Experimental Study of Semi-Active Device as Active Interaction Control Device

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SUMMARY:
Semi-active control device is a new challenge in research filed of structural control. Development of control devices is the key point among all tasks. The tendency of semi-active device development is "simple" and "high performance". Therefore, the objective of this research is to develop and improve the developed semi-active device DSHD (Displacement Semi-Active Hydraulic Damper) that has been converted to AIC (Active Interaction Control Device) with the addition of autonomous controller. To diminish the time delay problem, the predictive control is combined with this device. The full-scale elements and shaking table test under excitation of El Centro 1940 earthquake record are designed to verify the efficiency of seismic proof capability of this proposed AIC. Test results reveal that this method provide fine average of seismic proof percentage. The average of seismic proof percentage and structural response of story drift, absolute acceleration and base shear of this proposed method with predictive control is better than that without installed with autonomous controller and predictive control.

Keywords: Semi-Active control device, DSHD (Displacement Semi-Active Hydraulic Damper), AIC (Active Interaction Control Device)

1. INTRODUCTION

Recently, there are some strong earthquakes, happened in the world, cause many disasters. Especially, the unforgettable tsunami disaster caused by the earthquake in Indonesia and Japan with seismic Richter scale up to 9.0. These strong earthquakes cause large deformation of buildings and bridges. Therefore, civil engineers try to develop some device to reduce the deformation, caused by strong earthquake. When seismic force hit buildings, the instantaneous dynamic response will be excited by this earthquake excitation. Then, the structural internal mechanical energy, originates from the external load, is at a higher relative level. This structural internal mechanical energy cab be dissipated gradually via the internal friction in the material, damping and plastic energy. Therefore, these mechanics characteristics of material and building can be used to modify the structural dynamics response according to the safety, comfort and functional structure. This technology is defined as “Structural Control”. Generally, structural control is divided into: active control (Ribakov et. al, 1999), passive control (Tsai et al., 1999), and semi-active control (Abe, 1996; Dowell, 1994; Fujita, 1990)

The research achievements of Shih and Sung reveal that semi-active control is more reliable than the active control (Fujita, 1996). Therefore, the DSHD (displacement-dependent semi-active hydraulic damper) (Shih and Sung 2002) is proposed to add with autonomous controller to form as the semi-active AIC (Active Interaction Control) system (Iwan et al., 1998). But, this device will cause the time delay problem, thus, time compensation method is added to modify this defects. In order to verify the seismic proof capability of this device with the predictive control method, the two-story steel building is designed to test and investigate the structural response of building under excitation of shaking table test based on the El Centro earthquake record. Then, average of seismic proof percentage, average of seismic proof percentage and structural response of story drift, absolute acceleration and base shear of this test building added with AIC and predictive control method are compared those results of original building.

2. FRAME OF SEMI-ACTIVE DEVICE WITH AUTONOMOUS CONTROLLER

Displacement Semi-Active Hydraulic Damper, DSHD is proposed to add with autonomous controller as active interaction control device. DSHD is a kind of controllable energy-dissipating element of the passive control system and also treated as semi-active control device. The main design concept is based on the energy-dissipating component that the damping force can be generated by the flow of fluid through the orifice so as to conduct control. DSHD composed of Hydraulic Jack, Check Valve, Relief Valve and Throttle Valve, shown in Fig. 1. The energy-dissipating characteristics of the proposed damper are controlled by the flow of oil in the hydraulic jack. From the experiment in this research, it is discovered that the velocity

