HYBRID STRUCTURAL CONTROL COMBINING ACTIVE MASS DRIVER AND HYSTERETIC DAMPER SYSTEMS

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SUMMARY

Active structural control is a recently developed technology for earthquake resistance strategy of buildings. In the current stage, however, active control has not reached the level of providing safety to structures against severe earthquake. AMD systems are installed mostly for the response reduction to small earthquake or strong wind excitations and hence they are mostly designed to stop their operations during severe earthquake. To keep AMD operations even in strong earthquake, variable feedback gain control can be applied to an AMD system accounting for its performance limits. However, variable feedback gain control may not necessarily lead to an effective control performance. For the purpose of providing effective control during strong earthquake, this paper discusses a hybrid control system combining variable gain-based AMD with hysteretic damper system. To demonstrate the validity of such a hybrid system, computer simulations and experiments for multi-story buildings are conducted. The simulated and experimental results show that the hybrid control system provides an effective control regardless of an earthquake intensity.

INTRODUCTION

Active control is a new scheme for earthquake resistant strategy for civil structures. Since the world's first active-controlled building was born in Tokyo in 1989 [Kobori et al., 1991a and 1991b], a number of high-rise buildings in Japan have employed active control systems for reducing their responses [Housner et al., 1997; Nishitani, 1998]. In many of these buildings, active mass damper or driver (AMD) systems are installed near their top floors. However, active structural-control has not reached the point of providing safety to structures in case of severe earthquake. Most of AMD systems are designed to stop working during large earthquake. This is mainly because of the limitations with respect to AMD systems. For the purpose of keeping AMD control even during severe earthquake, several kinds of variable feedback gains have been proposed [Fujita et al., 1994; Iemura et al., 1996; Nagashima and Shinozaki 1997; Nishitani et al., 1996; Nishitani and Nitta 1998; Nitta and Nishitani 1998]. With variable feedback gains AMD could keep working during severe earthquake, but would not necessarily lead to an effective control performance, because some of the gains are aimed at reducing AMD stroke and control input force instead of reducing the response of a building.

In order to provide effective control during severe earthquake, this paper discusses a hybrid control strategy combining AMD and passive type of hysteretic dampers. In this system, AMD is for small and moderate earthquakes, while the hysteretic dampers are mainly for severe earthquake. In designing the control system, structural system is divided into two parts: the lower part having hysteresis dampers and the upper part having no hysteresis dampers. For the purpose of having AMD control stable, the responses of the upper part relative to the lower part is fed back to the AMD controller to diminish the nonlinear effect resulting from the hysteresis damper. The AMD controller employs variable feedback gains to account for the AMD stroke limit, and takes saturation control to account for the limitation of control input force. The yielding level of the hysteretic damper is determined so as to make up the decline of control performance of AMD. The effectiveness and validity of the proposed control system is demonstrated both theoretically and experimentally.

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DESIGN OF HYBRID STRUCTURAL CONTROL SYSTEM

A structural model shown in Figure 1 is an *N*-story building with AMD on the top floor and hysteretic dampers installed in the lowest *n* stories. In this hybrid control system, the following two are key items: how to determine the feedback gain of AMD and how to design the yielding level of passive hysteretic dampers.

The discrete-time state vector, $X(k)$, including the state of the AMD, can be written as:

$$X(k) = [\ \dot{x}_1(k),\ \ \cdots,\ \dot{x}_N(k),\ \ \dot{x}_a(k),\ \ x_1(k),\ \ \cdots,\ \ x_N(k),\ \ x_a(k)\ ]^{\mathrm{T}} \tag{1}$$

where *k* denotes discrete time, $k\Delta t$ with Δt the sampling time interval and the superscript T represents a matrix or vector transpose.

In designing the control algorithm of AMD, the following three aspects are taken into account: (1) Even the equilibrium positions of the upper (*N-n*) stories may fluctuate due to the nonlinear behavior of hysteretic dampers in the lower part; (2) Measuring all the states of a building is not feasible for actual building control; (3) AMD stroke limit and control input force limit may be exceeded.

