that may diminish the energy-dissipating capability of semi-active dampers.

Shih *et al* 2002; 2003; Shih & Sung 2004; Shih *et al* 2006 proposed new semi-active damper-Displacement dependent semi-active hydraulic damper (DSHD), accumulated semi-active hydraulic damper (ASHD), and velocity and displacement dependent hydraulic damper (VDHD) that include the electromagnetic valve implemented on the damper to select the correct switch. Thus, the quality of signals is somewhat improved to enhance the success of the control system. Recently, the optimal prediction theory (Ernst 1993; Schober *et al* 1998; Kjell 2002; Bolcskei & Hlawatsch 2001; Huang *et al* 2001; Janssens *et al* 2009; Sun *et al* 2009; Ciesielka & Golas 2006) and Kalman filter (Pavkovic *et al* 2009; Subrahmanyam *et al* 2008; Petersen *et al* 2008) provided signal-processing methodology to predict the response of structures with some restrictions. Therefore, Shih & Sung (2007) proposed a velocity predictor based on the least-square polynomial regression to improve the calculation of velocity for detecting the correct switch timing of semi-active dampers. Some characteristics of this velocity predictor are: (i) a linear acceleration regression module is used to successfully perceive the opportune moment for compensating the time delay; (ii) when the standard deviation of the predictive velocity noise is less than one-tenth of that of the original velocity, the probability of misjudging the control signal is only 10%; (iii) the standard deviation evaluated based on the viable velocity noise is less than the critical value regressed by displacement noise; (iv) for the actual design, the length of sampling history data is related to the natural frequency of the structure. For example, with 1-Hz natural frequency, 0·4% noise of displacement signal, and 0·1-sec history, the length of sampling history data is 0·2 seconds (Shih & Sung 2007). Therefore, this new methodology, which predicts the control signals based on the direction of structural motions, is further studied in this research for effective control of the semi-active damper system. The efficiency of this predictive control technique will be confirmed using the component and the shaking table tests with simulated bracing; the tests are carried out using a constant amplitude with different frequencies and underground motion generated by El Centro 1940 with 250 gal peak ground acceleration.

2. Predictive control

In the velocity predictor method (Shih & Sung 2007), diminishing the time delay and recovering the capacity loss are proposed herein as the method of time compensation. The structural reaction signals including displacement, velocity and acceleration, in a previous step are used to establish the signals for the next step. Thus, the requesting signal can be started before the optimal reverse point for compensating time delay by switching on the electromagnet valve on time. This methodology is derived based on the polynomial regression module with the least square formulation.

2.1 *Noise estimation*

By taking a dynamic sample of a fixed frequency from relative displacements of N structures, the sampling data is defined as:

$$x_i, i = 0 \rightarrow N - 1. \tag{1}$$

Where, x_i represents the displacement backward to i steps from current time step, and x_0 is current displacement.

If the function of displacement corresponding to time has $M - 1$ terms in variety of polynomial, it can be written as:

$$\hat{x}(t) = \sum_{j=0}^{M-1} a_j t^j. \tag{2}$$

Where, $\hat{x}(t)$ is defined as the regression displacement and a_j is the coefficient of the j-th term.

According to the least square regression, the optimal estimation of polynomial coefficient in Eq. (4) is:

$$\{a\} = [E]^{-1}\{y\}, \tag{3}$$

where, $\{a\}$ is a coefficient vector in M dimension, $[E]$ represents an M by M system matrix, and $\{y\}$ determines the M dimensional vector of sampling data.

$$[E] = \begin{bmatrix} N & \sum_{i=0}^{N-1} i & \sum_{i=0}^{N-1} i^2 & \cdots & \sum_{i=0}^{N-1} i^{M-1} \\ & \sum_{i=0}^{N-1} i^2 & \sum_{i=0}^{N-1} i^3 & \cdots & \sum_{i=0}^{N-1} i^M \\ & & \sum_{i=0}^{N-1} i^4 & \cdots & \sum_{i=0}^{N-1} i^{M+1} \\ & symm. & & \ddots & \vdots \\ & & & & \sum_{i=0}^{N-1} i^{2M-2} \end{bmatrix} \tag{4}$$

$$\{y\} = \begin{Bmatrix} \sum_{i=0}^{N-1} x_i \\ \sum_{i=0}^{N-1} i \cdot x_i \\ \sum_{i=0}^{N-1} i^2 \cdot x_i \\ \vdots \\ \sum_{i=0}^{N-1} i^{M-1} \cdot x_i \end{Bmatrix} \tag{5}$$

Practically, the data queue of displacement signals is stored in the signal creator as first-in-first-out (FIFO) information for executing semi-active control with the same frequency, which in general is greater than 100 Hz. Therefore, the real-time optimal polynomial coefficient can be derived by modifying Eq. (5) as:

$$\{y\} = [B]_{M\times N}\{x\}_N \tag{6}$$

where,

$$[B] = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 0 & 1 & 2 & \cdots & N-1 \\ 0 & 1^2 & 2^2 & \cdots & (N-1)^2 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 1^{M-1} & 2^{M-1} & \cdots & (N-1)^{M-1} \end{bmatrix};$$

$\{x\}$ is the vector of structure displacement.

Substituting Eq. (6) into Eq. (3), the optimal coefficient matrix is expressed as:

$$\{a\} = [E^{-1}][B]\{x\}. \tag{7}$$

Consequently, a new matrix of coefficient regression system $[F]$ is defined as:

$$[F]_{M\times N} = [E^{-1}]_{M\times M}[B]_{M\times N} \tag{8}$$

Therefore,

$$\{a\} = [E^{-1}][B]\{x\}. \tag{9}$$

$[F]$ is a constant matrix depending on the number of sampling points and regression ranks but independent of time or vector of data queue.

