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ANALYTICAL STUDY ON NON-LINEAR AND ACTIVE CONTROL SYSTEM FOR LARGE EARTHQUAKES

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ABSTRACT

Our experience of the recent earthquake has served to remind us that one can never predict the the oncoming seismic motion, and has demonstrated again that the best way to ensure structural safety is to actively control the seismic response in the buildings. This is a situation which calls for an urgent implementation of studies for practical application of full-fledged response control systems capable of controlling responses due to large-scale earthquakes. With in this view, the authors have devised a new type of an auxiliary-mass type structural control system, assuming non-linear control, and the groundwork has been provided for its practical application through the investigations conducted so far. The results of these investigations are reported here in outline.

KEYWORDS

Active control, Hybrid control, Non-linear control, Large earthquake, Analytical study, Bounded force

INTRODUCTION

Ten years have passed since the authors began full-scale studies on seismic response control systems as a means of ensuring the structural safety of buildings subjected to strong earthquakes, and there has been a gradual increase in the number of buildings provided with such systems. The Great Hanshin Earthquake of January 17, 1995, caused the collapse of a vast number of buildings, with a heavy toll of human lives. There were two buildings equipped with seismic isolation systems in the Kobe area, and a certain response control effect against the major earthquake was observed on these buildings. However, all of the several buildings with active control systems in the adjacent Osaka area, which had been designed for control of wind-induced vibrations, ceased to function when the earthquake struck. This experience has served to remind us that one can never predict oncoming seismic motions, and has demonstrated again that the best way to ensure structural safety of buildings is to actively control the seismic response of the buildings. This is a situation which calls for an urgent implementation of studies for practical application of full-fledged response control systems capable of controlling responses due to major earthquakes.

As an active response control system designed for major earthquakes, the Active Variable Stiffness (AVS) System (Kobori *et al.*, 1993) has already been put to practical use, and an experimental study on the Active Variable Damping (AVD) System (Kurata *et al.*, 1994) has been reported. Widely used active or active-passive (hybrid) structural control systems have an auxiliary mass located near the top of the building. Since auxiliary-mass type structural control systems are aimed at controlling vibrations due to strong winds and minor earthquakes, most of them are not effective against major earthquakes, as has been proved by the Great Hanshin Earthquake. In view of the fact, however, that auxiliary-mass type structural control systems have been extensively applied to actual buildings and are easy to install on buildings, it is important to develop control rules that make auxiliary-mass type systems effective against major earthquakes.

With this in view, the authors have investigated the possibilities of non-linear control rules and have devised promising sets of rules that may be effective on actual buildings. The results of these investigations are reported here in outline.

CONTROL TARGET

The current seismic design standards in Japan aim to "prevent collapse" during major earthquakes. However, the Great Hanshin Earthquake, which caused loss of life due to toppling of furniture and loss of property value due to irreparable damage to many buildings, demonstrated that "prevention of collapse" is not an adequate design goal. Establishment of control targets from the viewpoints of "human life protection", "property protection" and "maintenance of functionality" is hoped for, but criteria to be employed remain open to discussion. In this study, "keeping buildings within the elastic range during major earthquakes" was adopted as the design goal, and the possibilities of control rules for achieving this goal were explored.

In Japan, standard practice when designing a high-rise building is to assume an earthquake having a maximum velocity of 50 cm/s as the strongest earthquake that can occur during the service life of the building, and design the building so that excessive story drift will not occur, though plastic deformation is permitted, during that earthquake. Another criterion employed when designing a high-rise building is that the building is designed so that its response to a 25-cm/s earthquake is kept within the elastic range. Therefore, if the strongest earthquake is assumed to have a ground velocity of 50 cm/s, stresses occurring in the structural members can be kept within the elastic range by reducing the response of the building to a 50 cm/s input by half. Therefore, the control target for buildings equipped with a large-earthquake response control system was set on the basis of inputs currently used for high-rise buildings:

To reduce the elastic response of the building to a 50-cm/s input by half

CONTROL RULES FOR LARGE EARTHQUAKES

If an auxiliary-mass type active or hybrid structural control system is to be used for large earthquakes in practice, it is necessary to solve four problems:

(1) How can the weight of the auxiliary mass be reduced?
(2) How can the stroke of the auxiliary mass be reduced?
(3) How can the control force that needs to be exerted actively by an actuator be reduced?
(4) How can control power requirements be reduced?

The problem of control power (Problem 4), which is an important problem related to the amount of the energy supply for driving the active mass, can be solved automatically if the stroke of the auxiliary mass (Problem 2) and the control force required of the auxiliary mass can be reduced. So only Problems 1, 2 and 3 are considered here.

