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SEISMIC PERFORMANCE OF MEGA-SUB CONTROLLED BUILDINGS

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ABSTRACT

This paper examines the seismic performance of high-rise buildings controlled by an innovative method referred to as "mega-sub control". This method takes advantage of the so-called mega-sub structural configuration which is gaining wide popularity in the design and construction of high-rise buildings. In this study, the effect of the mega-sub controlled building's dynamic parameters on its structural response is investigated. These parameters consist of the frequencies and damping ratios of the sub structures, and their optimal values are determined to achieve the minimum response acceleration and displacement of the building, in order to improve human comfort, protect building contents, and ensure structural safety. In doing so, the mega structure is modeled as a cantilever beam to characterize the dominant bending mode of tall and slender buildings. Because of the low dominant frequency, wind loads have more significant effects than earthquake loads on high-rise buildings. For this reason, the dynamic parameters of the buildings are designed to the optimal values against wind loads. The fluctuating component of wind speed is modeled as a colored noise, and the random vibration theory is applied in the process of obtaining the optimal dynamic parameters. It is found that the mega-sub control method can significantly reduce the building vibration in all the modes, which cannot be achieved by the conventional tuned-mass-damper control. This gives the proposed control method an essential advantage in suppressing the excessive vibration of buildings caused by seismic loads, to which higher modes could have a significant contribution. The response spectrum matching program, which can retain general time domain characteristics of a real earthquake record and yet make the record consistent with any prescribed response spectra, is applied to generate the earthquake ground motion under different soil conditions for numerical simulation. The simulation demonstrates that even under the condition of dynamic parameters optimally designed against wind loads, the mega-sub controlled building behaves near optimally under variety of seismic loads as well. The hybrid mega-sub control method with actuators installed between the mega and sub structures has also been studied and its cost-effectiveness in further reducing some response values has been shown.

KEYWORD

Mega-sub building; high-rise building; passive control; hybrid control; turbulent wind; optimization.

INTRODUCTION

Extensive studies have been conducted to improve the structural performance under strong gusty wind and severe earthquake loads by implementation of control systems. Among those control systems, the supplemental dampers and tuned mass dampers (TMD) are two commonly used devices. Tuned-mass-damper systems have demonstrated their feasibility for building applications. In case of a massive high-rise building, however, the correspondingly large mass and moving space required for the mass damper could raise a significant safety concern. On the other hand, supplemental dampers usually cannot effectively dissipate energy in high-rise buildings where bending mode is dominant.

A structural configuration, called mega-sub building, is gaining wide popularity in the design of high-rise buildings. As shown in Fig. 1, the building consists of two major portions - a mega structure which is the main structural frame for the building and several sub structures with each of them containing several floors for residential and commercial purposes. In conventional design, the sub structures are near rigid and rigidly fixed on the mega structure. Feng and Mita (1995) are the first to propose the idea of properly designing the dynamic characteristics of the sub structures to control the entire building vibration. A preliminary study, on a two-degree-of-freedom structural model subjected to white-noise external loads, has demonstrated the significant effectiveness of this vibration control method (Feng and Mita, 1995). In this method, the sub structures function like mass dampers, but the mass ratio between the sub and mega structures (usually 100%) is much larger than that in the conventional mass damper system (usually 1%). Also of importance is the mega-sub control does not require additional masses. These advantages make the mega-sub control highly effective and practical.

In this study, the seismic performance of the mega-sub controlled building is investigated, using a multi-degree-of-freedom cantilever beam model to characterize the dominant bending mode of tall and slender buildings. The optimal dynamic parameters of sub structures, such as frequencies and damping ratios, are studied, and their optimal values are determined to achieve the minimum response displacement and acceleration of the mega structure and sub structures, respectively. This is because that excessive displacement may cause concerns of structural safety, while large response acceleration could not only result in damage of sensitive building contents but also make residents feel uncomfortable. Hybrid mega-sub control method is also studied, which utilizes actuators between the sub and mega structures to further improve some structural response characteristics. The control force of the actuator is designed by applying the optimal control theory. Numerical simulation in the time domain is performed to evaluate the seismic performance of the proposed control method. The performance of the passively and hybrid controlled mega-sub buildings is compared with that controlled with TMD. The ground motions used in numerical simulation are generated from the response spectrum matching program, which retain general time domain characteristics of a real earthquake record and also fit the specified response spectra corresponding to different soil conditions.