As far as the aspect (1) is concerned, the nonlinear effect of the hysteresis dampers' behavior involved in $X(k)$ may produce unstable control, if all the state $X(k)$ is fed back to the AMD controller. In this respect, the structure is divided into two parts: the lower part having the hysteresis dampers and the other upper part. The state of the upper part relative to the lower part is represented by $Y(k)$. More specifically, $Y(k)$ is

$$Y(k) = [\ \dot{y}_1(k),\ \ \cdots,\ \ \dot{y}_{N-n}(k),\ \ \dot{x}_a(k),\ \ y_1(k),\ \ \cdots,\ \ y_{N-n}(k),\ \ x_a(k)\ ]^{\mathrm{T}} \tag{2}$$

where $y_i(k)$ is the displacement of the (*n*+*i*) th story relative to the *n*th story, i.e.,

$$y_i(k) = x_{n+i}(k) - x_n(k), \quad i = 1, 2, \cdots, N-n$$

With this notation, the discrete-time state equation for the upper-part is provided by

$$Y(k+1) = A_s\, Y(k) + B_s\, u(k) + E_s\ (\ \ddot{x}_g(k) + \ddot{x}_n(k)\ ) \tag{3}$$

where $u(k)$: control input force; $\ddot{x}_g(k)$: earthquake ground acceleration; $\ddot{x}_n(k)$: *n*th story acceleration relative to the ground; A_s : a $2(N+1-n)\times 2(N+1-n)$ system matrix representing the upper part including AMD ; B_s : a $2(N+1-n)$ vector representing the applied point of a control input force; E_s : a $2(N+1-n)$ vector representing the applied point of external excitations. For the subsystem representing the upper part, the *n*th story movement can be regarded as the ground motion. The employment of the state vector, $Y(k)$, expectedly leads to stable AMD control, because the state, $Y(k)$, is expected to have linear behavior, even if the lower stories are in the range of nonlinearity.

Considering the aspect (2), a reduced-order model is utilized as the plant for AMD control design. The reduced-order model is produced by utilizing the modal characteristics, such as natural frequency and effective modal mass, and modal participation vectors [Nishitani et al 1996 and 1998].

Taking account for the aspect (3), variable feedback gain algorithm is connected with the saturation control. The variable feedback gain control utilizes several kinds of feedback gains. Each feedback gain, G_m, is determined on the basis of the LQ control theory incorporating with the following performance index :

$$J = \sum_{k=0}^{\infty} [\ Y(k)^T Q_m Y(k) + r_m\, u(k)^2\ ] \tag{4}$$

The weighting matrix, Q_m, corresponding to the gain, G_m, is taken to be the following diagonal matrix:

$$Q_m = \mathrm{diag}[\, q'_1,\ \cdots,\ q'_{(N-n)},\ q'_a,\ q_1,\ \cdots,\ q_{(N-n)},\ q_a \,] \tag{5}$$

where q'_a and q_a : coefficients for AMD velocity and stroke; q'_i and q_i : coefficients for the (n+i) th story velocity and displacement relative to nth story and diag [ ] represents a diagonal matrix whose diagonal elements are given in [ ].
Different kinds of feedback gains are determined by taking different values of q_a and r_m with all other components in constant.

The hysteretic damper is to make up the decline of AMD control effect. The ductility factor of the hysteretic dampers is chosen such that it should become two when AMD control effect gets to decrease. This is because the perfect elasto-plastic hysteresis would have the most efficient energy dissipation with ductility factor of two when subjected to a steady-state sinusoidal excitation [Tajimi, 1965].