First of all, let us consider the relationship between the weight and the stroke of the auxiliary mass. Since the ultimate force acting on the building are produced by the force of inertia of the auxiliary mass, it is evident that the larger the weight of the mass, the smaller the required stroke becomes, and, conversely, the smaller the weight of the auxiliary mass, the larger the required stroke becomes. With respect to the control force, since the control force acts on the auxiliary mass in the form of exciting force, it is necessary to devise a method for causing large motion of the auxiliary mass with a small control force. Possible methods for doing this may include the following:

(1) Tune the natural period of the auxiliary mass to that of the building
(2) Give the auxiliary mass a control force in the form of resonant external force
(3) Give control force in pulses, that is, in rectangular waves

Therefore, the concept of the control rules for efficient seismic response control for large earthquakes can be defined as follows: Use as large a mass as practicable to minimize the stroke and at the same time produce control forces that cause resonant vibration of the mass in rectangular pulses.

Many studies have been conducted of Approaches 1 to 3 mentioned above. For Approach 1, an Active-passive Composite Tuned Mass Damper (Koshika *et al.*, 1993) and a Hybrid Mass Damper (HMD) system (Shiba *et al.*, 1994) have been developed and used on actual buildings. With respect to Approach 3, an attempt has been made to realize pulse control by use of gas pressure(Masri *et al.*, 1981). Another study, which pursues the approach of using a tuned auxiliary mass to reduce the stroke, argues for effectiveness of using restraints on the stroke (Asano *et al.*, 1993). Another method is to place an upper limit on control force, based on the conventional AMD and HMD system. The authors suggested the possibility of achieving high efficiency of seismic response control by restraining control forces on an auxiliary mass so as to generate control forces in rectangular waves, and named the proposed method the Bounded-Force Control (BFC) method (Indrawan *et al.*, 1994). This method, which uses control rules physically characterized by Approaches 1 to 3 above, is thought to satisfy the requirements for efficient control rules.

ANALYTICAL STUDY OF CONTROL RULES

Keeping in mind the concept of control rules for large earthquakes mentioned above, let us consider analytically the method of limiting control forces under the control rules of the ordinary AMD (Active Mass Driver) and HMD (Hybrid Mass Damper) systems, and the BFC method. Thus, the control rules considered here are as follows:

(a) AMD system with limited control force
(b) HMD system with limited control force
(c) BFC (Bounded-Force Control) method

Overview of the Control Rules

The equation of motion for seismic response control of a structural system with an auxiliary mass is

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M]\{1\}\ddot{y}+\{u\} \tag{1}$$

where $\ddot{y}$ is a ground acceleration and u is a control force that is evaluated for each control rule as follows:

(a) AMD with limited control force : $u=G_1\dot{x}_b+G_2\dot{x}_a$ $\quad |u|\le u_{\lim}$ (2)

(b) HMD with limited control force : $u=G_1\dot{x}_b+G_2\dot{x}_a+G_3x_b+G_4x_a$ $\quad |u|\le u_{\lim}$ (3)

(c) BFC : $u=\begin{cases}+u_{\lim},+0.5u_{\lim},+0.25u_{\lim}\\-u_{\lim},-0.5u_{\lim},-0.25u_{\lim}\\0\end{cases}$ (4)

where $u_{\lim}$ is a limited control force, G_1,G_2,G_3,G_4 are the feedback gains, and x_a and x_b are displacements of the auxiliary mass and the building respectively.

The control rules of the BFC method, which are detailed in the Reference (Indrawan *et al.*, 1994), are outlined below. The concept of the control rules is illustrated in Figure 1. The control rules, unlike linear control rules using an optimum regulator, determine control force requirements from the response of the building and generate control forces accordingly. To be more specific, the response plane of the building is divided into a control region and a non-control region. A predetermined amount of control force is generated if it is judged necessary from the relation between the present building response and the control region, and no control force is generated if it is deemed unnecessary. Consequently, control forces are provided in rectangular wave forms. An example of a domain of controllability in a building response plane is given in Figure 2.

