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DEVELOPMENT OF ACCUMUMATED SEMI-ACTIVE HYDRAULIC DAMPERS

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SUMMARY

The objective of this research is to develop a new semi-active control device for displacement control of structures with long period. A new device, named as accumulated semi-active hydraulic damper (ASHD), is designed to improve the function of passive control system for seismic resistance. This device is composed of hydraulic jack, directional valve and accumulator. In order to achieve the optimal rate of energy dissipation, the acting direction of the device is regulated by controlling the flow of oil in hydraulic jack. The test results show that rate of energy dissipation of ASHD is extremely good with the minimum requirement of energy supply. In this paper, the authors will describe the construction of three different versions of dampers in detail. An analytical model describing the hysteresis behavior is proposed. Finally, results of a series of dynamic tests on shaking table will demonstrate the accuracy of the proposed analytical model for ASHD energy dissipation behavior and the vibration reduction effect of ASHD.

INTRODUCTION

In recent years, due to the advance of the engineering technology and because of the increase in population and concentration of the city, the trend of constructing high-rise building is inevitable and necessary. However, many cities are facing threats from earthquakes, such as Japan, Taiwan, Philippines and Iran in Asia, California in United States, South America and South Europe etc. and these earthquakes had all resulted in considerable losses of life and properties. Due to the comparative soft characteristic of high-rise buildings, the buildings often generate large deformation during attacked by earthquake or strong wind. Not only the safety of structure but also the comforts of building are affected by the large deformation. In regard to the design concept of the traditional structure, it is mainly applied in construction material during occurrence of subjugation or damage so as to absorb and dissipate the energy induced by earthquake or strong wind. For example, the steel structural building is based on the plastic hinge generated by beam and pillar so as to absorb the energy induced by earthquake and wind. However,

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this will lead to damage on the concrete of the structure filler of the URM (Un-Reinforced Masonry). In order to seek for the foundational solution of structural protection, the application of structural control system for enhancing the safety and reducing the dynamic reaction of the structure is effective and appropriate solution under consideration of many factors.

The structural control systems are usually applied to reduce the vibration response of the structure subjected to seismic or wind force. The control systems may be classified into three categories: active control, passive control and semi-active control. The functions of these control systems are essentially to produce viscous damping force or plastic deformation in order to dissipate energy. The system models such as Semi-Active Hydraulic Damper, SHD[1,2,3], Magnetorheological Damper, MRD[4], Electrorheologic Damper, ERD[5] and Passive Damper, Taylor Device[6] are widely discussed or used. Nevertheless, they encounter difficulties of implementing precise control, which leads to high expense and less reliability. In addition, the mechanical property of fluid medium causes unstable performance and limits the capability of energy dissipation for sufficient use. Herein, an improved model, accumulated semi-active hydraulic damper (ASHD), is developed for improvement[7,8,9]. The action of ASHD is similar to the semi-active design[1,2,3]. The deformation of stiffened member bracing to the structure is used for dissipating energy. With an ON-OFF control strategy, the action direction of stiffened brace in ASHD is changeable to effectively reduce the energy of the vibrating structure. Mechanically this device shows a well-stacked hysteresis loop.

However, the existence of time-delay could extremely affect the energy dissipation performance of ASHD systems. The experimental results indicate a serious consequence of this phenomenon. In some cases, the efforts to improve earthquake resistance are entirely eliminated. In the cause of mitigating the influence, a predictive control is developed. The basic idea is to predict the response of the structure, and produce a control signal prior to the physical moment. A third ordered polynomial regression function is used to reconstruct the velocity signal, which is needed by the control law, and to eliminate the noise of the measured signals. Based on the shaking table test result, it shows that 1.) The computational requirement of the predictive control is so small that it can be simply implemented for on-line processor; 2.) The time delay can be successfully compensated and results a distinct improvement of performance of energy dissipation. These merits are demonstrated in this paper.

PRINCIPLE AND ORGANIZATION OF ASHD

Function of ASHD components

Herein, the ASHD system is composed of a hydraulic jack, directional valve, accumulator, check valves, relief valves, and appropriate circuits as shown in figure 1 and photo 1. Functions of the components above are demonstrated below:

A. Hydraulic jack translates the control force between conjunction points of the structure to be controlled. Under the assumption of incompressibility of oil, the deformation of the jack is strictly restrained, if the entire opening of the jack is close. In case that an appropriate flowing circuit is possible, the elongation or shortening is possible without resistant.

B. Directional valve is a solenoid valve, which controls the flow direction of oil. In comparison to proportion valves and servo valves, the directional valve regulates the flow direction in switching type, in general three states. As a result of requirements on precise controller, the directional valve is more economical and feasible than the others.