NUMERICAL EXAMPLE

To demonstrate the effectiveness of the methodology, numerical simulation is conducted for a 10-story building model with AMD on the top floor and three hysteretic dampers in the lowest three stories. The parameters with respect to the controlled building are shown in Table 1. The limitation of AMD stroke is assumed to be 0.25 m, and the limitation of control force is 1000 kN(1.0 % of the total weight). The hysteretic damper is assumed to have a perfect elasto-plastic hysteresis with the initial stiffness 400,000 kN/m.

Table 1: Parameters of 10-story building model

story	mass [t]	stiffness [$\times 10^4$ kN/m]	dmaping [kN$\cdot$s/m]
1	1000	160	3060
2	1000	151	2900
3	1000	142	2710
4	1000	130	2500
5	1000	118	2260
6	1000	104	2000
7	1000	89	1710
8	1000	72	1380
9	1000	54	1030
10	1000	32	620
AMD	100	0	0

In designing three different feedback gains for the AMD controller, a reduced-order model representing the behaviors of the 10th, 8th and 6th stories and AMD is employed. The weighting matrices and coefficients are:

$$Q_1 = \mathrm{diag}\,[\,12.1,\ 2.0,\ 1.0,\ 0.001,\ 597.7,\ 85.7,\ 44.1,\ 1000\,],\quad r_1 = 50$$
$$Q_2 = \mathrm{diag}\,[\,12.1,\ 2.0,\ 1.0,\ 0.001,\ 597.7,\ 85.7,\ 44.1,\ 25\,],\quad r_2 = 3.3$$
$$Q_3 = \mathrm{diag}\,[\,12.1,\ 2.0,\ 1.0,\ 0.001,\ 597.7,\ 85.7,\ 44.1,\ 0.1\,],\quad r_3 = 1.7$$

Corresponding to these three kinds of weights, the feedback gains G_1, G_2 and G_3 are obtained by solving the corresponding Riccati equations. Then,

$$G_1 = [\ 0.0650 \quad 0.284 \quad -0.671 \quad -0.922 \quad 0.442 \quad 1.49 \quad -3.32 \quad -4.37]$$
$$G_2 = [\ -0.137 \quad 0.0707 \quad -0.182 \quad -0.747 \quad -0.0545 \quad 1.71 \quad 2.42 \quad -2.68\ ]$$
$$G_3 = [\ -0.0823 \quad 0.445 \quad 1.02 \quad -0.237 \quad 0.837 \quad 0.298 \quad 2.88 \quad -0.243\ ]$$

For the purpose of determining the yield level of the hysteretic damper, the maximum displacement responses of the top story to sinusoidal excitations of 0.83 Hz with different PGA values under AMD control only are calculated. The results are shown in Figure 2. It is found that the control effect begins to decrease at PGA of around 12 cm/s^2. In response to this result, the yield level of the hysteretic damper of passive type is taken 280 kN in such a way that the ductility factor of the damper should become two in the case of PGA = 12 cm/s^2.

Having the EW component of the 1968 Hachinohe earthquake with several PGA values as seismic excitations, simulations are conducted. Four different kinds of responses are compared: (1) uncontrolled responses; (2) controlled responses with AMD employing the variable feedback gains; (3) controlled responses with hysteretic dampers; (4) controlled reponses with hybrid system combining AMD and hysteretic dampers. Figures 3-6 show the maximum and RMS values of the top story velocities and displacements. For the purpose of confirming the stability of the hysteretic dampers, Figures 7-8 show the maximum and RMS values of the inter-story displacements of the first story. These simulated results indicate: i) The controlled responses considerably decreases in comparison with uncontrolled responses; ii) AMD can be utilized from small to large earthquakes in the hybrid system; iii) The responses of the hysteretic damper for the hybrid control decreases in comparison with the control employing only the hysteretic dampers; iv) The hybrid control systems provides an effective control regardless of the intensity of seismic excitation.