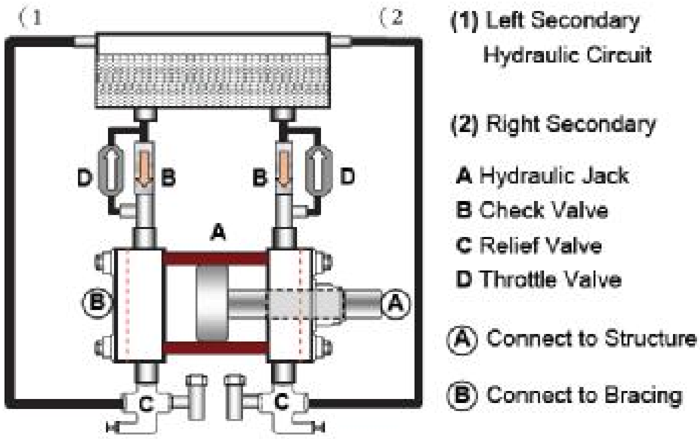

Figure 1. Framework of Displacement Semi-Active Hydraulic Device

2.1. Autonomous Controller

There are three functions of autonomous controller to connect with the DSHD and structure. Thus, these three functions of autonomous controller can perceive the dynamic responses of structure, sending out the control order which depends on the semi-active control law and tuning the behaviors of semi-active damper. The above mentions are the necessary performance requirements of the autonomous controller. Making the descriptions here about the semi-active control law, signal types of feedback, tuning methods of damper and the strategies, performance requirements of the autonomous controller. The tolerance of stretch direction of DSHD is controlled by the directional control valve. By using the inverse valve in the oil path, the damper can switch between the two situations. The two situations are “free shortening, can’t elongate” and “free elongating, can’t shorten”. Push the control stem of the directional control valve to the left side or right side. Fig. 2 shows the operating theorem about the directional control valve. It can be found from Fig.2 that the driven sources of the control stem of the directional control valve can be classified as override, electromagnetic reaction, guide pressure drive and drive of connecting rod. The driven sources of the directional control valve of the traditional semi-active hydraulic dampers are electromagnetic reaction. However, the autonomous controller which this research mentions is adopting a connecting-rod like to drive the directional control valve so as to form a semi-active hydraulic pressure damper without electricity.

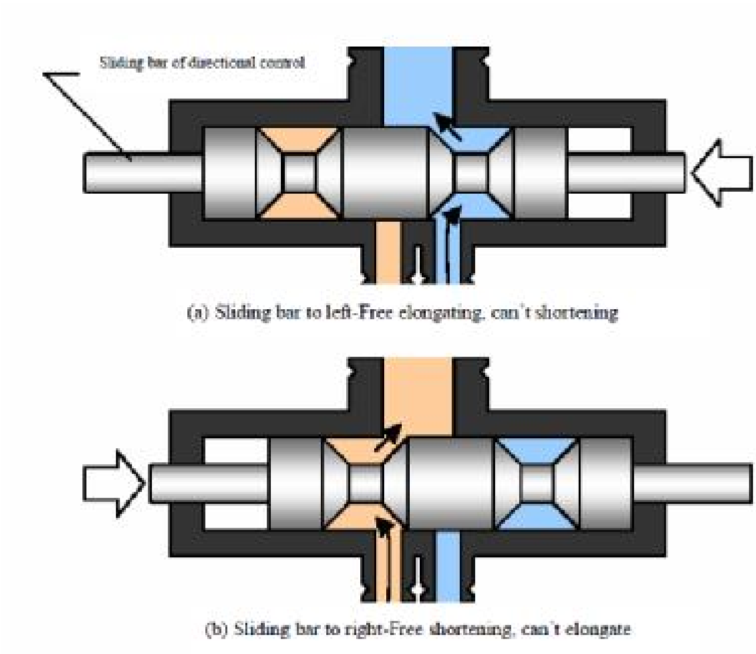

Figure 2. The theoretical diagram of directional valve

3. CONTROL LAWS AND PREDICTIVE CONTROL

3.1. Control Laws of DSHD With Autonomous Controller

The judging bases of semi-active control law are the position where damper sets up and the relative velocity of structure. The optimum control order is judged by the following equation:

$$u_i \bullet \dot{x}_{r,i} \leqq 0 \text{ , for } i=1 \text{ to } N_D \tag{3.1}$$

Where:

u_i is the ith inner force of damper force, tension force is positive and compressive force is negative in the equation;

$\dot{x}_{r,i}$ is the relative velocity of the ith damper that sets up at the story which have displaced, elongation represents positive and shortening represents negative;

N_D is the number of dampers.