ANALYTICAL MODEL OF BUILDING AND EXTERNAL LOAD

Since the bending mode contributes significantly to the vibration of high-rise buildings, a cantilever beam is adopted to model the mega structure of the mega-sub building. This beam is further discretized as a MDOF system. A shear-type structural model is appropriate for a sub structure. For simplicity, each sub structure is assumed as a single concentrated mass. The analytical model of a mega-sub controlled building is shown in Fig. 2. The models of a conventional building without control and the one with the TMD control are also given for the comparative study later. The conventional building is discretized into a set of lumped masses with each possessing a weight equal to the sum of the weights of a mega and sub mass. The TMD controlled building is modeled as a mass damper added on the top of the conventional building.

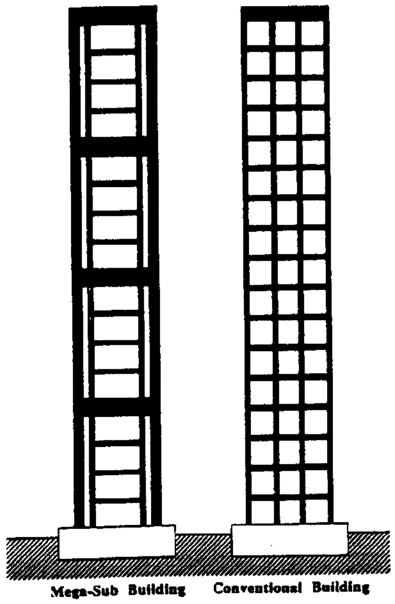

Fig. 1 Configuration of Mega-Sub Building

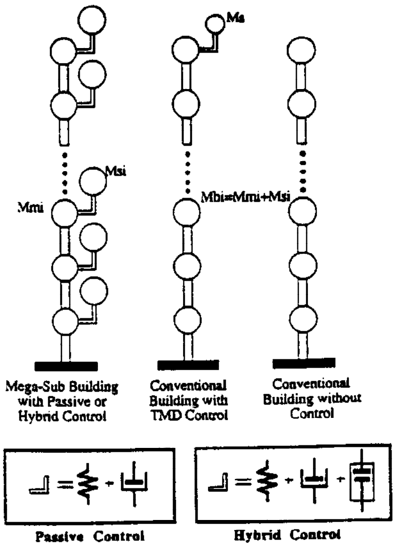

Fig. 2 Analytical Model of Buildings

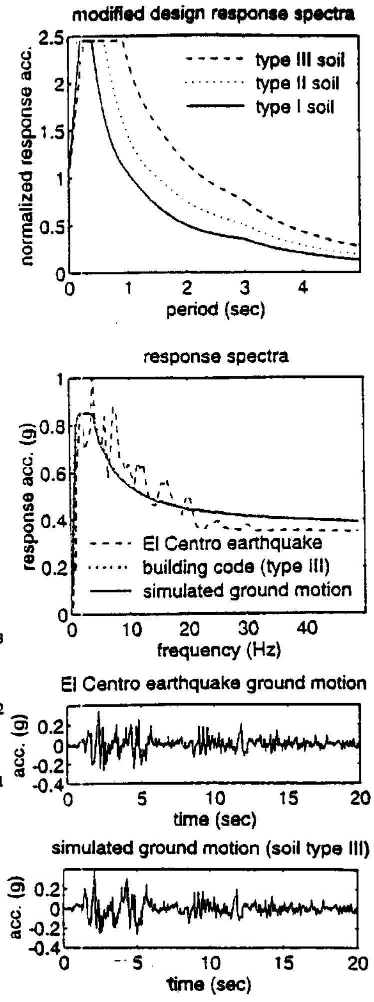

Fig. 3 Response Spectra and Time Histories of Ground Motion

Height : 200 m Shape : Cylinder Diameter : 40 m

Mega-Sub Building	Conven. Bulg. (w. MD)
weight of mega mass	weight of building mass
8000 (KN)	160000 (KN)
weight of sub mass	weight of mass damper
8000 (KN)	4800 (KN)
EI of mega structure	EI of conven. bulg.
14*10^10 (KN-m^2)	14*10^10 (KN-m^2)
fund. freq. of mega structure	fund. freq. of conven. bulg.
2.22 (rad/sec)	1.57 (rad/sec)
damping ratios of all modes for mega structure	damping ratios of all modes for conven. bulg.
1 %	1 %
fund. freq. of mega-sub structure	fund. freq. of conven. bulg. with MD
1.22 (rad/sec)	1.50 (rad/sec)

