SEISMIC REDUCTION PERFORMANCE OF PREDICTIVE CONTROL VELOCITY PREDICTOR FOR SEMI-ACTIVE HYDRAULIC DAMPER

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ABSTRACT :

The component tests of velocity predictor based on displacement signals for semi-active hydraulic damper reveal that this calculation method can promote the seismic proof effect successfully. The displacement response of structure is random with random of earthquake excitation. In order to ensure the predictive application of this calculation method, shaking table tests are used to demonstrate the feasibility of this predictive method, predicting the reverse timing of moving direction of structure properly. Shaking table tests results indicate that the seismic reduction performances of this method are: 1.) the displacement reduction effect can promote 30%-40%; 2.) the acceleration reduction effect rise to 43%. This predictive method is suitable for strong earthquake and small-scale magnitude earthquake, happened frequently, based on the analytical results of this research.

KEYWORDS: predictive calculator; velocity predictor; semi-active hydraulic damper

1. INTRODUCTION

Recently, the high-rise buildings increase gradually because of the modernization of city plus the gradual concentration in population. Nevertheless, many of strong earthquakes have caused major loss of life and property around the world. In order to protect the safety of people and safety of building structure, many structural control methods are developed to reduce vibration effect caused by seismic waves. These structural control techniques are used the extra control components to resist the structural vibration subjected to earthquake-induced force or strong wind force. In accordance with the providing control force to reduce vibration of structure, current structural control methods are classified as active, passive, and semi-active controls (Housner, et.al. 1997, Yao, 1972, Meirovitch, 1990, Spencer, 2002). The control forces of active and semi-active controls come from the vibration reactions of structure. Consequently, these control systems need a core unit to control and create signals in response to structural vibration. This core precisely systematizes the sequence of signals as querying structural dynamic responses, subjected to external forces, and properly changes the action forces of active or semi-active systems in accordance with structural reaction data. An electromagnetic valve, installed on the damper, is used to select the correct switch to control the action of damper for reducing the structural vibration. The signal qualities of structural reaction have great importance to the success of this control system. Presently, the best way of the signal process is to install a low pass filter in the measured circuit to filter out noises. But, this filter will produce additional time delay to hinder energy-dissipating capability of control systems. Time delay problems (Ernst, 1993) result in poor seismic proof capability of these kind control systems. Three types of time delay may be classified by following reasons (Ernst, 1993): (1) Caused by filter process; (2) Caused by the detection point of discrete control; (3) Caused by electromagnetic valve. In order to mend time delay problems, this research proposes speed calculator, based on structural displacement response, to compensate this time delay. Actually, the structural displacement responses are random because that earthquake load is random. Therefore, the shaking table test is used to investigate the feasibility of this proposed calculator, installed in semi-active hydraulic damper (Shih et. al., 2006).

2. MATHEMATICAL MODELLING FOR PREDICTIVE CONTROL

The control direction of semi-active hydraulic dampers (Shih et. al., 2004) must be reversed when the relative movement of story drift is at the reverse point according to control rules of these dampers. The complete procedure can be divided into several steps: (1) the signal creator of semi-active control component detects the relative velocity responses of structural floor, (2) the damper switches the circuit direction of electromagnet valve depending on reverse of velocity, (3) the electric current switches the electromagnet valve, and (4) once the valve is completely switched, the brace spring of semi-active component pushes the damper to neutral position to accomplish the control cycle. Each of above four steps will cause time delay and diminish the capacity of dissipation energy.

2.1 Noise Estimation – The Regression Polynomial Function of Least Square

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

$$x_i, \qquad i = 0 \rightarrow N-1 \tag{2}$$

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, then it can be written as follows:

$$\hat{x}(t) = \sum_{j=0}^{M-1} a_j t^j \tag{3}$$

Where, $\hat{x}(t)$ is defined as regression displacement and a_j is the coefficient of the j-*th* term.
Herein, the absolute value of structure velocity is not necessary computed; the discrete formulation is available. If the current time step is 0 then the time backward to i steps is $-i$. Similarly, the time forward to k steps is k. Eq. (3) can be rewritten as:

$$\hat{x}_i = \sum_{j=0}^{M-1} a_j i^j \tag{4}$$

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

$$\{a\} = \left[E^{-1}\right]\{y\} \tag{5}$$

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.

$$[E] = \begin{bmatrix} N & \sum_{i=0}^{N-1} i & \sum_{i=0}^{N-1} i^2 & \cdots & \sum_{i=0}^{N-1} i^{M-1} \\ & \sum_{i=0}^{N-1} i^2 & \sum_{i=0}^{N-1} i^3 & \cdots & \sum_{i=0}^{N-1} i^{M} \\ & & \sum_{i=0}^{N-1} i^4 & \cdots & \sum_{i=0}^{N-1} i^{M+1} \\ & symm. & & \ddots & \vdots \\ & & & & \sum_{i=0}^{N-1} i^{2M-2} \end{bmatrix} \tag{6}$$

$$\{y\} = \begin{Bmatrix} \sum_{i=0}^{N-1} x_i \\ \sum_{i=0}^{N-1} i \cdot x_i \\ \sum_{i=0}^{N-1} i^2 \cdot x_i \\ \vdots \\ \sum_{i=0}^{N-1} i^{M-1} \cdot x_i \end{Bmatrix} \tag{7}$$