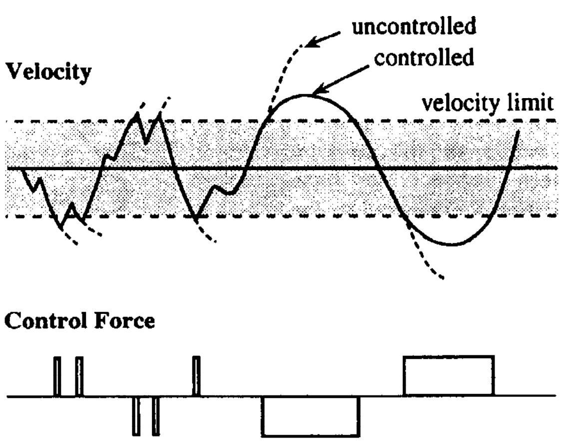


Figure 1 Simplified illustration of BFC method

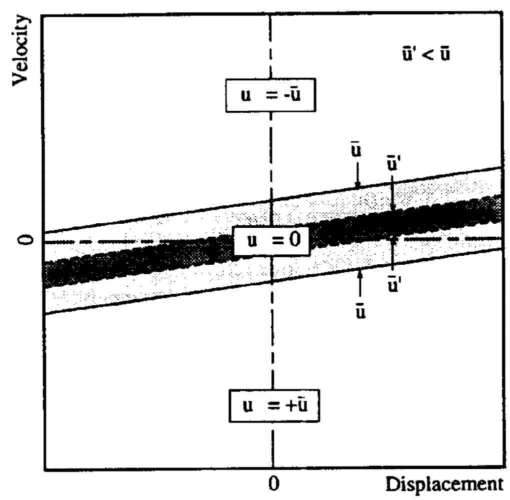


Figure 2 Domain of controllability for 1DOF system

Steady-State Response of 1DOF System

The Kyobashi Seiwa Building (Kobori et al., 1992) introduced the first active response control system in the world designed to reduce structural response to minor earthquakes and strong winds. In this study, the possibility of upgrading the building's response control system for major earthquakes by altering the control system was investigated. As a first step, the building was modeled as a 1DOF system, and the transfer function for steady-state excitation was evaluated. The model is shown in Figure 3 and Table 1.

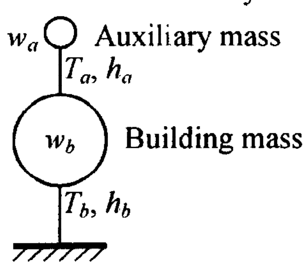


Figure 3 1 DOF model

Table 1 Parameter for 1DOF model

	AMD with limiter			HMD with limiter			BFC		
w_a(tf)	2	4	10	2	4	10	2	4	10
T_a(sec)	3.0	3.0	3.0	1.01	1.02	1.05	1.01	1.02	1.05
h_a	0.0	0.0	0.0	0.06	0.09	0.13	0.09	0.13	0.2
w_b(tf)	200								
T_b(sec)	1.0								
h_b	0.02								

From the results of past analyses, the damping factor for achieving the control target described in the third Section is estimated at h = 10~15%. The weight of the auxiliary mass and the feedback gain in the control rules were adjusted so that an overall damping factor of 10~15% (a damping of the building of 2% and a target additional damping of 8~13%) was attained. This damping factor can be expressed in terms of the ratio of the building response to the earthquake input, 1/2h (h = damping factor); thus, the peak value at the damping factor is four through five.

Each of the above control rules involves non-linear control forces; therefore, the amplitude was evaluated and the transfer function was drawn after the response due to sinusoidal excitation became steady. Figures 4 shows the transfer function of the response acceleration of the building, the stroke of the auxiliary mass, control force, and control power to ground acceleration. In this case several levels of the limited control force are considered under 10-t weight auxiliary mass ($\mu = w_a/w_b = 0.05$). From the figures, with respect to the influence of limited control force level on the effectiveness of seismic response control, the AMD-plus-limiter method was much less effective than linear control, while the HMD-plus-limiter method was only slightly less effective than linear control. In the HMD system, the stroke and power, that tended to increase at longer periods in linear control, reduced under the limited control force. In the BFC method, reduction in the effectiveness of response control were small even when control forces were considerably small, and stroke and power were efficient over a wide frequency range.

As a next step, changes in the effectiveness of seismic response control of the HMD and BFC method were compared in Figure 5, parameterizing the weight of the auxiliary mass. The weight of the auxiliary mass is equal to 1%(2 t), 2%(4 t), and 5%(10 t) of the primary mass. In this case, the limit of control force u_{lim} is 2 tf. From the figures, the influence of the weight of the auxiliary mass on the effectiveness of response control was predominant, indicating that the control system with the 4-t weight (μ =0.02), which is installed at the Kyobashi Seiwa building, is less effective than 10-t weight (μ =0.05) and requires much more stroke and power.