Furthermore, Eq. (9) can be substituted into Eq. (3) to obtain the regression value of displacement in matrix form as:

$$\hat{x}_i = \begin{bmatrix} 1 & i & i^2 & \cdots & i^{M-1} \end{bmatrix}[F]\{x\}. \tag{10}$$

Then, an optimal coefficient vector $\{F_i\}$ estimated for the displacement at previous i steps from current time can be defined as:

$$[F_i^T] = \begin{bmatrix} 1 & i & i^2 & \cdots & i^{M-1} \end{bmatrix}[F]. \tag{11}$$

Values of $\{F_i\}$ can be stored in computer memory for carrying out real-time computations and estimating the optimal displacement $\hat{x}_i$ based on the following equation:

$$\hat{x}_i = \{F_i\} \bullet \{x\}. \tag{12}$$

2.2 *Velocity estimation*

The optimal displacements can be easily predicted using Eq. (12). Meanwhile, the velocity can be obtained by differentiating the displacement equation with respect to time as:

$$\dot{\hat{x}}_i = \frac{d}{dt}\hat{x}(t), \quad t = i \cdot \Delta t. \tag{13}$$

Therefore, Eq. (13) can be rewritten as:

$$\dot{\hat{x}}_i = \left(\frac{d}{dt}\{F_i\} \bullet \{x\}\right) \Big/ \Delta t. \tag{14}$$

Substituting Eq. (11) into Eq. (14), one obtains:

$$\dot{\hat{x}}_i = \{G_i\} \bullet \{x\}. \tag{15}$$

Where, $\{G_i\}$ is the optimal vector of estimation velocity. And,

$$[G^T] = \begin{bmatrix} 0 & 1 & 2i & 3i^2 & \ldots & (M-1)i^{M-2} \end{bmatrix} [F], \tag{16}$$

$\{G_i\}$ can be stored in computer memory for predicting the real-time velocity or regressing velocity at any arbitrary time step; i.e., the optimal velocity for previous i time steps from the current time can be estimated by multiplying $\{G_i\}$ with the derivative of the displacement vector shown as Eq. (14).

3. Experimental set-up

This research has planned for a series of component tests along with shaking table tests to investigate the signal process and predictive control performance of this proposed predictive control method. The component tests are conducted using 15mm amplitude with frequencies varying from 0·2 Hz to 2·0 Hz. The shaking table tests are conducted to demonstrate the predictive control capability of this proposed method. El Centro (1940) earthquake record is used as an input excitation to the shaking table.

3.1 *Set-up for component test*

Figure 1 shows the installation of devices and implementation of sensors to test the predictive capability and signal quality for verifying the validity of the proposed prediction theory. Detailed data descriptions are listed in tables 1 and 2. The dynamical signal query device (NI-PSI-6035) used for the noise test retrieves signals 100 times per second for 10 seconds. The deformation behaviour of the bracing in the actual building is an important factor to influence the earthquake proof feasibility of the damper such that this phenomenon affects the predictive control performance. Therefore, in this component test, a soft spring is utilized to simulate its bracing element. The set-up for conducting the component test to test the predictive control performance of this proposed method is shown in figure 2.

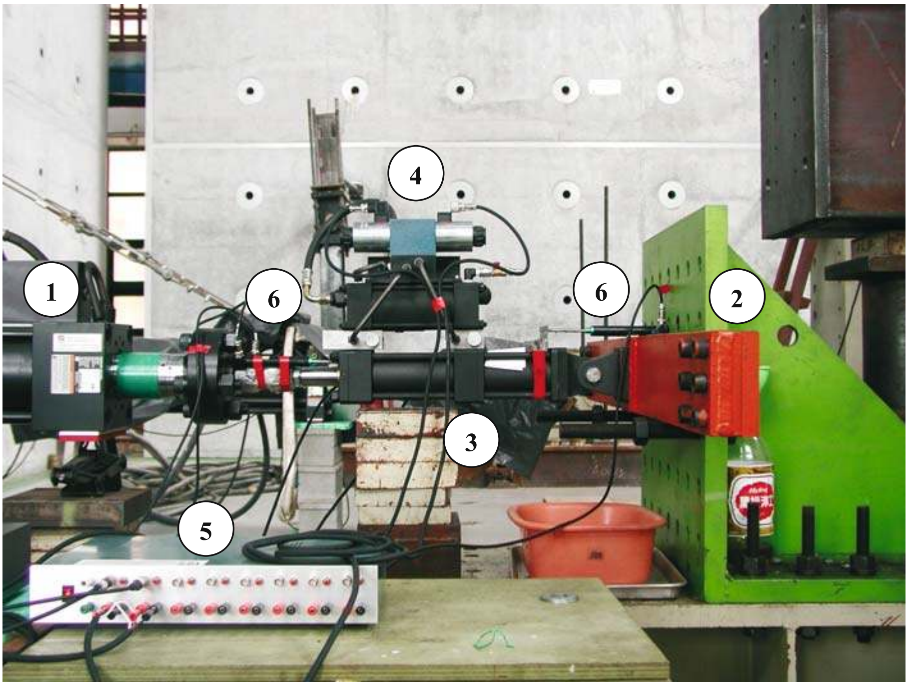

Figure 1. Installation of experimental set-up and arrangement of perception implement. 1. actuator; 2. simulated spring for bracing; 3. damper; 4. directional valve; 5. switch control box of directional valve; 6. perception and measurement system.

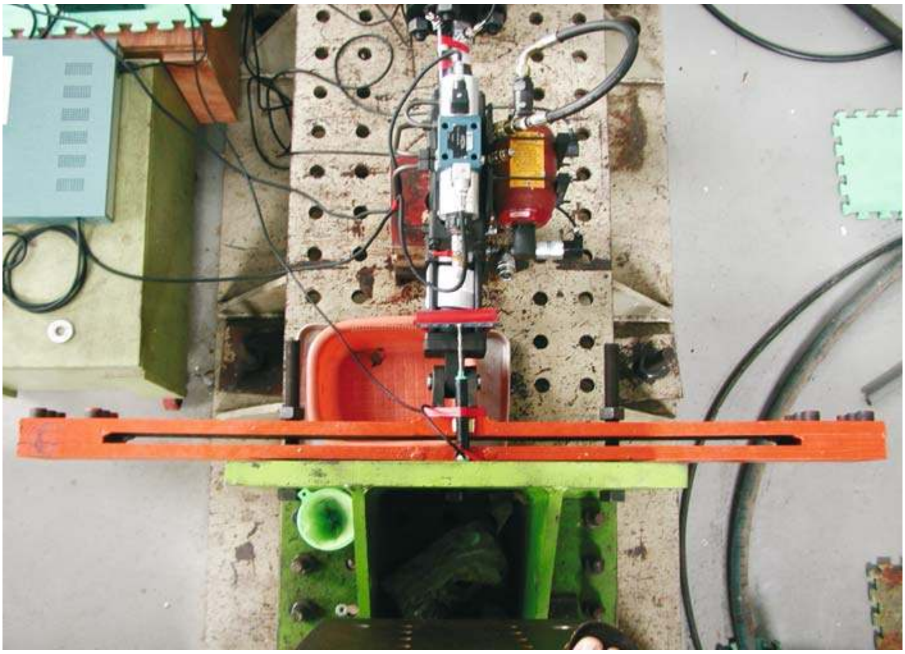

Figure 2. The simulated bracing for component test.