Practically, data queue of displacement signal is stored in the signal creator by first-in-first-out (FIFO) to executing semi-active control with the same frequency, which in general is greater than 100Hz. Therefore; the real-time optimal polynomial coefficient can be modified from Eq. (7) as:

$$\{y\} = [B]_{M\times N}\{x\}_N \tag{8}$$

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. (8) into Eq. (5), the optimal coefficient matrix is expressed as:

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

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

$$[F]_{M\times N} = \left[E^{-1}\right]_{M\times M}[B]_{M\times N} \tag{10}$$

Therefore,

$$\{a\} = [F]\{x\} \tag{11}$$

Based on its definition, [F] is a constant matrix depending on the number of sampling points and regression ranks, but is independent to time or vector of data queue.
Furthermore, Eq. (11) can be substituted into Eq. (5) to obtain the regression value of displacement in matrix form, it is:

$$\hat{x}_i = [1 \quad i \quad i^2 \quad \cdots \quad i^{M-1}][F]\{x\} \tag{12}$$

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

$$[F_i^T] = [1 \quad i \quad i^2 \quad \cdots \quad i^{M-1}][F] \tag{13}$$

$\{F_i\}$ can be stored in computer memory for real-time computation to estimate the optimal displacement $\hat{x}_i$ using following equation:

$$\hat{x}_i = \{F_i\} \bullet \{x\} \tag{14}$$

2.2 Velocity Estimation

It is easily to predict optimal displacements using Eq. (14). Meanwhile, differentiating the displacement equation with respect to time will result in the velocity as:.

$$\dot{\hat{x}}_i = \frac{d}{dt}\hat{x}(t), \qquad t = i \cdot \Delta t \tag{15}$$

Therefore, Eq. (15) can be rewritten as:

$$\dot{\hat{x}}_i = \left(\frac{d}{dt}\{F_i\} \bullet \{x\}\right) \Big/ \Delta t \tag{16}$$

Substituting Eq. (13) into Eq. (16) to yield the following equation:

$$\dot{\hat{x}}_i = \{G_i\} \bullet \{x\} \tag{17}$$

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

$$[G^T] = [0 \quad 1 \quad 2i \quad 3i^2 \quad \ldots \quad (M-1)i^{M-2}][F] \tag{18}$$

$\{G_i\}$ can be stored in computer memory to predict real-time velocity or regressing velocity at any arbitrary time step; i.e., the optimal velocity for previous i time steps from current time can be estimated by multiplying $\{G_i\}$ by the displacement vector derived in Eq. (16).

3. SHAKING TABLE TEST

The shaking table test is used to conduct predictive control performance of this proposed predictive theory. The dimension of shaking table is 3.0 $m \times$ 3.0 m. A maximum acceleration of this shaking table is $\pm 1.0g$ with loads of hydraulic actuator up to 15 tones. Two-thirds reduced scale test structure used in this experiment a one-storey, single-bay, steel frame as shown in Fig. 1. In order to acquire obvious elastic deformation, four columns of this test structure is made of 100 $mm \times 32mm$ 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 this tested shear buildings. The purpose of this test is to test and demonstrate the real predictive control capability of this proposed predictive control theory. Sensors are installed in this model building for measuring the accelerations and displacements of damper, test frame and shaking table. The arrangement of sensors of this shaking table test is drawn on Fig. 1.

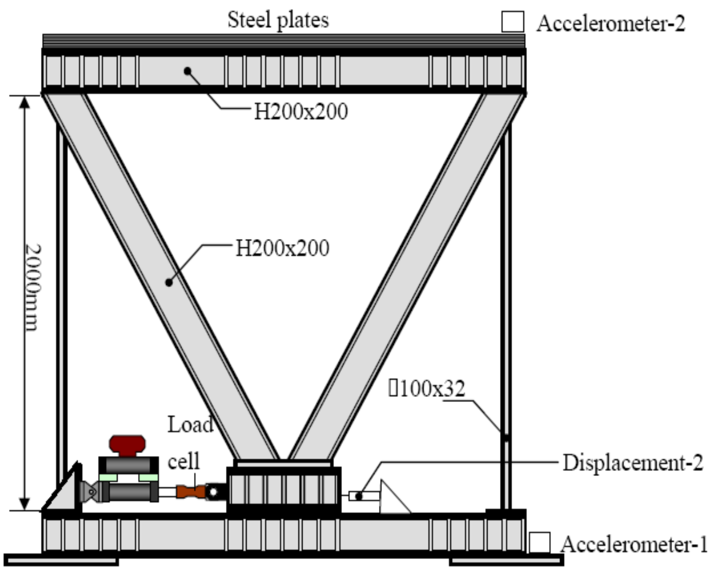

Fig. 1 Model for shaking table test and arrangement of sensors.