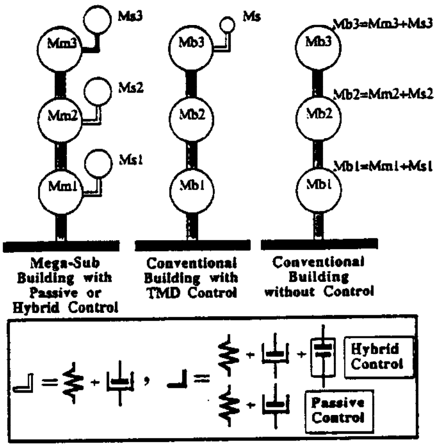

Fig. 4 Models and Structural Parameters of Example Building

The one-sided spectral density function of the fluctuating wind was suggested by Davenport (1961, 1962) and used by Vaicaitis, et al. (1975). Without considering the spatial variation, it can be expressed as

$$S(\omega) = \frac{K\Phi^2}{2\pi^2} \frac{|\omega|}{[1+\Phi^2\omega^2/(2\pi\overline{U}(10))^2]^{4/3}} \tag{1}$$

where Φ = scale of turbulence, K = surface drag coefficient
$\overline{U}(10)$ = mean wind speed at 10m height above the ground

The wind speed profile along the vertical direction of a building is expressed as $U(z,t) = \overline{U}(z) + u(t)$, where $\overline{U}(z)$ is the mean wind speed at height z, and $u(t)$ is the fluctuating wind speed with the non-white spectrum given in Eq. 1. Neglecting the acceleration term, which is generally believed to be small compared with the velocity term, of the drag force expression (Simiu and Scanlan, 1986; Vaicaitis, et al. 1973, 1975), the wind force in along-wind (x) direction can be expressed as

$$f_{x,i}(t) = \frac{1}{2}\rho C_D A_i(\overline{U}(z_i)^2 + 2\overline{U}(z_i)u(t) - 2\overline{U}(z_i)\dot{w}^m_{x,i} - 2u(t)\dot{w}^m_{x,i} + u(t)^2 + \dot{w}^{m\,2}_{x,i}) \tag{2}$$

where ρ = air density, C_D = drag coefficient,

A_i = tributary area of the i^{th} mass of the building in the along wind direction

$w^m_{x,i}$ = deflection of i^{th} mass in the along wind direction

In order to acquire the ground motions corresponding to different soil conditions without losing the time domain characteristics of a real earthquake record, the response spectrum matching program is used to generate the accelerograms for numerical simulation. The simulated accelerograms are expected to fit the response spectra with 5% damping specified by the UBC and at the same time, retain important time domain characteristics such as amplitude, duration and shape, similar to the El Centro (1940 NS) earthquake. Taking into consideration the fact that tall buildings usually have fundamental periods longer than three seconds, the UBC design spectrum was modified to cover the range beyond 3 seconds where the response spectrum is controlled by the maximum ground displacement as shown in Fig. 3. This modified response spectrum is used in the non-stationary spectrum matching method (Abrahamson, et al., 1994) for generation of ground motion time histories. The time histories and their corresponding response spectra are also shown in Fig. 3.

DESIGN OF PASSIVELY CONTROLLED MEGA-SUB BUILDING

The passively controlled mega-sub building is designed through the optimization of the dynamic parameters of building to minimize the building vibration responses. As mentioned before, because of the low dominant frequency and long duration, wind loads usually have more significant effects than the seismic loads on the high-rise buildings. With this recognition, the goal of the optimization is to find the optimal values of dynamic parameters of the mega-sub building so that the wind responses of the building can be minimized. The seismic responses of the building designed in such a way needs to be examined later.

The dynamic parameters to be designed are the frequency ratio of the sub structure to the mega structure and the damping ratio of the sub structures. In the present study, the following assumptions are made for applying the random vibration theory to obtain the optimal values β_{opt} and h_{sopt}. (1) The spatial variation of the wind load is not taken into account. (2) The optimization procedure is based on the minimization of certain target responses in the along wind direction. These target responses are the response acceleration of the sub structures (which affects human comfort and safety of sensitive equipment) and the displacement of the mega structure (which is related to structural safety). (3) Since the first term in Eq. 2 represents the static force which will not affect the dynamic behavior of the building, it is ignored in the optimization procedure. Finally, (4) compared with the mean wind velocity, the velocity response of the mega structure and the velocity of fluctuating wind are small, and thus the last three higher order terms in Eq. 2 are also neglected. The validity of this assumption has been numerically verified in this study.