Table 1. Properties data and signal quality of perception device.

ID Number	Position	Signal type	Sensor type	Range
D1	Actuator	Displacement	Potential meter	0–100 mm
D2	Damper	Displacement	Potential meter	0–100 mm
F1	Damper	Force	Strain gauge	±50 kN
A1	Actuator	Acceleration	Capative	±3 G

Table 2. Signal quality parameters of perception device.

ID Number	Sensitivity	Nonlinearity	Noise, standard deviation
D1	20 mm/Volt	<0·1% F.S.	0·024 mm
D2	20 mm/Volt	<0·1% F.S.	0·023 mm
F1	14·3 kN/Volt	<0·05%F.S.	9·62 N
A1	1 G/Volt	<0·1%	0·321 Gal

3.2 *Set-up for shaking table test*

This experiment is based on the shaking table test to conduct predictive control performance of the proposed predictive theory. Dimensions of the shaking table are 3·0 m × 3·0 m. The maximum acceleration of this shaking table is ±1·0 g with loads of hydraulic actuator up to 15 tones. A two-thirds reduction of a one-story single-bay, steel frame as shown is used as the test structure in figure 3. In order to acquire the obvious elastic deformation, all four columns of this test structure are made of 100 × 32 mm solid steel. In the shear-building test of this research, a soft spring is utilized to simulate the deformation behaviour and inter-function of the bracing in the lateral movement of the building caused by shear. The purpose of this test is to examine and demonstrate the real predictive control capability of the proposed predictive control theory. The mechanical characteristics of the test structure are listed in table 3.

4. Test results

4.1 *Component test results*

4.1a *Passive behaviour of component test:* A useful quantity of real deformation of the energy-dissipation system is always less than the displacement phase of the structure with consideration of elastic deformation in the bracing. The stiffness of the practical passive control system should be greater than the stiffness of the structure in order to ensure the deformability of obvious shock absorption. Thus, this research conducts passive behaviour simple harmonic reciprocal motions with frequencies varying from 0·2 Hz to 2·0 Hz. Figure 4 shows that the measured hysteretic loops approach parallelogram. The quantity of energy-dissipating capability is obviously less than the energy-dissipating characteristics of pure damper under the limitation of equivalent damping force and displacement amplitude. These results demonstrate that the passive damper has the required rigid stiffness.

4.1b *Semi-active behaviour of component test without predictive control:* These component tests for semi-active behaviour without predictive control are carried out by applying forced

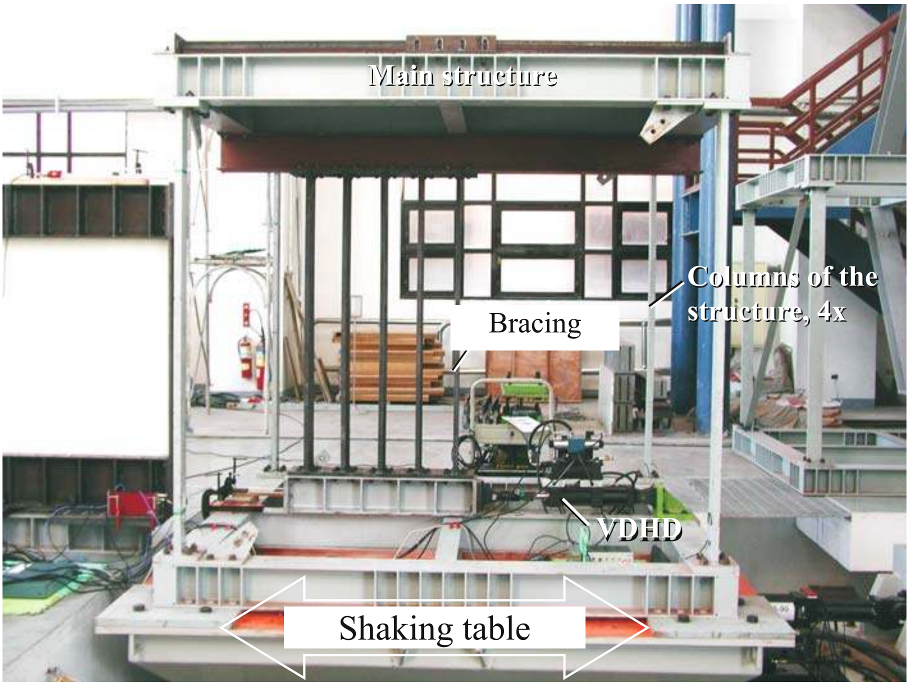

Figure 3. Set-up for shaking table test.

reciprocal motion with 15 mm amplitude to investigate the feasibility of dynamic immediate feedback control. The purpose of these tests is to demonstrate the damage of seismic proof performance due to time delay problems. Figures 5 to 10 reveal the various hysteretic loops of semi-active behaviour for the structure excited by forced reciprocal motion. These results show that the performance of energy-dissipating behaviour is not ideal under high-frequency excitations. The main reason of this phenomenon is that the inter force of bracing cannot be released at the right moment in accordance with the time delay problem. Thus, the seismic proof performances of passive and semi-active behaviours are equivalent at frequency of 2·0 Hz.

Table 3. Natural frequency, damping ratio and mass of test structure.