4. TEST RESULTS

The purpose of shaking table test is to examine the seismic resistant performance of this predictive calculator. The natural frequency, damping ratio and mass of test structure with and without VDHD are shown in Table 1. The functions of shock absorption should include the displacement and acceleration response of structure that both of these responses need to be diminished.

Table 1. Natural frequency, damping ratio and mass of test structure

Structure type	Original	VDHD
Frequency, Hz	1.31	5.24
Damping ratio	0.006	0.027
Mass, ton	4.901	4.901
Stiffness of structure, KN/m	332	332
Stiffness of bracing, KN/m	-	4980
Max. force of VDHD, KN	-	5, 10, 15
Damping force-Weight ratio	0	0.1、0.21、0.31

4.1 Comparison of structural displacement reduction effect

The shaking table results show the structural displacement responses under the excitation of El Centro earthquake with 0.25G peak ground acceleration in Fig. 2. These results indicate that the structural displacement reduction percentage reach 70% and 80% for structure added control system without predictive control and with predictive control respectively. The comparison of structural control system without and with this proposed techniques reveal that the structural displacement reduction effects promote about 30% to 40 %.

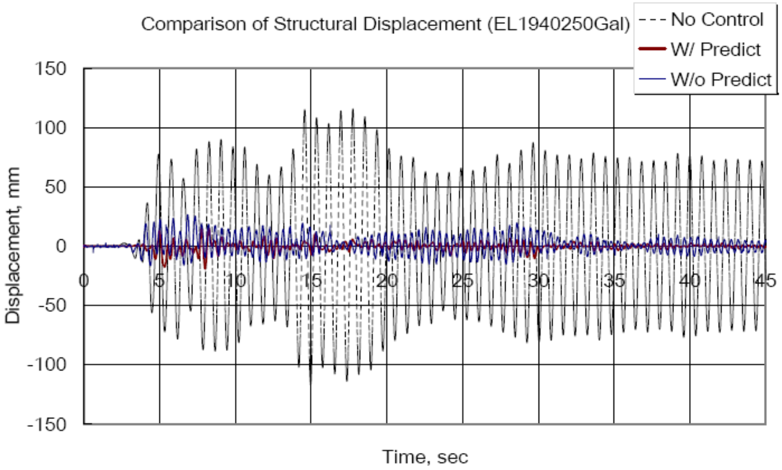

Fig. 2. The comparison of structural displacement for structure without control, added control system w/ predictive control and w/o predictive control

4.2 Comparison of structural acceleration reduction effect

The shaking table results show the structural acceleration responses under the excitation of El Centro earthquake with 0.25G peak ground acceleration in Fig. 3. Fig. 3 is the typical time history of structural acceleration responses. This figure shows that the maximum acceleration reduce about 35% for structure added control system without predictive control technique. But, the maximum acceleration reduction percentage rise up to 45% for structure added control system with this proposed technique.

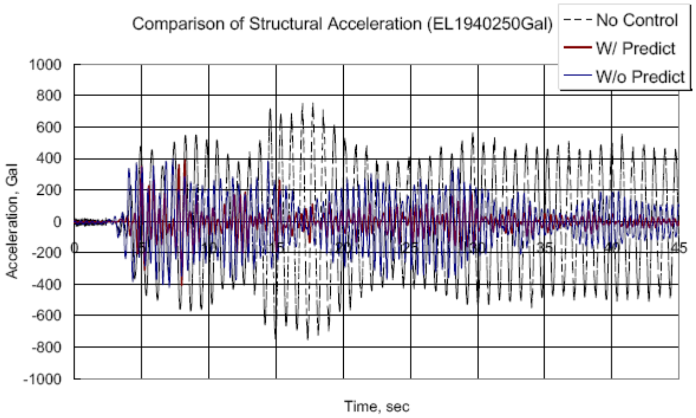

Fig. 3. The comparison of structural acceleration responses for structure without control, added control system w/ predictive control and w/o predictive control

4. CONCLUSIONS

The quality of noise signal on structure dynamic respond significantly affects estimation of velocity signal. When the displacement noise is too large, it will export wrong control signal, even lose normal functionality of the semi-active control damper. Fortunately, the natural frequency of structures with energy dissipation ability is usually from 0.25 Hz to 2.0 Hz. Within this range, the proposed velocity predictor can actually estimate the switch timing of semi-active damper. From the shaking table test results reveal that this proposed predictive control technique is available to detect the reverse point of velocity prior to change the direction of structure motion and diminish unexpected effects caused by time delay. The experimental results reveal that the seismic proof effects for structure added control system with this predictive control technique promote about 30% to

40%. Therefore, this proposed technique can be applied to promote the seismic proof capability of semi-active hydraulic damper.

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