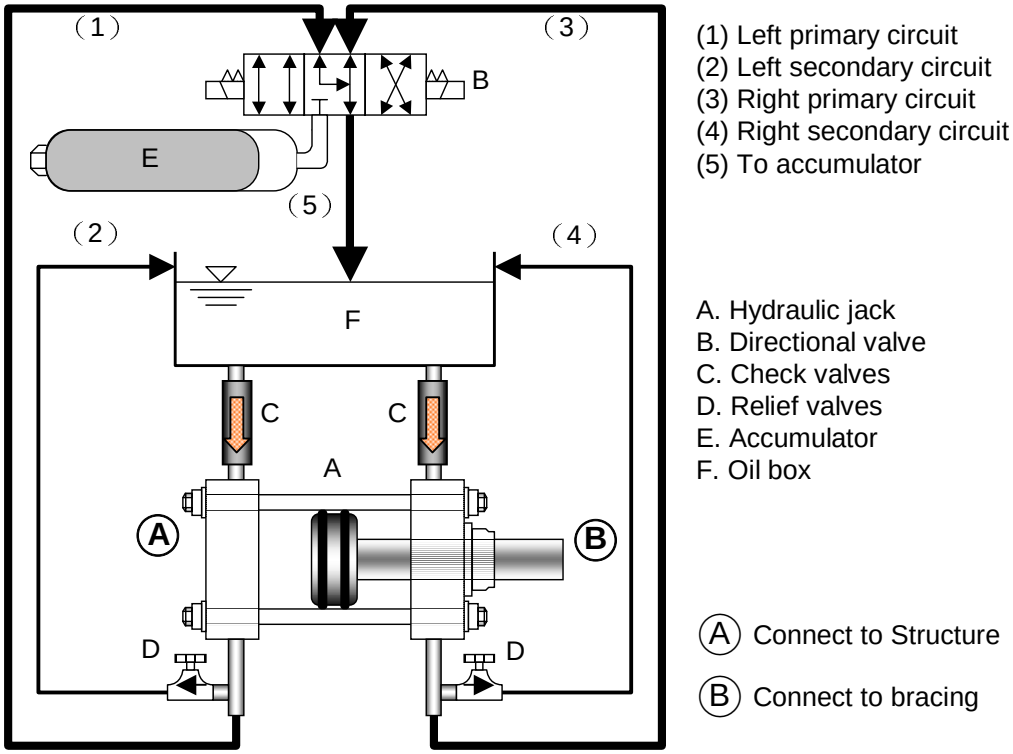

Fig. 1 Construction of an ASHD

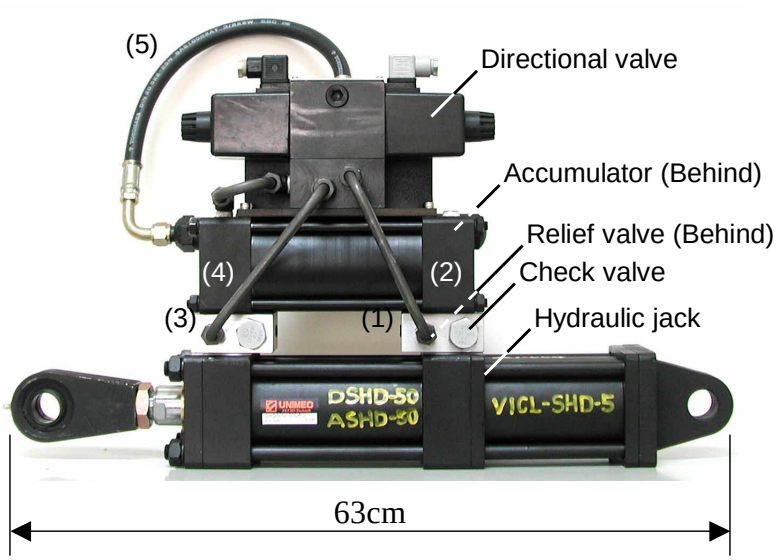

Photo 1 The prototype of ASHD with 50KN capacity

C. Check valves are generally used to restrain the flow direction of oil pipes. Refer to the function of check valves, the ASHD can release the deformation of jack in one specific direction.

D. Relief valve can also restrain the flow direction. Additionally, the relief valve limits the maximal pressure of the oil in connected pipe. By exceeding the preset maximal pressure, the flow through the valve is permissible.

E. Accumulator is generally used to minimize the fluctuation of oil pressure. The ASHD utilizes the accumulator to temporarily store the energy transferred from the mechanical energy of the structure. Additionally, the accumulator provides a high initial pressure by changing the state of directional valve.

F. Oil box contains the oil for balancing the volume loss induced by compressive deformation.

Mechanical behavior of ASHD

For convenience of describing the mechanical behavior of ASHD, the figure 1 will be used. The orientation in the explanation refers to the figure. Suppose that Point Ⓐ is fixed to structure and Point Ⓑ is connected to bracing element. The following variables should be defined:

P_B	Basic backpressure of the oil box.
P_R	Pressure limit (differential) defined by relief valve.
P_A	Pressure of the accumulator, $P_A \leq P_R$.
P_r	Pressure in the right oil chamber.
P_l	Pressure in the left oil chamber.
A_P	Effective area of piston.

The resistance force of ASHD has characteristics below:

1. Force at point Ⓑ acting toward right:
   - 2-1. Directional valve located at right position: The right oil chamber of jack is connected via circuit (3) to accumulator. The pressure in the left chamber P_l is equal to the basic pressure P_B of the oil box.
     - $P_r < P_A$: The oil in accumulator flows backs into the right chamber and increases the pressure P_r therein. This action helps the ASHD to produce a larger initial resistance force against deformation. This condition is only happen in the moment of switching the directional valve to right position. Short after that moment, the two pressures become balanced. The length of the jack decreases or holds in this process.
     - $P_r \geq P_A$: The oil flows into the accumulator, the pressure P_A increases. The length of the jack increases.
     - $P_r \geq P_R$: The oil begins flowing backs into the oil box via circuit (4). Pressure P_r decreases until it equals the relief pressure P_R. In this process, the length of jack continuously increases without raising the resistance force.
   - 2-2. Directional valve located at neutral or left position: Pressures in right and left chamber, P_r and P_l, are equal to basic pressure of oil box, P_B. The resulting resistance force is zero. The jack can be elongated and shortened without any resistance.
2. Force at point Ⓑ acting toward left:

2-1. Directional valve located at right or neutral position: Pressures in right and left chamber, P_r and P_l, are equal to basic pressure of oil box, P_B. The resulting resistance force is zero. The jack can be elongated and shortened without any resistance.

2-2. Directional valve located at left position: The left oil chamber of jack is connected via circuit (1) to accumulator. The pressure in the right chamber P_r is equal to the basic pressure P_B of the oil box.