Structure type	Original	Semi-active control
Frequency, Hz	1·27	2·24
Damping ratio	0·006	0·01
Mass, ton	5·143	5·143
Stiffness of structure, kN/m	332	332
Stiffness of bracing, kN/m	-	690
Max. force of DSHD, kN	-	7, 12
Damping force-Weight ratio	-	0·13, 0·24
Stiffness ratio	-	2·08

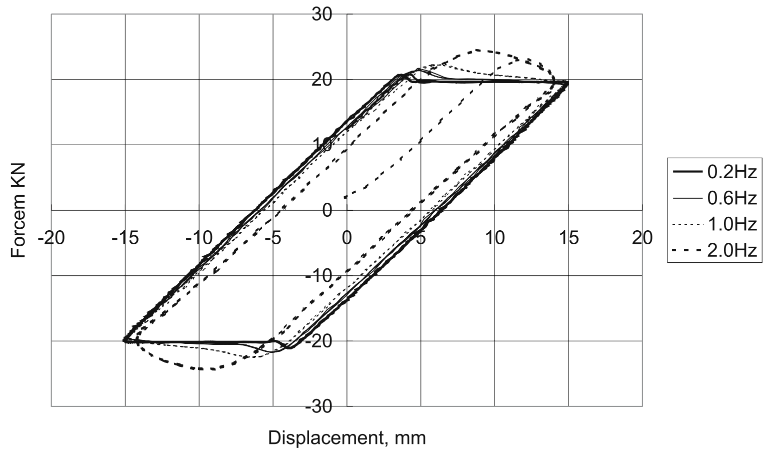

Figure 4. The hysteretic loops of passive behaviour measured component tests.

4.1c *Semi-active behaviour of component test with predictive control:* The objective of these tests is to demonstrate the predictive control capability for semi-active behaviour measured in component tests. All experimental parameters are the same as those shown in the above section (section 4·1b). In order to investigate the optimal quantity of time compensation, three different time compensation quantities, i.e. 0·07 sec, 0·10 sec and 0·13 sec, are used to conduct the predictive control tests. The experimental results are shown in figures 11 to 13.

These figures demonstrate that the proposed time compensation technique obviously improves the energy-dissipating capability. In spite of the quantity of time compensation, the seismic proof performance of the bracing has been promoted with the 0·10-sec quantity of time compensation being the best to improve the seismic proof capability. At 0·07 sec, the switch action seems to be still some dilatoriness while at 0·13 sec, the switch action may change too early. The seismic proof performance slightly decreases but not obvious to cause

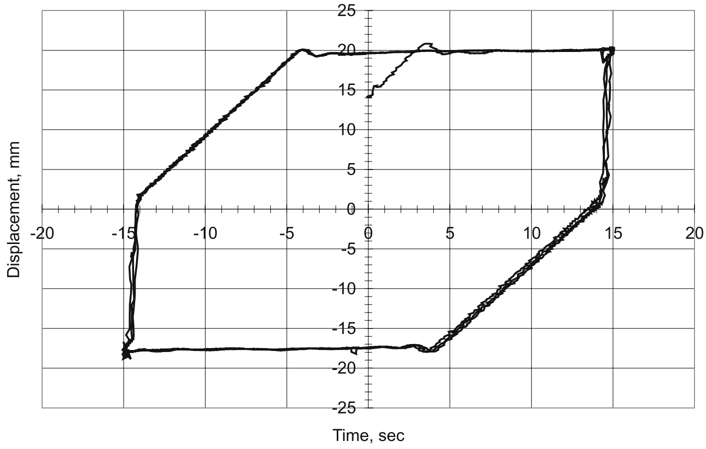

Figure 5. The hysteretic loops of semi-active behaviour measured in component tests w/o predictive control under the excitation of 0·2-Hz simple harmonic motion.

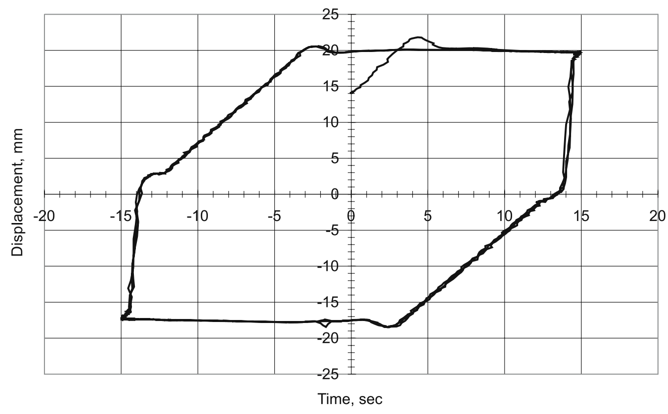

Figure 6. The hysteretic loops of semi-active behaviour measured in component tests w/o predictive control under the excitation of 0·4-Hz simple harmonic motion.

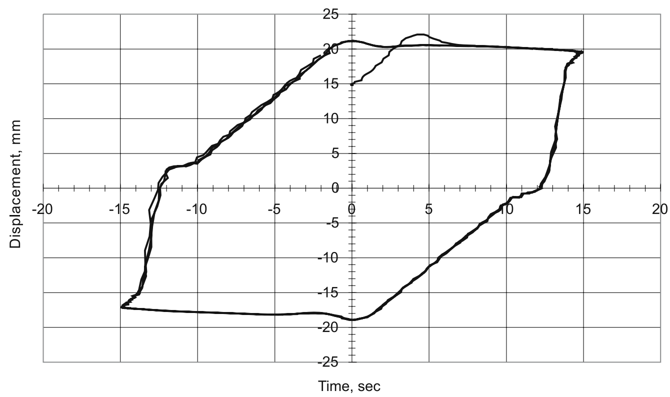

Figure 7. The hysteretic loops of semi-active behaviour measured in component tests w/o predictive control under the excitation of 0·6-Hz simple harmonic motion.

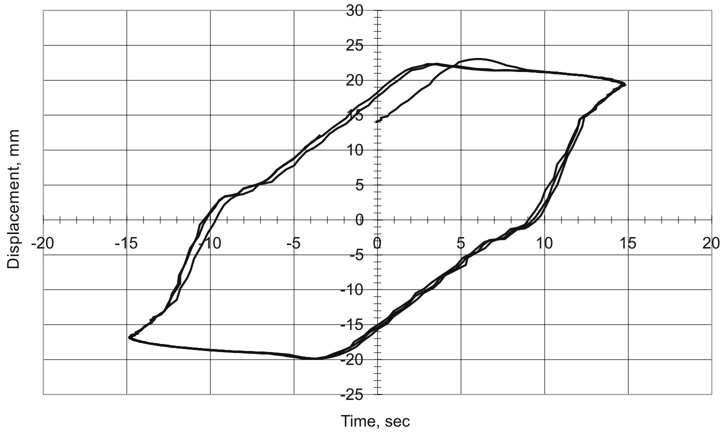

Figure 8. The hysteretic loops of semi-active behaviour measured in component tests w/o predictive control under the excitation of 1·0-Hz simple harmonic motion.