EXPERIMENTAL VERIFICATION

Following the numerical simulations, experimental verification is conducted for a 7-story building model with AMD on the top floor and hysteretic damper in the first story. The mass of each story is : m_7 =3.8 kg ; m_6 = 2.0 kg ; m_5 = 2.0 kg ; m_4 = 2.0 kg ; m_3 = 2.0 kg ; m_2 = 2.0 kg ; m_1 = 2.3 kg. The mass of AMD is 0.77 kg, which is equal to 4.8 % of the total mass. The maximum stroke of AMD is 1.5 cm, and the maximum control input force is 1.5 N(1.0 % of the total weight of the building model). The initial stiffness of the hysteretic damper is 800 N/m. In the experiment, the damper generated force is magnetic force generated by linear motor.

In conducting experiments, the state vector of the plant for the design of AMD system represented by the velocities and displacements of the top story and third stories relative to the first story is employed. The reduced-order model represents the relative responses of the top and 3rd stories relative to the first story. Three gains, G_1, G_2 and G_3, are employed:

$$G_1 = [\ 3.27 \quad -10.4 \quad -16.6 \quad 50.4 \quad -105.6 \quad -186.3\ ]$$
$$G_2 = [\ -3.93 \quad -4.17 \quad -16.6 \quad -8.81 \quad 154.3 \quad -166.4\ ]$$
$$G_3 = [\ 0.125 \quad 11.6 \quad -4.95 \quad 25.6 \quad 76.2 \quad -15.3\ ]$$

The yield force of the hysteretic damper is taken as 1.2N to make up for the decline of control performance of AMD.

Figures 9 and 10 show the displacements of the top and 1st stories. Figures 11 and 12 are the AMD stroke and control input force. Figure 13 represents the relationship between the damper generated force and displacement. Figure 14 demonstrates how the variable gains are employed during the earthquake. It is recognized that effective control is achieved by incooperating AMD with the hysteretic damper.

CONCLUDING REMARKS

The design of hybrid control system combining AMD and hysteretic damper has been discussed. The validity of the proposed methodology is demonstarated through the simulations and experiments. The proposed control system provides an effective control with a structure regardless of the intensity of seismic excitation.

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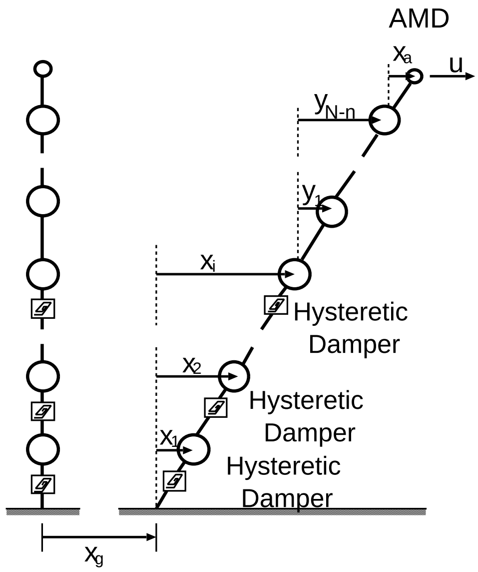

Figure 1: Building model

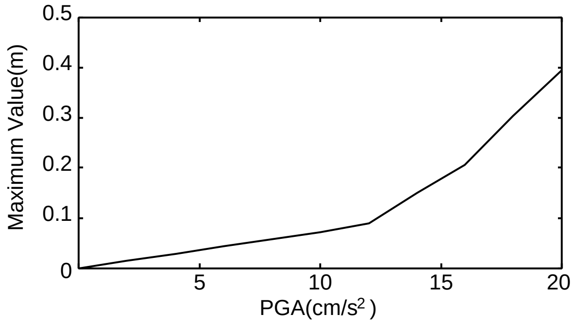

Figure 2: Maximum top story displacements for different PGA with only AMD control