It can be known from the equation (1) that every damper controls independently, and the optimal situation of every damper is only related to the P-N signal of the relative velocity at the position where the damper sets up.

3.2. Predictive Control

In the velocity predictor method (Shih and 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.

3.2.2. Noise Estimation

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

$$x_i, \qquad i = 0 \rightarrow N-1 \tag{3.1}$$

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:

$$\hat{x}(t) = \sum_{j=0}^{M-1} a_j t^j \tag{3.2}$$

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. (3.4) is:

$$\{a\} = \left[E^{-1}\right]\{y\} \tag{3.3}$$

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.

$$[E] = \begin{bmatrix} N & \sum_{i=0}^{N-1} i & \sum_{i=0}^{N-1} i^2 & \cdots & \sum_{i=0}^{N-1} i^{M-1} \\ & \sum_{i=0}^{N-1} i^2 & \sum_{i=0}^{N-1} i^3 & \cdots & \sum_{i=0}^{N-1} i^{M} \\ & & \sum_{i=0}^{N-1} i^4 & \cdots & \sum_{i=0}^{N-1} i^{M+1} \\ & symm. & & \ddots & \vdots \\ & & & & \sum_{i=0}^{N-1} i^{2M-2} \end{bmatrix} \tag{3.4}$$

$$\{y\} = \begin{Bmatrix} \sum_{i=0}^{N-1} x_i \\ \sum_{i=0}^{N-1} i \cdot x_i \\ \sum_{i=0}^{N-1} i^2 \cdot x_i \\ \vdots \\ \sum_{i=0}^{N-1} i^{M-1} \cdot x_i \end{Bmatrix} \tag{3.5}$$

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 100Hz. Therefore, the real-time optimal polynomial coefficient can be derived by modifying Eq. (3.6) as:

$$\{y\} = [B]_{M\times N}\{x\}_N \tag{3.6}$$

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. (3.6) into Eq. (3.3), the optimal coefficient matrix is expressed as:

$$\{a\} = [E^{-1}][B]\{x\} \tag{3.7}$$

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

$$[F]_{M\times N} = [E^{-1}]_{M\times M}[B]_{M\times N} \tag{3.8}$$

Therefore,

$$\{a\} = [F]\{x\} \tag{3.9}$$

[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. (3.9) can be substituted into Eq. (3.3) to obtain the regression value of displacement in matrix form as:

$$\hat{x}_i = [1 \quad i \quad i^2 \quad \cdots \quad i^{M-1}][F]\{x\} \tag{3.10}$$

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

$$[F_i^T] = [1 \quad i \quad i^2 \quad \cdots \quad i^{M-1}][F] \tag{3.11}$$

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:

$$\hat{x}_i = \{F_i\} \bullet \{x\} \tag{3.12}$$

3.2.3. Velocity Estimation

The optimal displacements can be easily predicted using Eq.(3.12). Meanwhile, the velocity can be obtained by differentiating the displacement equation with respect to time as:

$$\dot{x}_i = \frac{d}{dt}\hat{x}(t), \qquad t = i \cdot \Delta t \tag{3.13}$$

Therefore, Eq. (3.13) can be rewritten as:

$$\hat{\dot{x}}_i = \left(\frac{d}{dt}\{F_i\} \bullet \{x\} \right) \Big/ \Delta t \tag{3.14}$$

Substituting Eq. (3.11) into Eq. (3.14), one obtains:

$$\hat{\dot{x}}_i = \{G_i\} \bullet \{x\} \tag{3.15}$$

Where:

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

And,

$$\left[G^T\right] = \left[0 \quad 1 \quad 2i \quad 3i^2 \quad \mathbf{K} \quad (M-1)i^{M-2}\right]\left[F\right] \tag{3.16}$$

$\{G_i\}$ 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. (3.16).