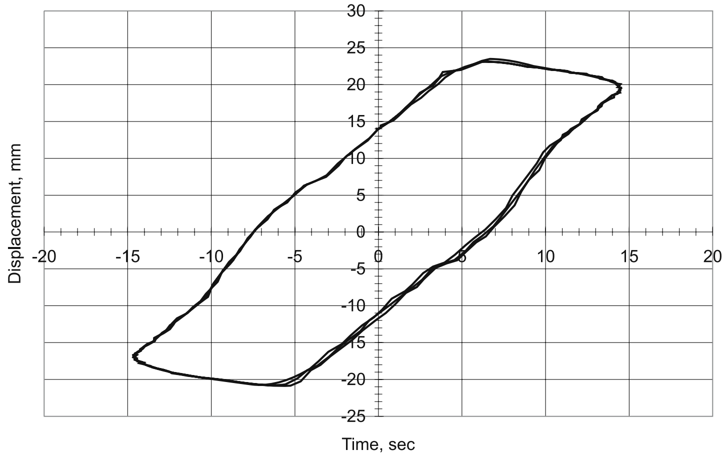

Figure 9. The hysteretic loops of semi-active behaviour measured in component tests w/o predictive control under the excitation of 1·4-Hz simple harmonic motion.

a concern. These test results indicate that the superior efficiency of the proposed time compensation technique has been demonstrated for all levels of time compensation used in the test.

4.2 *Shaking table test results*

4.2a *Comparison of structural displacement reduction effect:* Results of the shaking table test on the structural displacement responses under the excitation of El Centro earthquake with 250 gal peak ground acceleration are shown in figure 14. These results indicate that the structural displacement reduction percentage reaches 70% for structure equipped with control

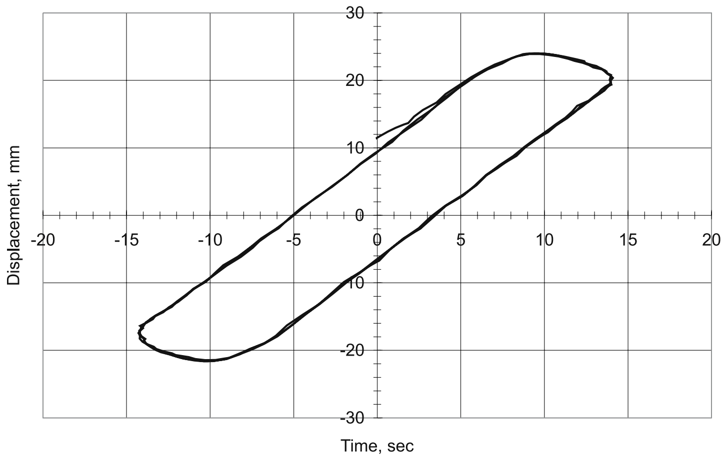

Figure 10. The hysteretic loops of semi-active behaviour measured in component tests w/o predictive control under the excitation of 2·0-Hz simple harmonic motion.