Effectiveness of Seismic Response Control against Earthquake Inputs and Performance Requirements

Since the influence of higher-mode components is substantial in the case of earthquake response, a 10-lumped mass system (shown in Figure 6), which is a whole structure model of the Kyobashi Seiwa Building, was used for analysis. The control rules used were the two cases given below, which were thought to be very effective judging from the results of steady-state excitation analyses:

(a) HMD with limited control force, (b) BFC

The weight of the auxiliary mass is 4 t, which is corresponding to the existing system, and 10 t.

Input Ground Motion Level Covered by the Existing System (4-t auxiliary mass) The specification of the system installed at the Kyobashi Seiwa Building is shown below:

Weight $w_a = 4$ t, Control force limit $u_{\mathrm{lim}} = 1$ tf, Stroke limit $x_a = \pm 25$ cm

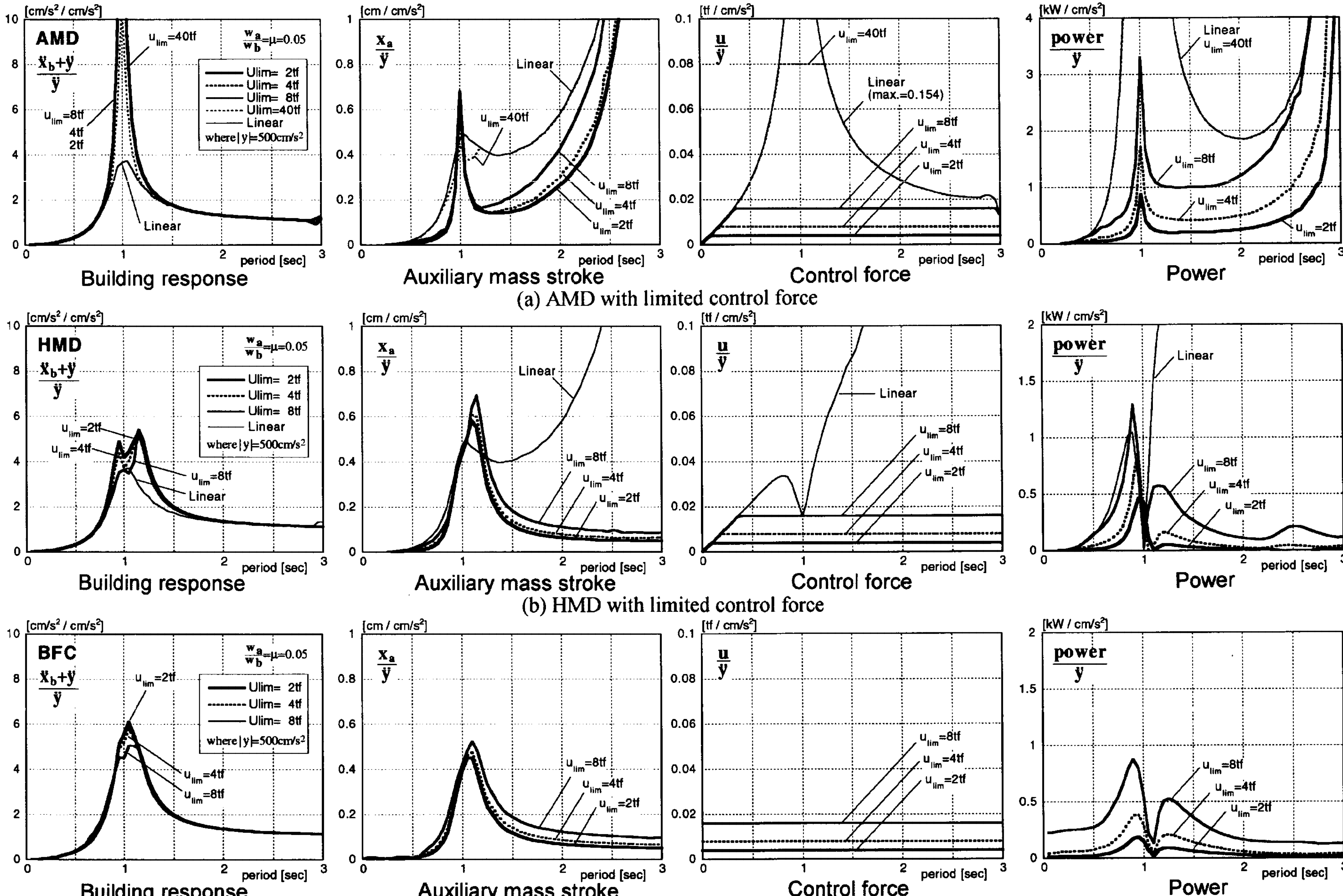
It is difficult to reduce the seismic responses to a 50-cm/s input ground motion by half using this system, judging from the resonance curve shown above. Here, using the wave form of NS component of JMA-Kobe ground motion (recorded maximum acceleration: 820 cm/s^2, velocity: 91cm/s) of the Great Hanshin Earthquake as an input earthquake, adjusting the maximum velocity, it is investigated that the existing system could control the building responses under what level of the input motion by changing only the control algorithm. It is concluded that the 4-t weight system with HMD-plus-limiter or BFC method could control the responses to 10 cm/s-input ground motion as shown in Figure 7. The figure shows the response time histories of displacement of top floor, auxiliary mass stroke, control force, and control power.