4. EXPERIMETAL SET-UP

The shaking table test is planned for investigating the control performance of DSHD added with autonomous controller and predictive control performance of predictive control method. The shaking table tests are conducted to demonstrate the predictive control capability of this proposed method. El Centro (1940) earthquake record is used as input an excitation to the shaking table. 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 $\pm 1.0g$ with loads of hydraulic actuator up to 15 tones. A two-story single-bay, steel frame as shown is used as the test structure in Photo 1. In order to acquire the obvious elastic deformation, all four columns of this test structure are made of 100 *mm* × 32*mm* solid steel. 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 1.

Photo 1. The shaking table test for DSHD with Autonomous Controller

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

Original/FL	Stiffness(N/m)	Mass(kg)
1^{st} Fl	327680	4402
2^{nd} Fl	327680	4329
Dynamic Parameters		
Parameters	Mode 1	Mode 2
Frequency	0.85 Hz	2.256 Hz
Damping Ratio	0.0028	0.0033
Mode Vector	0.608 1.000	-1.241 1

5. TEST RESULTS AND DISCUSSIONS

The purpose of this research is that the shaking table test used to test and verify the performance of DSHD added with autonomous controller as active interaction control device. Otherwise, the predictive control method is also combined with this active interaction control device to test the seismic resistant performance. Therefore, a series of experimental tests are planned to verify the performance of this proposed method such as without predictive control, predictive control with 0.07 sec, 0.10 sec and 0.13 sec respectively to test the seismic proof capability. The test results of these tested plans with average of seismic proof percentage are shown in Fig. 3. These results reveal that average of seismic proof percentage of this proposed device with predictive control method 0.10 sec and 0.13 sec are higher than this proposed device with predictive control method 0.07 sec and without predictive control. Besides, all averages of seismic proof percentage of this proposed method are higher than passive control device.

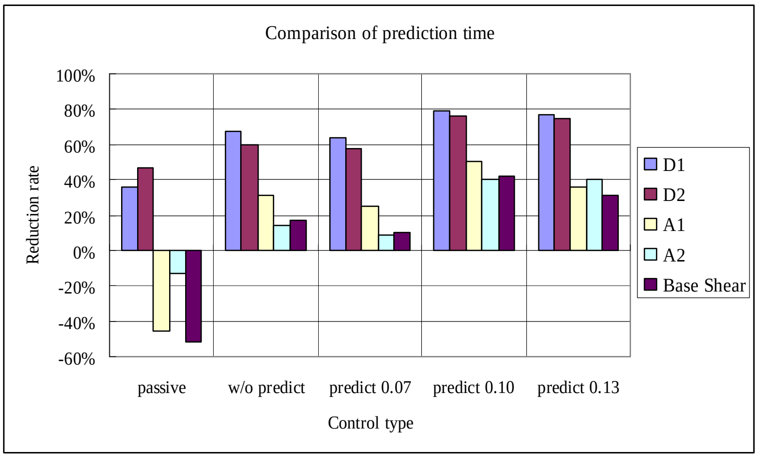

Fig. 3. The average of seismic proof percentage of this proposed method with and without predictive control combined with passive control device.

The time history of shaking table test without active interaction control device and predictive control under excitation of Elcentro 1940 earthquake record are shown in Fig. 4. The time history of shaking table test with active interaction control device and predictive control under excitation of El Centro 1940 earthquake record are shown in Fig. 5. These figures included the time history response of story drift, absolute acceleration and base shear.