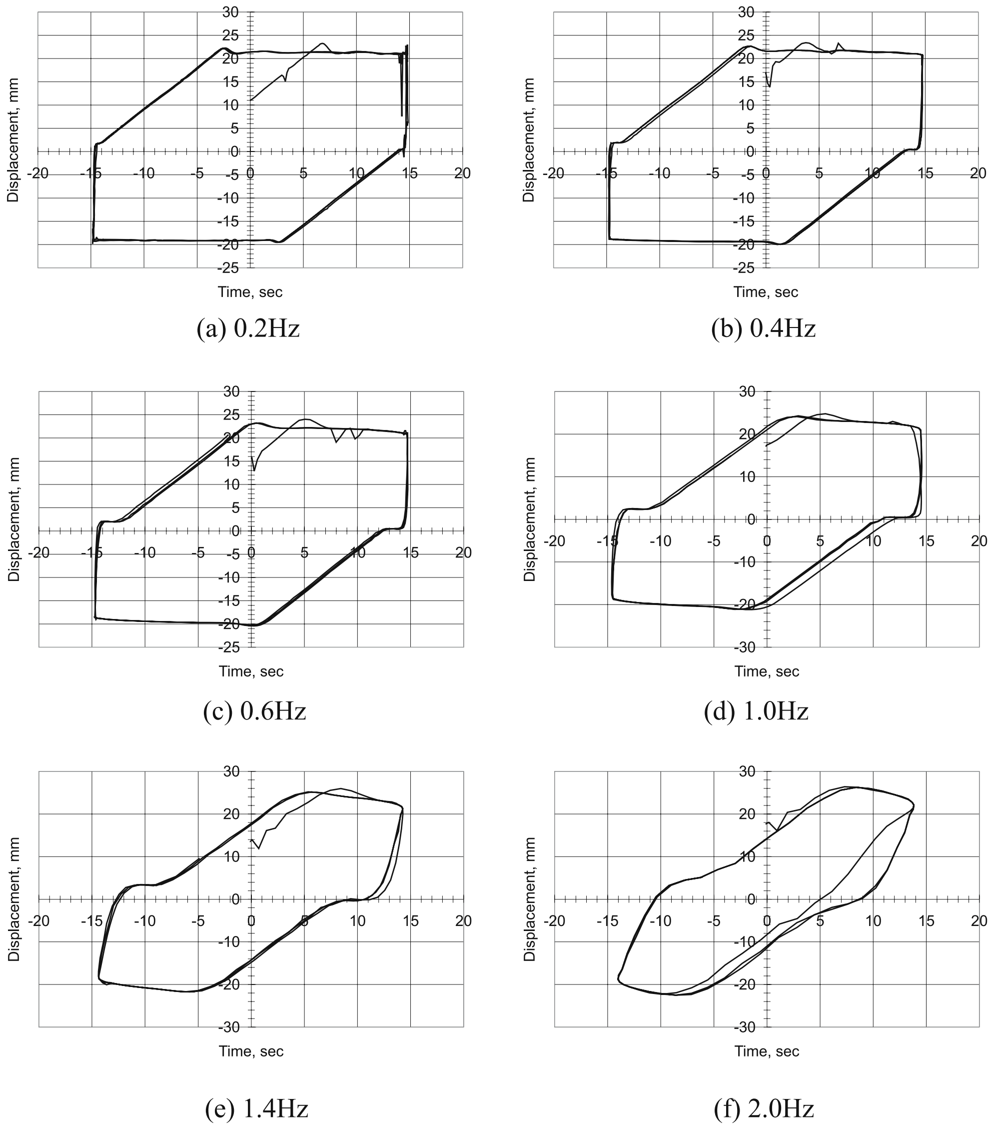

Figure 11. The hysteretic loops of semi-active behaviour measured in component tests with 0·07 sec time compensation predictive control under the excitation of simple harmonic motion.

system without predictive control and 80% with predictive control. The comparison of the results for structural control system with and without the proposed techniques reveals that the proposed control has about 30% to 40% reduction of the structural displacement.

4.2b *Comparison of structural acceleration reduction effect:* The shaking table results on the structural acceleration responses under the excitation of El Centro earthquake with 250 gal peak ground acceleration as shown in figure 15 is a typical time history of structural acceleration responses. This figure shows that the maximum acceleration reduces about 35% for structure equipped with control system without predictive control technique. But, the

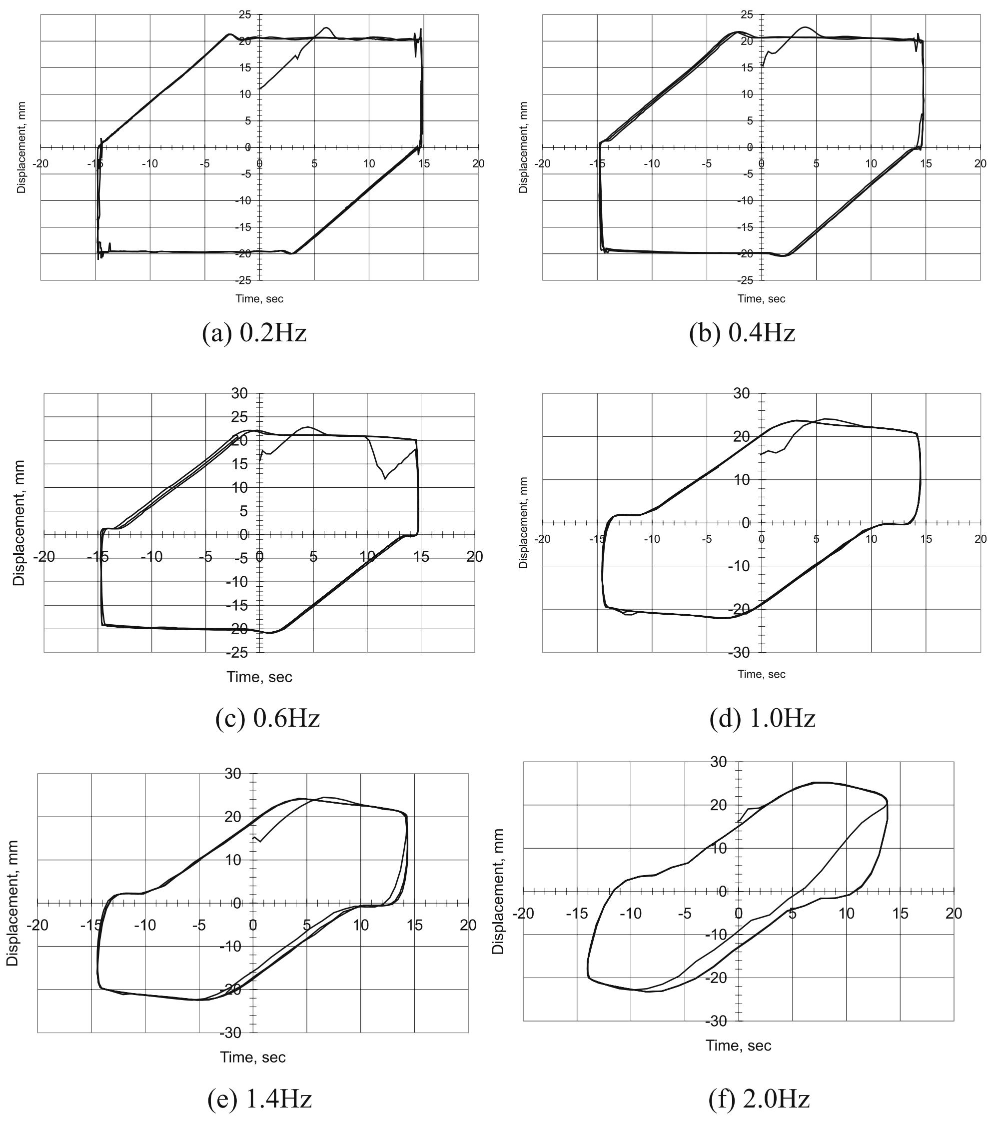

Figure 12. The hysteretic loops of semi-active behaviour measured in component tests with 0·10 sec time compensation predictive control under the excitation of simple harmonic motion.

maximum acceleration reduction percentage rises up to 45% for structure equipped with control system using the proposed predictive technique.