- $P_l < P_A$: The oil in accumulator flows backs into the left chamber and increases the pressure P_l therein. This action helps the ASHD to produce a larger initial resistance force against deformation. This condition is only happen in the moment of switching the directional valve to left position. Short after that moment, the two pressures become balanced. The length of the jack increases or holds in this process.
- $P_l \geq P_A$: The oil flows into the accumulator, the pressure P_A increases. The length of the jack decreases.
- $P_l \geq P_R$: The oil begins flowing backs into the oil box via circuit (2). Pressure P_l decreases until it equals the relief pressure P_R. In this process, the length of jack continuously decreases without raising the resistance force.

Mathematical model of ASHD

The action of the device in time history is always designed to resist the structural vibration. The bounceback of the device deformation will not exert force on the structure. Therefore, the work function by the device ensures the fulfillment of energy dissipation on the structure. The organization of ASHD is shown in figure 1. The mathematical model of the ASHD is described in figure 2. Assuming the bracing spring is perfect elastic, it satisfies the following expression

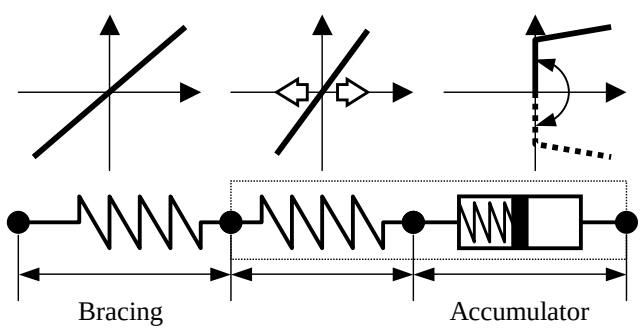

Fig. 2 The mechanics behavior of serial connection of accumulator and elastic brace[7]

$$f_b = k_b x_b \tag{1}$$

Where f_b, k_b and x_b are defined as bracing force, stiffness and deformation respectively. Additionally, inconsideration of the compressive deformation of oil, the oil pressure in cylinder acts like an elastic spring. Thus, the equation can be shown as follows:

$$f_c = k_c \varepsilon_c \tag{2}$$

Where f_c is spring force of fluid pressure, k_c is the elastic effect of stiffness caused by compression of fluid pressure and the deformation of hydraulic accessories, ε_c is the elastic shortenage of cylinder.

Accumulator simulates as a nonlinear elastic spring and allows slip at initial. When force exerted on the accumulator excesses the allowed initial slip force, the accumulator deforms to store fluid. The internal force then rises. The deformation of accumulator x_{aku} is defined as the ratio of the stored fluid to the piston area. Based on Boyle law, the multiplication of the gas pressure and the gas volume is constant. The gas volume is varied with fluid quantity in accumulator. Therefore, the relationship for the pressure and deformation of accumulator can be shown as follows:

$$p = \frac{V_0 p_0}{V} = \frac{V_0 p_0}{V_0 - x_{aku} A_c} \tag{3}$$

Where, V_0 is the initial volume of fluid. V is the volume and is not greater then V_0. p_0, p is initial pressure and pressure. A_c is area of piston.
The pressure of accumulator multiplied by the piston area of fluid pressure in cylinder is the supply force f_{aku} by accumulator.

$$f_{aku} = \pm \frac{A_c V_0 p_0}{V_0 - x_{aku} A_c} \tag{4}$$

The plus/minus sign of Equation (4) implies that accumulator action can function at two opposite directions. Reactions defined by equations (1), (2) and (4) must be equal, that satisfy the following equation:

$$f_b = f_c = f_{aku} \tag{5}$$

The ASHD deformation x_a is defined as the summation of elongation of hydraulic damper x_c and the deformation of stiffened brace x_b. The elongation of damper is composed of three parts: elastic deformation of cylinder ε_c, deformation of accumulator x_{aku} and neutral equilibrium position of piston x_s. The x_s at normal situation is constant. For bracing force to be zero, the piston must slide a length at the switch of directional valve. x_s will be changed in the twinkling of an eye. Thus, the equation matching the principle of deformation can be expressed as follows:

$$x_a = x_b + \varepsilon_c + x_{aku} + x_s \tag{6}$$

CONTROL LAW

The ASHD system aims to dissipate the mechanical energy of the structures. The control law will be designed to provide maximal energy dissipation effect. Because of the nonlinearity of the device the control law should derive from minimizing the work done by ASHD at every time instant.

Direct output feedback control

The direct output feedback control guarantees the unreserved stability of the control system. Additionally, the direct output feedback results in robust and reliable control to build up direct output feedback control, the sensor and ASHD will be located at the same position and be in the same orientation. Figure 3 shows the schematic setup of the ASHD system.