Control Effectiveness under 50-cm/s Input To investigate the possibility of the control system that achieve the control target under the large earthquake, the parameters of the system shown below are adopted here.

Weight w_a=10 t, Control Force limit u_{lim}=2 tf

The input ground motion is JMA-Kobe NS component whose maximum velocity is normalized to 50 cm/s. Figure 8 shows, from among the results of the seismic response analysis, the time histories of building top displacement, the stroke of the auxiliary mass, the control force and required control power. As shown in the figure, the building response was roughly within one half of the response in the uncontrolled case except the first peak of the response. So, the control target was almost achieved. The control force, stroke and control power requirements of the BFC and HMD-plus-limiter method were well within the practical range, though the BFC method required less strokes, and less power than HMD.

Original JMA-Kobe NS Ground Motion as an Input For reference, original ground motion of JMA-Kobe NS component was input to the Kyobashi Seiwa Building model with 10-t weight auxiliary mass and 2-tf control force. Responses are shown in Figure 9. One meter auxiliary mass stroke and 120 kW control power of the system make the sufficient control effectiveness.

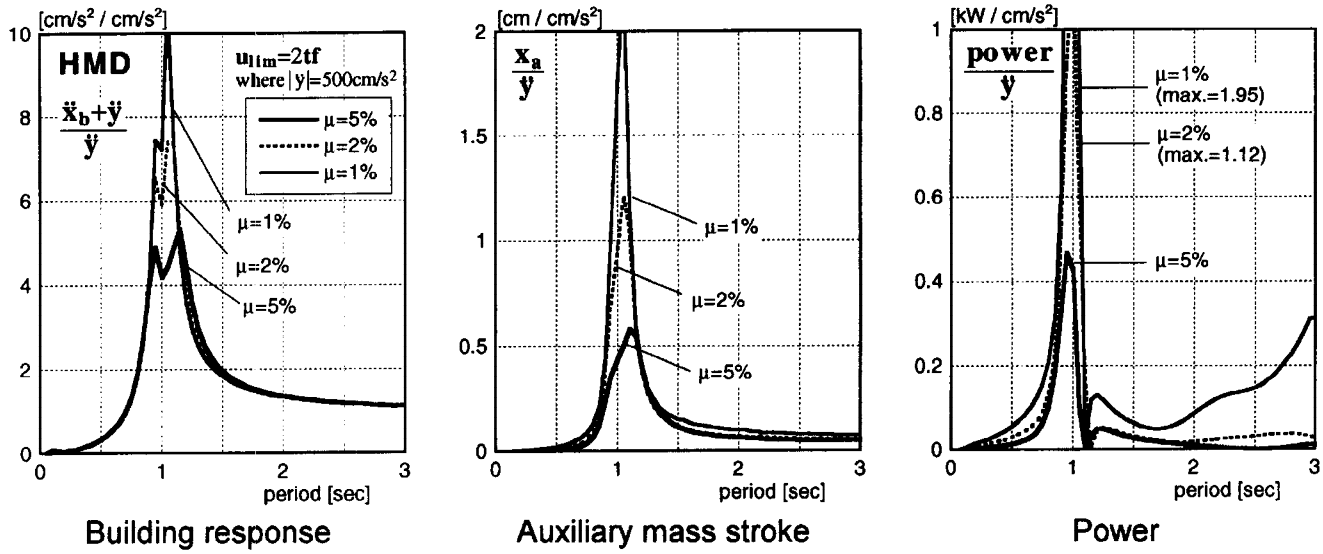


(a) AMD with limited control force

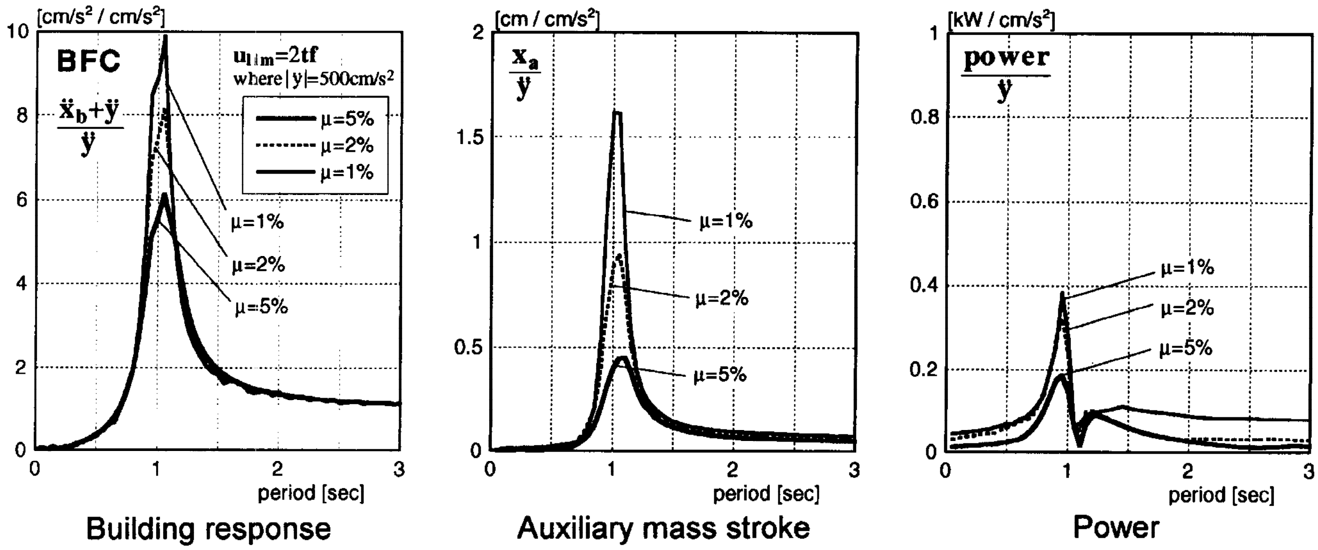
(b) HMD with limited control force

(c) Bounded-Force Control method

Figure 4 Frequency response function parameterizing the level of limited control force $u_{\lim}$

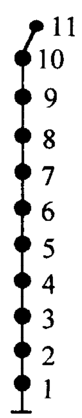


(a) HMD with limited control force



(b) Bounded-Force Control method

Figure 5 Frequency response function parameterizing the weight of auxiliary mass w_a



T_1 = 0.93sec

w_{total}= 393 t

Figure 6 10-lumped mass model

Table 2 Parameters of lumped mass model

	Mass No.	Weight (t)	Stiffness (tf/cm)	Damping factor
Auxiliary mass	11	4.0	0.18	0.086 (HMD)
				0.129 (BFC)
		10.0	0.42	0.134 (HMD)
				0.2 (BFC)
Building	10	83.7	39.9	0.02
	9	33.6	49.1	
	8	33.6	56.9	
	7	34.0	64.1	
	6	34.0	71.9	
	5	34.2	81.9	
	4	34.6	93.7	
	3	34.6	109.0	
	2	34.7	135.1	
	1	36.3	192.6	