5. Conclusions

The quality of noise signal on structure dynamic respond significantly affects the estimation of velocity signal. When the displacement noise is too large, it will export a wrong control signal or even lose the normal functionality of a semi-active control damper. To ensure the

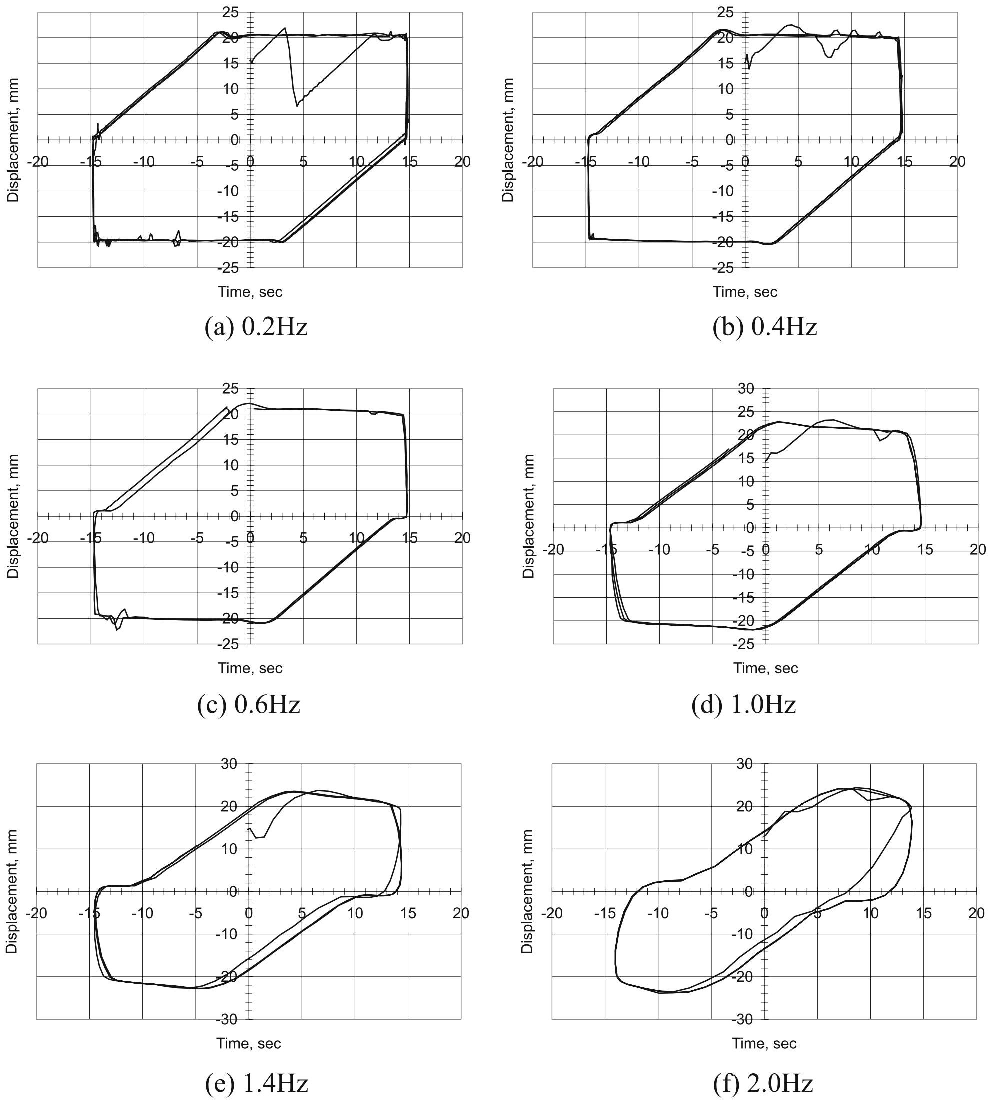

Figure 13. The hysteretic loops of semi-active behaviour measured in component tests with 0·13 sec time compensation predictive control under the excitation of simple harmonic motion.

measured displacement with the highest quality signal for achieving the sampling history with the shortest length, the measured signal needs to be processed for the so-called ‘non-ideal condition’ at the engineering site. For practical engineering applications, the most acceptable method is installing a low pass filter in the measuring circuit. However, this filter will produce additional time delay to defect the energy dissipation effect. Fortunately, the natural frequency of most structures with energy dissipation ability is usually between 0·25 Hz and 2·0 Hz. Within this range, this proposed velocity predictor can actually estimate the switch timing of semi-active damper by using polynomial regression of least square with calculations carried using linear acceleration module. The experimental test results reveal that this proposed predictive control technique is available to detect the reverse point of velocity prior to changing

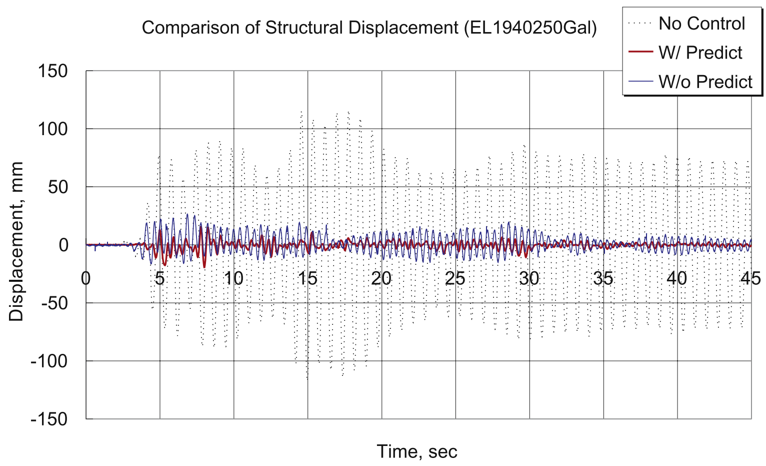

Figure 14. The comparison of structural displacement for structure without control, equipped with control system with predictive control and without predictive control.

the direction of structure motion and diminishing the unexpected effects caused by time delay. Conclusions of the findings are summarized as follows:

(i) This linear acceleration regression module can successfully perceive the opportune moment to compensate time delay, which always causes terrible influences on semi-active control damper.
(ii) In spite of the quantity of time compensation, seismic proof performances of the bracing have been promoted.
(iii) The experimental results reveal that seismic proof effects for structure equipped with control system this predictive control technique promote about 30% to 40% reduction of the structural displacement.