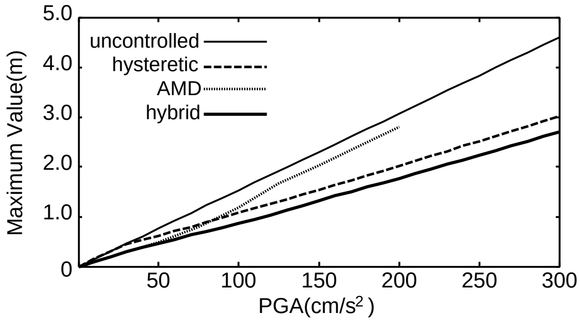

Figure 3: Maximum top story velocities for different PGA

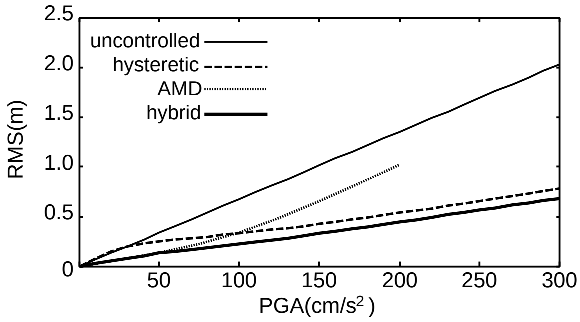

Figure 4: Top story velocity RMS for different PGA

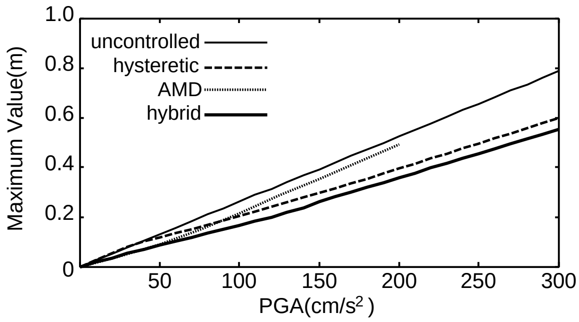

Figure 5: Maximum top story displacements for different PGA

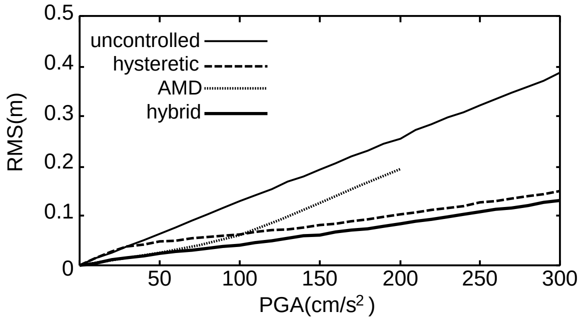

Figure 6: Top story displacement RMS for different PGA

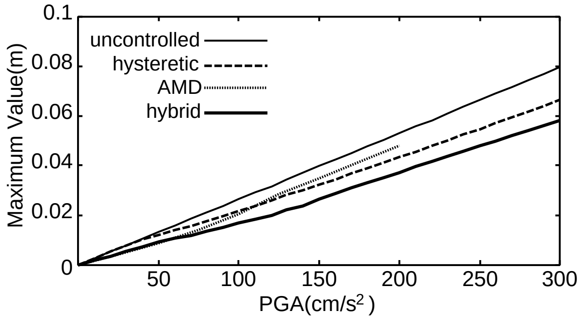

Figure 7: Maximum 1st story displacements for different PGA

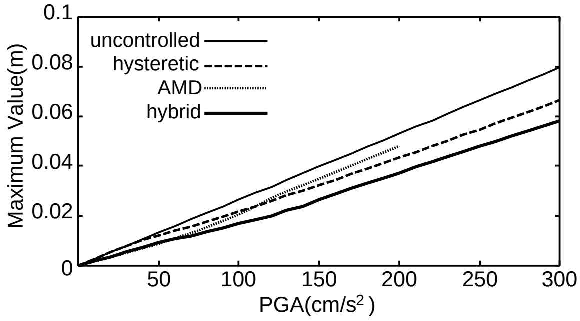