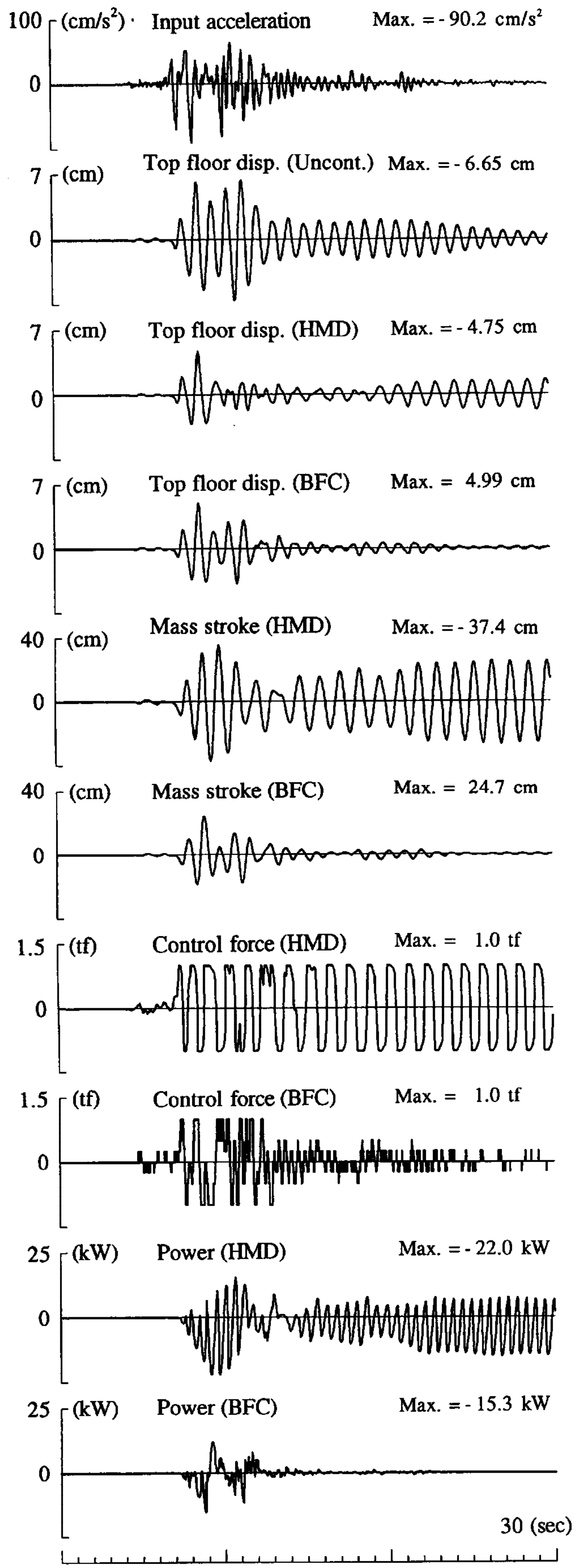


Figure 7 Response time histories under JMA-Kobe (v_{max}=10cm/s)

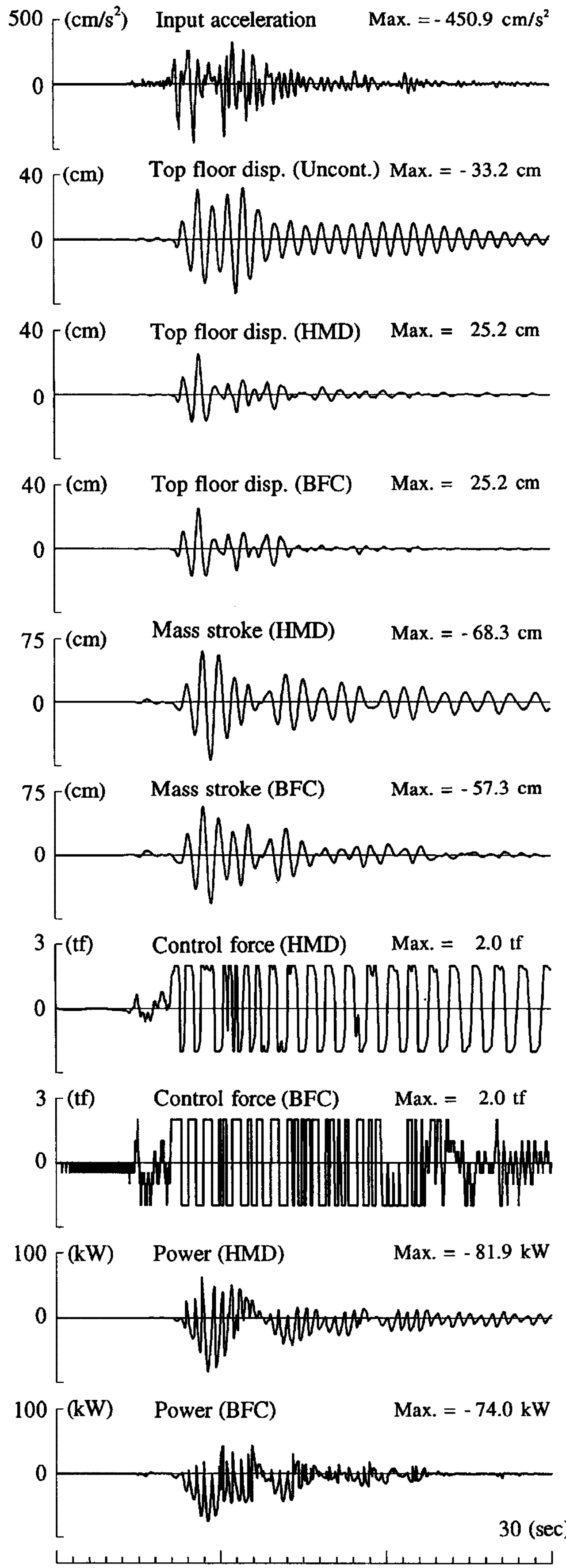


Figure 8 Response time histories under JMA-Kobe (v_{max}=50cm/s)