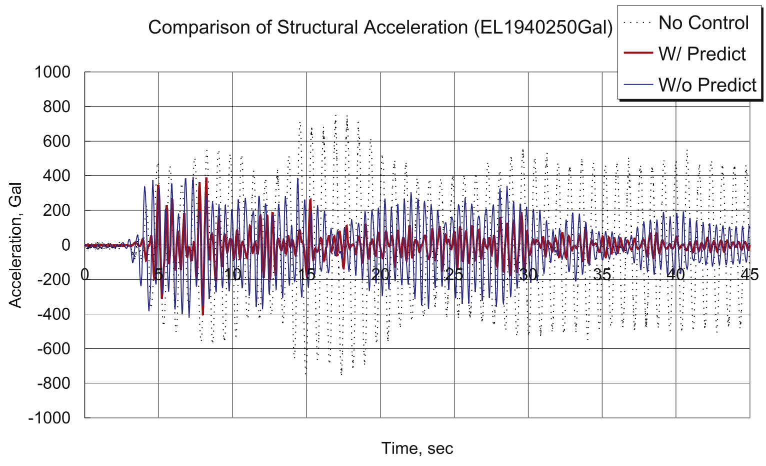

Figure 15. The comparison of structural acceleration responses for structure without control, equipped with control system using and without using the proposed predictive control.

(iv) The maximum acceleration reduction percentage for structure equipped with control system can reach to 35% without predictive control technique and attain 45% using this proposed predictive technique.

The National Science Council of Taiwan, R.O.C. supported this research through grant No. NSC 97-2626-M-167-001 and NSC 97-3114-E-167-001 and this support is gratefully acknowledged.

References

Bolcskei H, Hlawatsch F 2001 Noise reduction in oversampled filter banks using predictive quantization. *IEEE Transactions on Information Theory* 47(1): 155–172

Ciesielka W, Golas A 2006 Active control of sound by means of digital equalizers. *Archives of Acoustics* 31(1): 89–97

Ernst D 1993 Noise prediction equalizer and decision feedback equalizer for high speed digital subscriber line transmission – A comparison of performance. *European Transactions on Telecommunications and Related Technology* 4(1): 63–67

Hayano T, Shibutani I, Ohishi K, Miyazaki T, Koide D, Tokumaru H 2007 Achievement method of high-speed response of error prediction tracking control for optical disk system. *IEEJ Transactions on Industry Applications* 127(9): 942–949

Housner G W, Bergman L A, Caughey T K, Chassiakoes A G, Claus R O, Masri S F, Skelton R E, Soong T T, Spencer B F, Yao J T P 1997 Structural control: Past Present and Future. *J. Eng. Mech.* 123(9): 897–971

Huang H G, Chen C M, Wang S D, Lu H H 2001 Adaptive symmetric mean filter: A new noise-reduction approach based on the slope facet model. *Applied Optics* 40(29): 5192–5205

Janssens K, Gajdatsy P, Van der Auweraer H, Varoto P S, Sas P, Desmet W 2009 Active sound quality control of engine induced cavity noise. *Mechanical Systems and Signal Processing* 23(2): 476–488

Kawachi O, Mitobe S, Tajima M, Inoue S, Hashimoto K 2007 Low-loss and wide-band double-mode surface acoustic wave filters using pitch-modulated interdigital transducers and reflectors. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control* 54(10): 2159–2164

Kjell G 2002 Predicting response spectra for earthquake signals generated as filtered noise. *Probabilistic Eng. Mech.* 17(3): 241–252

Lin C C 2008 Structural control and health monitoring: Editorial. *Structural Control and Health Monitoring* 16(1): 1–6

Loh C H, Lynch J P, Lu K C, Wang Y, Chnag C H, Lin P Y, Yeh T H 2007 Experimental verification of a wireless sensing and control system for structural control using MR dampers. *Earthquake Eng. and Struct. Dynam.* 36(10): 1303–1328

Maheshwari S 2007 A new current-mode current-controlled all-pass section. *J. Circuits, Systems and Computers* 16(2): 181–189

Meirovitch L 1990 Dynamics and control of structures. (New York: Copyright by John Wiley & Sons) 244–257

Pavkovic D, Deur J, Kolmanovsky I 2009 Adaptive Kalman filter-based load torque compensator for improved SI engine idle speed control. *IEEE Transactions on Control Systems Technology* 17(1): 98–110

Petersen C D, Fraanje R, Cazzolato B S, Zander A, Hansen C H 2008 A Kalman filter approach to virtual sensing for active noise control. *Mechanical Systems and Signal Processing* 22(2): 490–508

Qin X, Zhang X, Cherry S 2008 Study on semi-active control of mega-sub controlled structure by MR damper subject to random wind loads. *Earthquake Eng. and Eng. Vib.* 7(3): 285–294

Schober R, Gerstacker W H, Huber J B 1998 Improving differential detection MDPSK by noise prediction. IEEE Global Telecommunications Conference 1: 567–572

Shih M H, Sung W P, Go C G 2002 Development of accumulated semi-active hydraulic damper. *Experimental Techniques* 26(5): 29–32

Shih M H, Sung W P, Go C G 2003 A design concept with a displacement dependent semi-active hydraulic damper for energy dissipation. Experimental Techniques 27(6): 53–56

Shih M H, Sung W P 2004 The energy dissipation behaviour of displacement dependent semi-active hydraulic damper. *J. Struct. Mech. Earthquake Eng.* Japan Society of Civil Engineering 21(2): 121s–129s

Shih M H, Sung W P, Go C G 2006 Development and seismic reduction performance of velocity and displacement dependent hydraulic damper. Experimental Techniques 41(3): 41–45

Shih M H, Sung W P 2007 Predictive control and signal on noise reduction for semi-active hydraulic damper. *Int. J. Struct. Stability and Dynam.* 7(1): 129–149

Soong T T, Spencer Jr. B F 2002 Supplemental energy dissipation: state-of-the-art and state-of-the-practice. *Eng. Struct.* 24: 243–259

Soong T T, Cimellaro G P 2008 Future directions in structural control. *Structural Control and Health Monitoring* 16(1): 7–16

Subrahmanyam G R K, Rajagopalan A N, Aravind R 2008 Importance sampling-based unscented Kalman filter for film-grain noise removal. *IEEE Multimedia* 15(2): 52–63

Sun X, Liu N, Meng G 2009 Adaptive frequency tuner for active narrowband noise control systems. *Mechanical Systems and Signal Processing* 23(2): 845–854

Yao J T P 1972 Concept of structural control. *J. Struct. Div.* 123(9): 1567–1574

Xu L H, Li Z X 2008 Semi-active multi-step predictive control of structures using MR dampers. *Earthquake Eng. and Struct. Dynam.* 37(12): 1435–1448