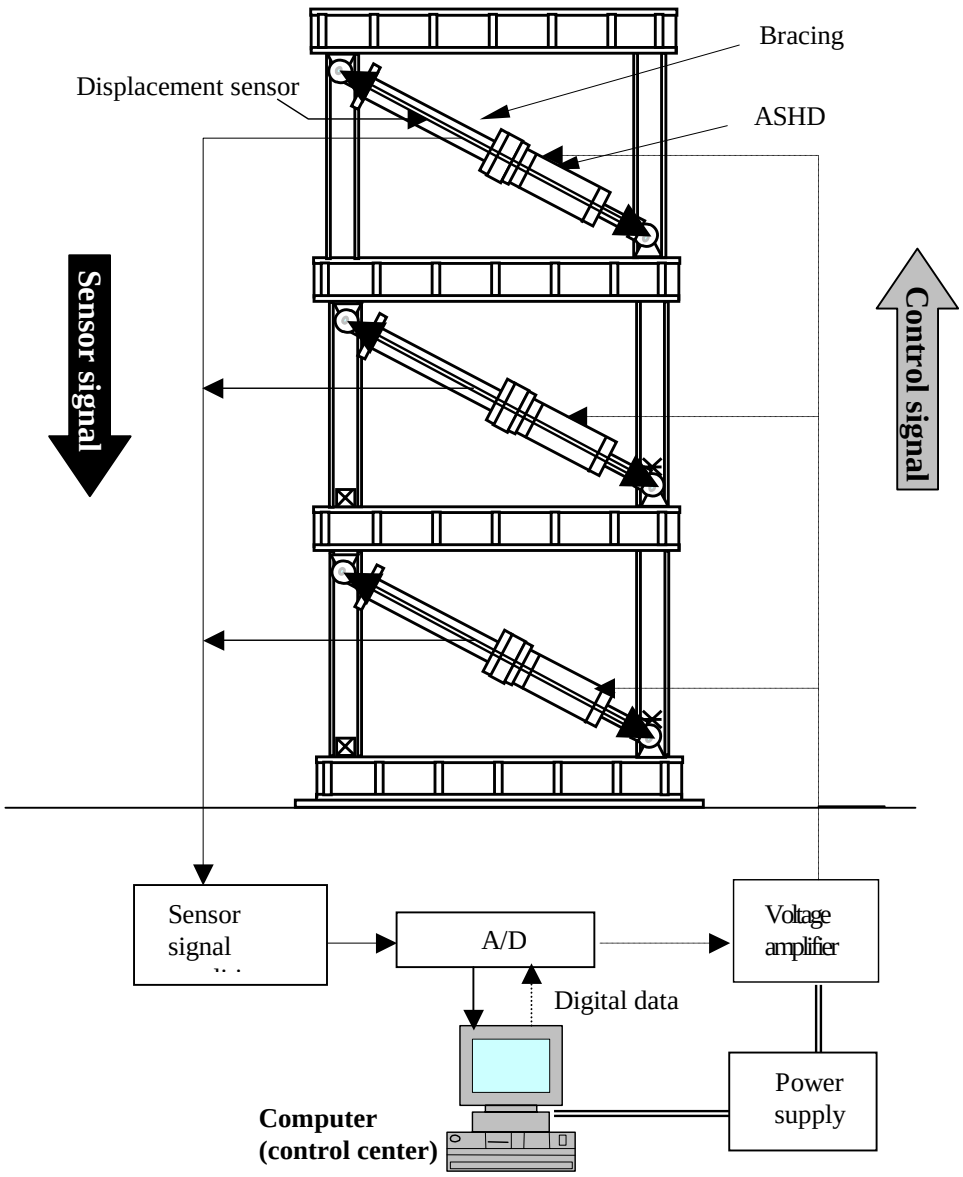

Fig. 3 Setup of an ASHD system

Instantaneous optimal control law

The work done by an ASHD can be expressed as below:

$$W_i(t) = \int_{t_0}^{t} f_b(\tau)\dot{x}(\tau)d\tau \tag{7}$$

In which t_0 denotes the start of the considering interval; f_b is the element force of bracing; $\dot{x}$ is the relative velocity of the structure at the location of ASHD and conjunction bracing. By differentiating the work function with respect to time, *t*, we obtain the power of ASHD at instant *t*.

$$\dot{W}(t) = f_b(t)\dot{x}(t) \tag{8}$$

In equation (8), the value of the power of ASHD depends only on the element force and relative velocity at time t. Recall that the structural response couldn't be altered immediately. We can alter the value and sign of the element force, f_b, by means of switching the directional valve of ASHD. Consequently, the control law can be denoted as follow:

$$\text{Valve position} = \begin{cases} left & if\ \ \dot{x}(t) < 0(shortening) \\ right & if\ \ \dot{x}(t) > 0(extending) \end{cases} \tag{9}$$

Hysteretic behavior of ASHD system

The ASHD can change the acting direction of resistance force of the bracing effectively, making the structural control force always against the direction of motion of structure, and performs forever the negative work. So, this damper has the most stacked hysteretic loop. Figure 4 illustrates the theoretical hysteretic loop of an ASHD in conjunction with a bracing element. Figure 5 shows an experimental result of ASHD element test. In both cases, the stiffness of the bracing is equal to 1.9KN/mm. Figure 5 shows also the hysteretic behavior of a semi-active hydraulic damper, say displacement dependent semi-active hydraulic damper[8], DSHD. There is mirror difference between the organization of DSHD and ASHD. Figure 6 shows the organization of a DSHD.

In fact the ASHD is a suction energy machine, absorbing the mechanical energy of the structure, and convert into the power that holdout structure's motion. As a result the ASHD has the best energy dissipation capability.