Figure 8: 1st story displacement RMS for different PGA

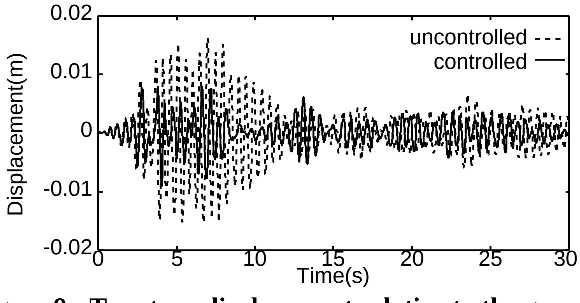

Figure 9: Top story displacement relative to the ground

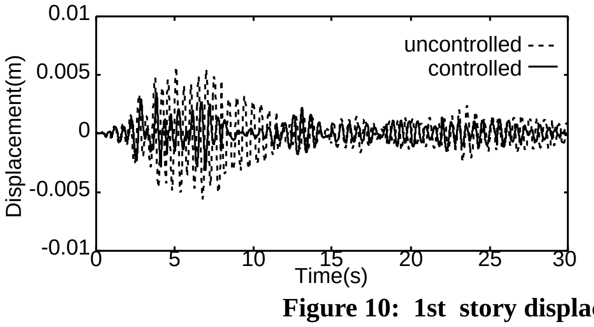

Figure 10: 1st story displacement relative to the ground

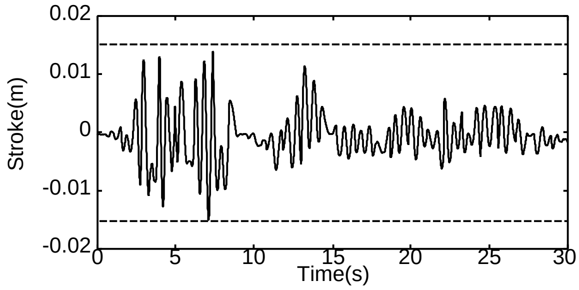

Figure 11 AMD stroke

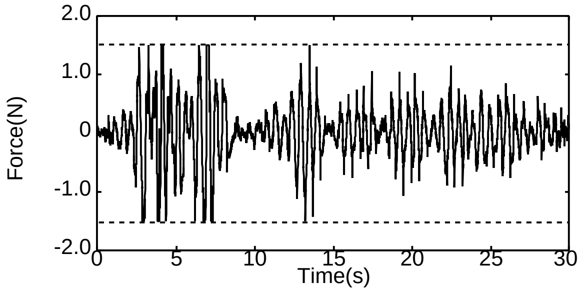

Figure 12: Control input force

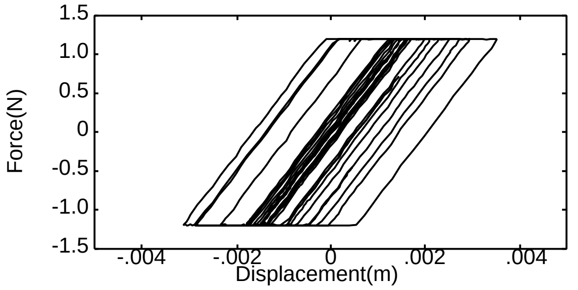

Figure 13: Hysteresis loop of damper

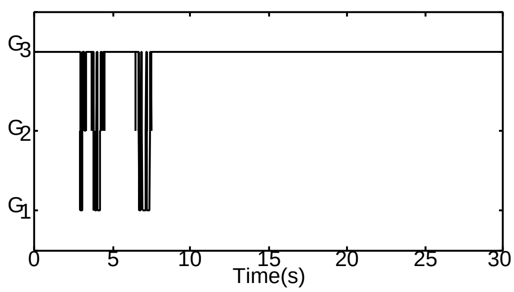

Figure 14: Choice of feedback gains