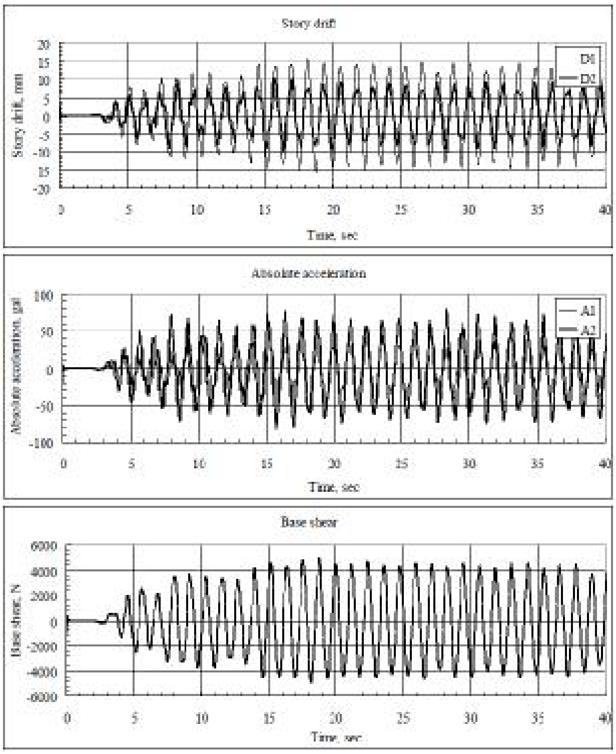

Fig. 4. The test results of shaking table without active interaction control device and predictive control under excitation of El Centro 1940 earthquake record

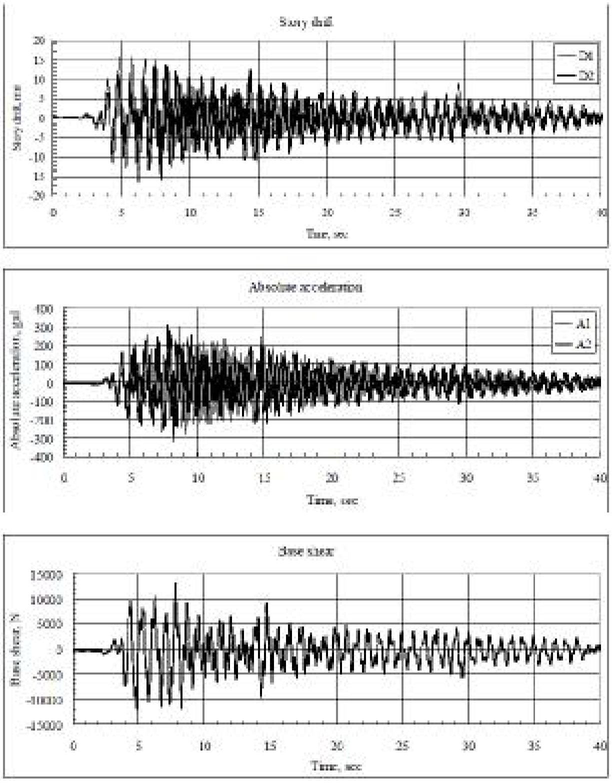

Fig. 5. The test results of shaking table with active interaction control device and predictive control under excitation of El Centro 1940 earthquake record

The comparison of these two figures show that the structural response of time history response of story drift, absolute acceleration and base shear of shaking table with AIC device and predictive control are lower than those without AIC device and predictive control.

6. CONCLUSIONS

Displacement Semi-Active Hydraulic Damper, DSHD installed with autonomous controller as active interaction control device. DSHD combined with predictive control method is investigated in this research. The characteristics of this autonomous controller provide two situations, “free shortening, can’t elongate” and “free elongating, can’t shorten”. But, it causes time delay problem, therefore, the method of time compensation is combined with this AIC device. The experimental results verify that this proposed method provide fine average of seismic proof percentage of this proposed method with predictive control. The average of seismic proof percentage of this proposed method with predictive control is better than that without installed with autonomous controller and predictive control. Otherwise, the structural response of story drift, absolute acceleration and base shear of structure added with this AIC device is lower than that structure without adding this AIC device. The seismic proof efficiency of this AIC device has been proved by this research.

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