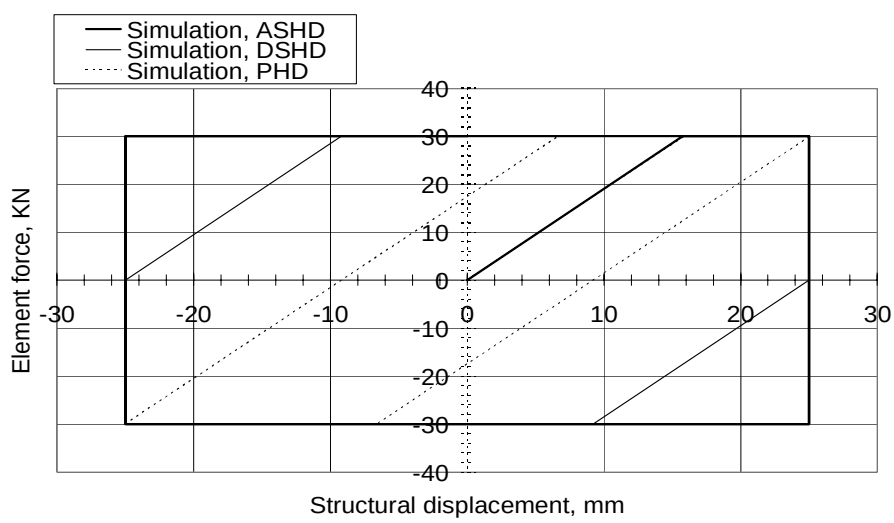

Fig. 4 Theoretical hysteretic behavior of ASHD, DSHD and passive damper

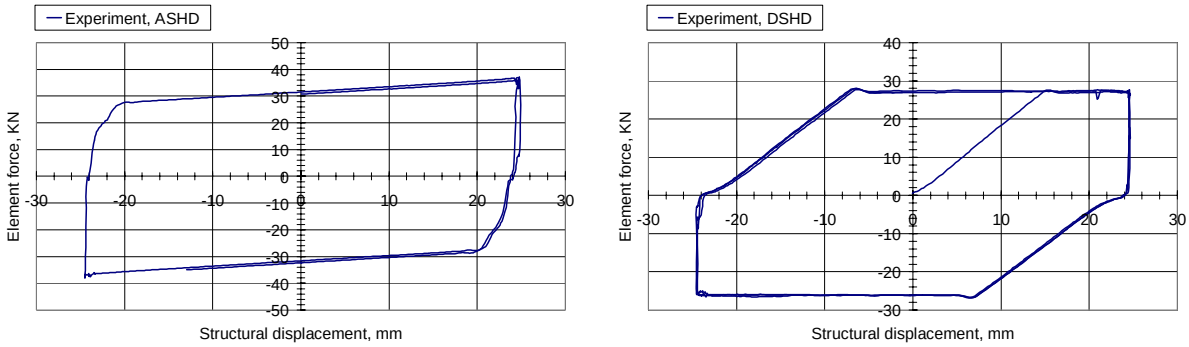

Fig. 5 Experimental hysteretic behavior of ASHD and DSHD

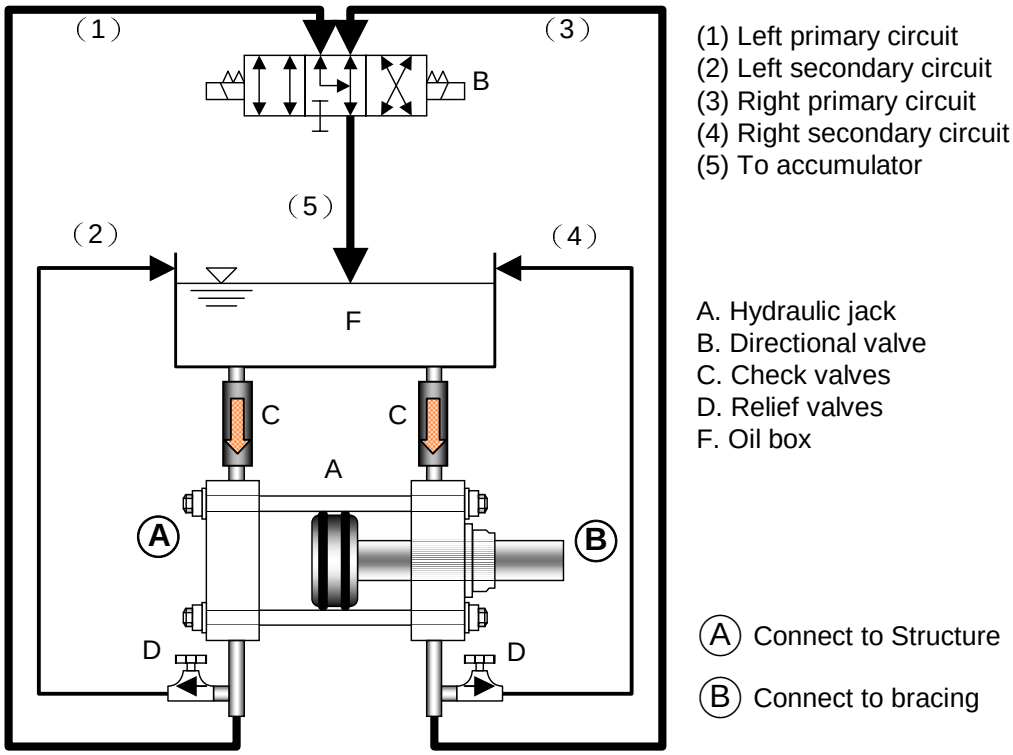

Fig. 6 Construction of a DSHD

PREDICTIVE CONTROL

Time delay

The switch-type control is simple and economical. But it has a major disadvantage, time delay. Time delay, is defined as the difference between the optimal switching time and the end of the real switching process, including the computational time, time for switching action of

directional valve and time for reflecting the deformation of bracing element. This phenomenon and its influence are illustrated in figure 7.

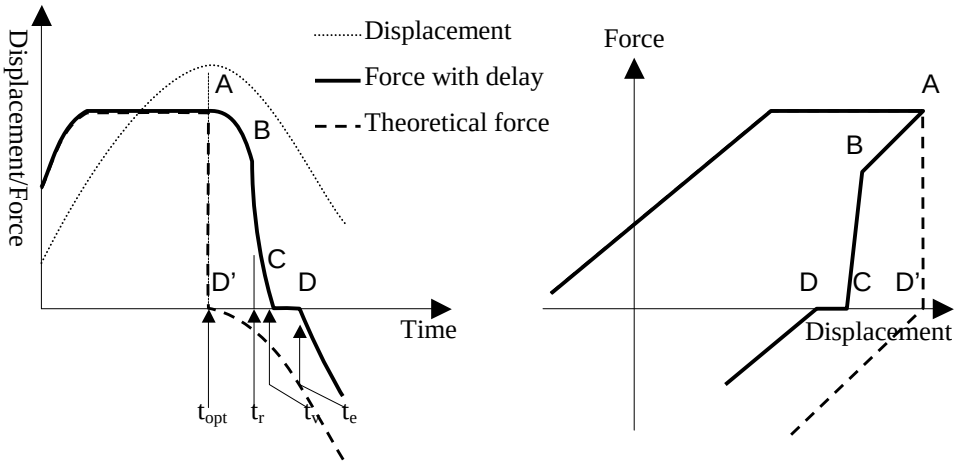

Fig. 7 Definition of time delay and its influence on the force-displacement relation

By component test of an ASHD, we observe the problem describe above. The figure 8 shows the time history of displacement and force. A harmonic waveform with amplitude of 25mm and frequency of 0.4Hz is produced in the test. We can observe a obvious difference between the theoretical optimal switching time, t_{opt}, and the end of the real switching process, t_e. The time delay is about 0.13 seconds.