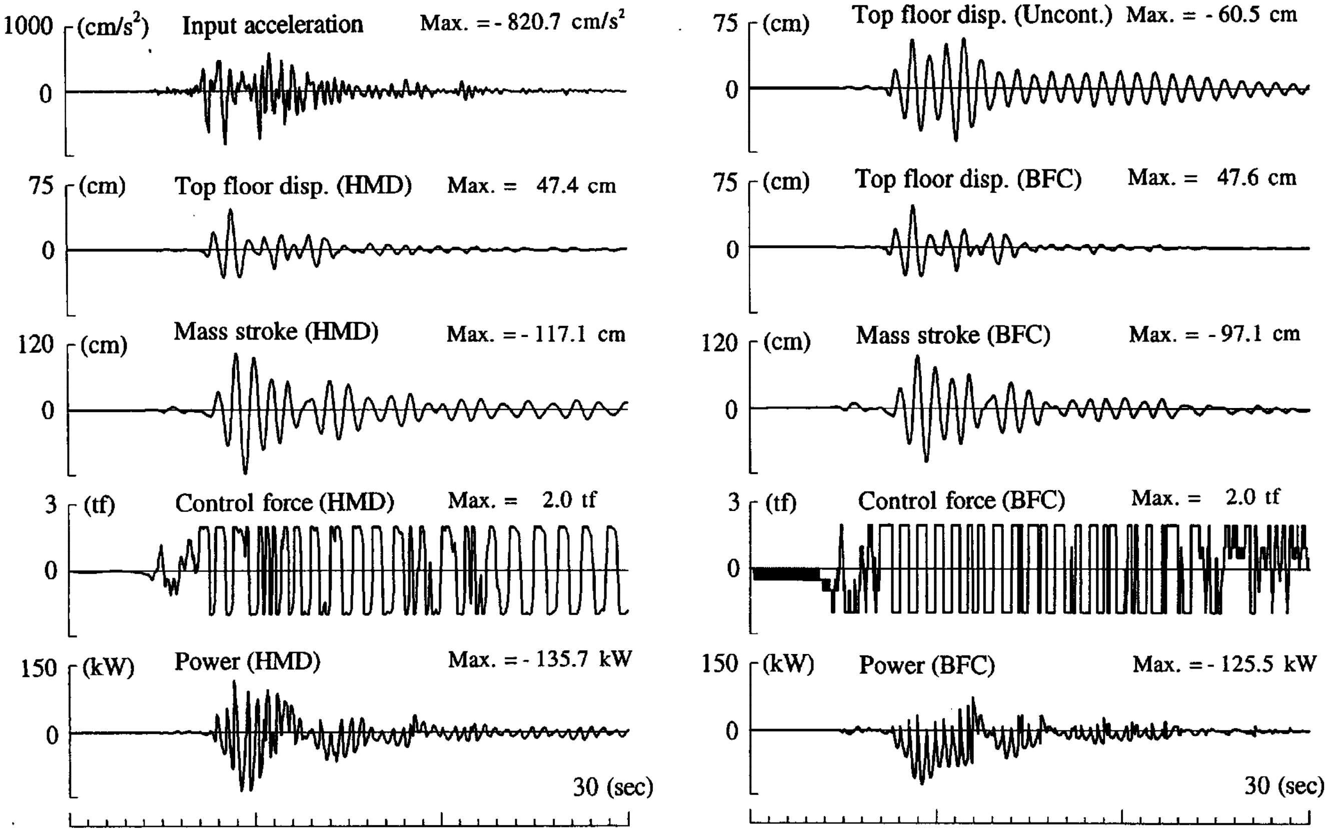


Figure 9 Response time histories under JMA-Kobe (Original, a_{max}= 820cm/s^2, v_{max}= 91cm/s)

CONCLUSION

The feasibility of non-linear control rules consisting of the conventional AMD or HMD method with a control force limiter and of the Bounded-Force Control (BFC) method on an existing building, Kyobashi Seiwa Building, which is equipped with an active seismic response control system, were investigated analytically using the JMA-Kobe ground motion of the Great Hanshin Earthquake as an input. As a result, its has been concluded that the existing system can control the responses to 10-cm/s ground motion by changing only the control algorithm. And the control system with 10-t weight (μ =0.025), and HMD-plus-limiter and BFC method are promising to 50-cm/s ground motion. The control force, stroke and control power requirements of the BFC and HMD-plus-limiter method were well within the practical range.

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