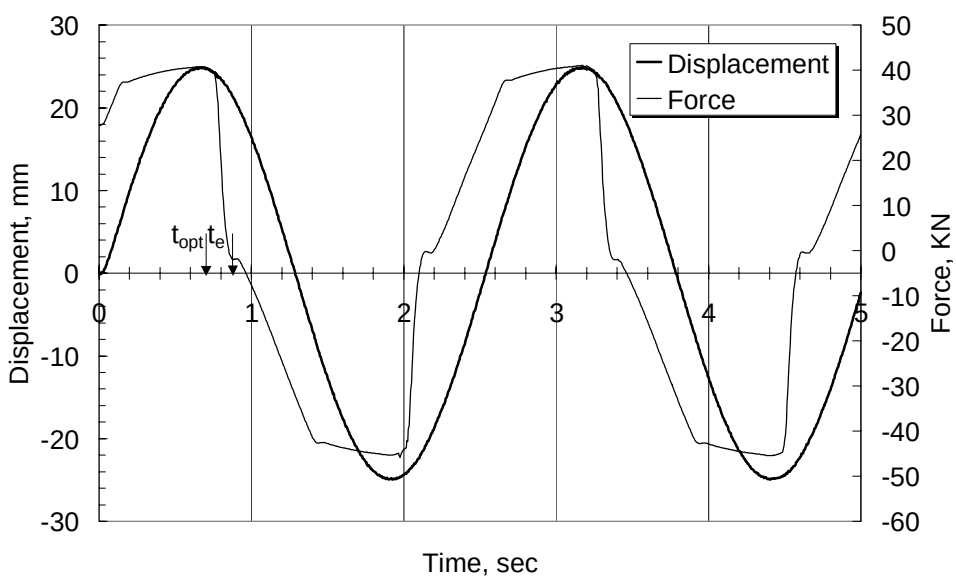

Fig. 8 Time history of the element force and displacement of ASHD element test

Consequently, the energy dissipation effect is seriously affected by the time delay, as shown in figure 9.

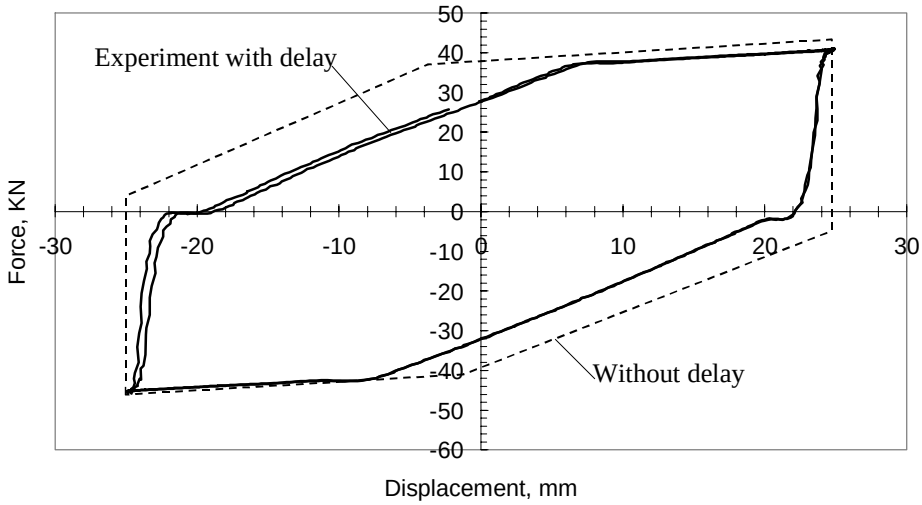

Fig. 9 Hysteretic behavior of ASHD with influence of time delay

Compensating the time delay

To overcome the influence of time delay, this paper proposes a predictive control strategy, which includes the following processes:

1. Filtering of the noise signal

   As shown in figure 3, the control system utilizes the relative displacement signal of the structure to calculate the velocity response. The noise signal of the displacement will be many times magnified, when the backward difference method is used. The noise level of the calculated velocity is so serious that often leads to wrong control signal.

   The least square regression method is used to filter the noise signal out. A third order polynomial displacement function is supposed to be a good regression function, because it can good reflect the change of sign of velocity response.

2. Prediction of the velocity response

   Once the noise signal is filtered out and the optimal 3rd polynomial displacement function is found, $\hat{x}(t)$, the velocity function can be found by differentiating the displacement function with respect to time. Then substitute an appropriate value, equal to time delay quantity, into the velocity function, and the velocity can be found in prior.

   Table 1 shows the optimal predict vectors of velocity, which uses the newest 20 displacement signals to predict the velocity in 7, 10 and 13 steps respectively.

   Providing a vector including 20 displacement signals such as below:

$$\bar{x} = \begin{bmatrix} x_0 & x_{-1} & x_{-2} & \cdots & x_{-19} \end{bmatrix}^T \tag{10}$$

Where, x_{-i} denote the recorded displacement signal at $i\Delta t$ ago; Δt is the acquisition period. Then the velocity can be predicted by performing the inner product of $\bar{x}$ and predict vector.

Table 1 The optimal predict vectors of velocity

Data item	7 steps	10 steps	13 steps
0	-40.59	-59.98	-82.94
-1	-12.32	-18.85	-26.69
-2	7.57	10.23	13.20
-3	20.12	28.73	38.73
-4	26.35	38.12	51.87
-5	27.30	39.87	54.62
-6	23.99	35.45	48.95
-7	17.45	26.33	36.85
-8	8.72	13.98	20.30
-9	-1.18	-0.13	1.29
-10	-11.22	-14.53	-18.20
-11	-20.37	-27.75	-36.19
-12	-27.60	-38.33	-50.69
-13	-31.88	-44.78	-59.71
-14	-32.19	-45.65	-61.28
-15	-27.48	-39.45	-53.41
-16	-16.74	-24.73	-34.11
-17	1.08	-0.01	-1.41
-18	26.98	36.18	46.69
-19	62.02	85.31	112.16

RESULTS OF SHAKING TABLE TESTS

Experiment setup

A series of shaking table tests on a single degree of freedom model were performed for verifying the energy dissipation effect of the ASHD system. Photo 2 shows the model and shaking table. Important structural parameters of the test model are outlined in Table 2.

Table 2 Properties of the test model and ASHD dampers

Properties of structure		Properties of ASHD	
Mass	51.4 KN/G	Time delay	0.13 sec.
Stiffness (structure)	327.7 KN/m	Preset pressure of	0.20KN/cm^2
Stiffness (bracing)	691.9 KN/m	Accumulator	0.35KN/cm^2
Natural Frequency (original)	1.26 Hz	Preset capacity	7.5KN
Natural Frequency (braced)	2.25 Hz		13.2KN
Damping ratio	0.004		

Energy Dissipation Performance of ASHD system

The model with various capacities of ASHD was excited by simulated ground motion of El Centro Earthquake at 1940 in USA. The peak ground accelerations (PGA) were attenuated to 0.1G, 0.2G, 0.3G and 0.4G.

The reduction ratios of maximal displacement and acceleration are shown in figure 10 and 11 respectively. The entire reduction ratio is compared with respect to the response of elastic structure without any stiffening. For comparison reason, the reduction ratios of passive control are shown in these figures. The passive control is conducted by removing the directional valve and accumulator of the ASHD. The hysteretic behavior is illustrated in figure 4, which is denoted as PHD.

For convenient of explanation, the symbols in figure 10 and 11 have the meanings shown in table 3.

Table 3 Definition of the symbols in figure 10 and 11

Symbol	**Damper type**	**Predicted time length sec**	**Preset pressure KN/cm^2**	**Preset capacity KN**
Passive	DHD	-	0.35	13.2
ASHD-10-35	ASHD	0.10	0.35	13.2
ASHD-13-35	ASHD	0.13	0.35	13.2
ASHD-10-20	ASHD	0.10	0.20	7.5

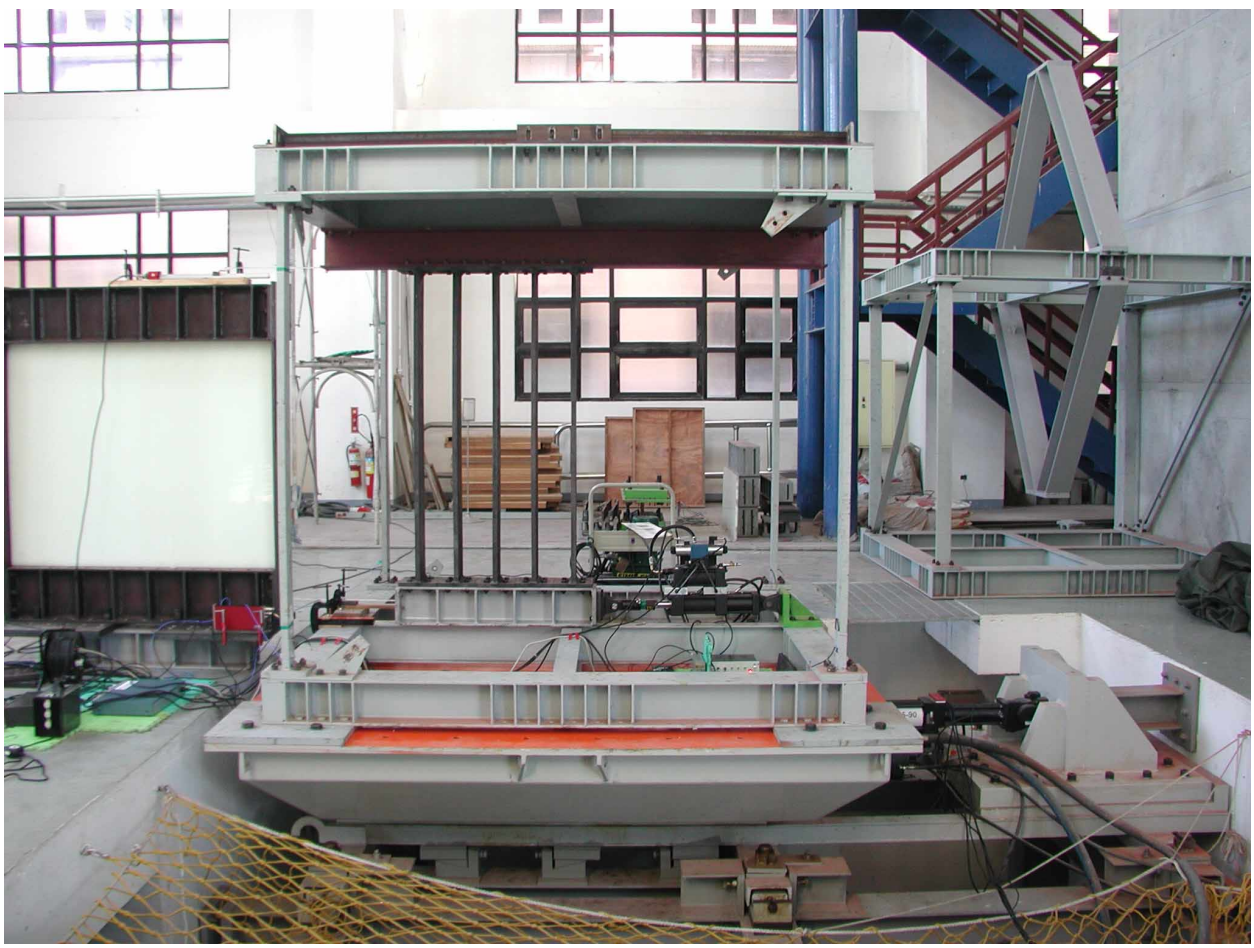

Photo 2 Setup of shaking table tests

Reduction of displacement response

In figure 11, we notice that approximately 85% of the maximal displacement eliminated by the ASHD. Additionally, the reduction ratio is nearly constant for entire range of peak ground acceleration. In comparison with that of passive control, the proposed idea is an important improvement for semi-active control device. Because the ASHD system can effectively reduce the displacement response already by very slight excitation.

The reduction ratio of displacement is not strong affected by the preset capacity of the damper. In the experiment, two different preset capacities are used, 13.2 KN and 7.5 KN respectively. The capacity to structural weight ratio is equal to 0.257 and 0.146. As shown in figure 10, the reduction ratios of all semi-active systems approximate 85%. However, it is expected, that the reduction ratio of damper with lower capacity decrease by larger ground excitation.

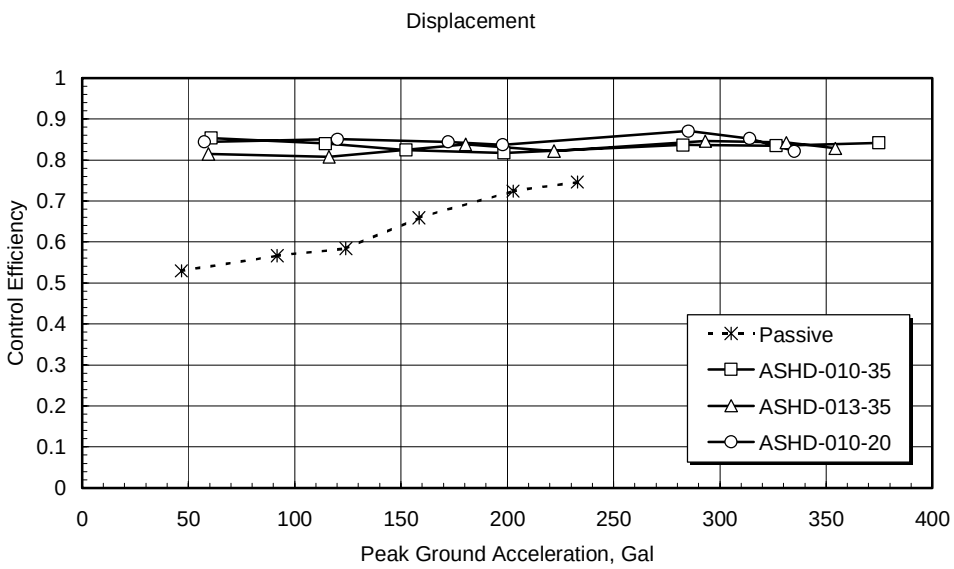

Fig. 10 Comparison of maximal displacement response

Reduction of acceleration response

Beside the benefit of reducing displacement response, the acceleration response is also reduced by the ASHD system. The reduction ratio of maximal acceleration response is approximately 45%, and is nearly constant too.

The passive control is able to reduce the maximal acceleration response by strong excitation. It is expected, that the passive systems and semi-active systems with the same capacity yield the same reduction ratio by very strong excitation.

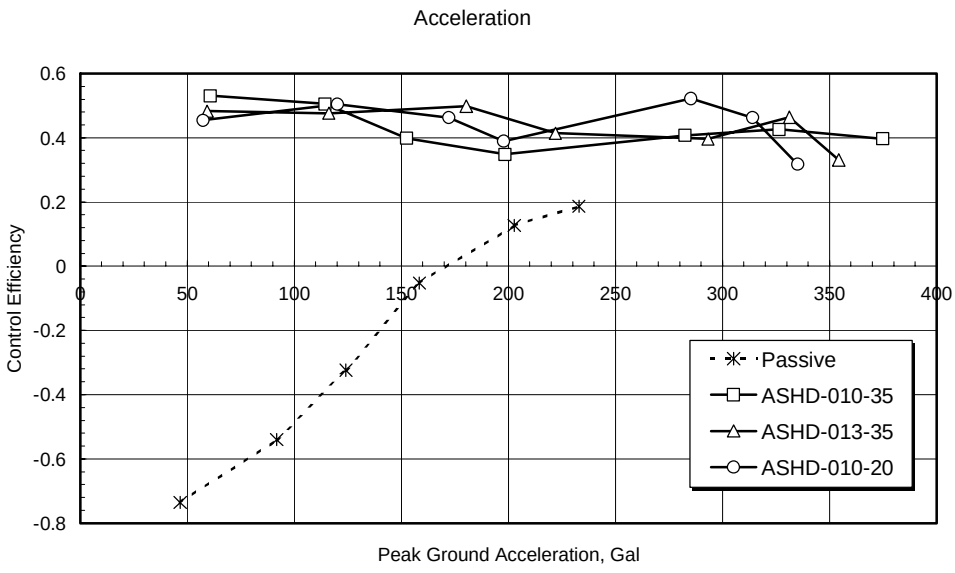

Fig. 11 Comparison of maximal acceleration response

CONCLUSIONS

A semi-active hydraulic damper and an optimal control law based on instantaneous optimal are proposed in this paper. The organization and principle of this damper are described in detail on above sections. Because of the simplicity of the control law, the direct output feedback control can be independently implemented in all ASHD dampers. On the other hand, the time delay problem of the ON-OFF type control can be overcome by means of combining the control law with a predicting process and numerical filtering, proposed in this paper.

From experimental results of shaking table tests, the following conclusions can be summarized:

1. Using a very soft stiffening bracing can reduce 80% of the maximal displacement response.
2. The ASHD system can reduce about 45% of the maximal acceleration response.
3. The reduction ratio of the maximal displacement and acceleration response is independent of the magnitude of ground acceleration.

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