The equations of motion for a passively controlled mega-sub building can be expressed as a state-space form

$$\begin{aligned} \dot{X}(t) &= AX(t) + BF(t) \\ Y(t) &= CX(t) + DF(t) \end{aligned} \tag{3}$$

where $X(t) = \left\{\{\dot{x}^m_1(t) \sim \dot{x}^m_n(t)\}_{1\times n}, \{\dot{x}^s_1(t) \sim \dot{x}^s_n(t)\}_{1\times n}, \{x^m_1(t) \sim x^m_n(t)\}_{1\times n}, \{x^s_1(t) \sim x^s_n(t)\}_{1\times n}\right\}^T$

= state vector, with superscripts m and s denoting mega and sub structures, respectively.

$Y(t) = \left\{ \{x_1^m(t) \sim x_n^m(t)\}_{1\times n}, \{(x_1^s(t) - x_1^m(t)) \sim (x_n^s(t) - x_n^m(t))\}_{1\times n}, \{\ddot{x}_1^m(t) \sim \ddot{x}_n^m(t)\}_{1\times n} \{\ddot{x}_1^s(t) \sim \ddot{x}_n^s(t)\}_{1\times n} \right\}^T$
= output vector
$F(t)$ = wind force vector, A, B, C, D = coefficient matrices

From Eq. 2, neglecting the static and higher order terms, the wind force can be expressed in a matrix form

$$F(t) = \{\mathrm{P}\}u(t) - [\mathrm{P}]X(t) \tag{4}$$

where $\{\mathrm{P}\}$ = constant vector, and $[\mathrm{P}]$ = constant matrix. Substituting Eq. 4 into Eq. 3,

$$\begin{aligned} \dot{X}(t) &= \left[A - B[\mathrm{P}]\right]X(t) + B\{\mathrm{P}\}u(t) = \bar{A}_{2n\times 2n}X(t) + \bar{B}_{2n\times 1}u(t) \\ Y(t) &= \left[C - D[\mathrm{P}]\right]X(t) + D\{\mathrm{P}\}u(t) = \bar{C}_{2n\times 2n}X(t) + \bar{D}_{2n\times 1}u(t) \end{aligned} \tag{5}$$

The transfer function, $H_{YY}(\omega)$, of response $Y(t)$ is obtained as $H_{YY}(\omega) = \bar{C}[i\omega \mathrm{I} - \bar{A}]^{-1}\bar{B} + \bar{D}$, where I represents the identity matrix. Using the Wiener-Khinchin transformation, the auto-correlation function, $R_{YY}(\tau)$, of response is obtained

$$R_{YY}(\tau) = \int_0^{\omega_u} | H_{YY}(\omega) |^2 \, S(\omega) e^{i\omega\tau} d\omega \tag{6}$$

where, $S(\omega)$ is the spectrum and ω_u is the upper cut-off frequency of the fluctuating wind velocity expressed in Eq. 1. From Eq. 6, the mean square response is obtained as $E[Y(t)^2] = R_{YY}(0)$. The mean response $E[Y(t)] = 0$ and therefore, $E[Y(t)^2] = \sigma_Y{}^2$ where σ_Y is the standard deviation of response.

The σ_Y is a function of β and h_s, and the values of β and h_s, which give a minimum σ_Y are the optimal values. A different target response will obviously result in a different set of optimal values β_{opt} and h_{sopt}. It is noted that β and h_s are defined as $\beta = \omega_s / \omega_{m_i}$ and $h_s = c_s/(2m_s\omega_{m_1})$, where ω_{m_i} is the frequency of the mega structure at i^{th} mode, ω_s the frequency of the sub structure and c_s the damping of sub structure.

DESIGN OF HYBRID CONTROLLED MEGA-SUB BUILDING

Since the optimal parameter values β_{opt} and h_{sopt} depend on the choice of the target response of the building, it is impossible to find one set of optimal values which can simultaneously make two response quantities minimum, such as the displacement of the bottom mega mass and the acceleration of the top sub mass. This makes it difficult to optimally design a passively controlled mega-sub building. It is for this reason that a hybrid controlled mega-sub building is proposed in which actively-controlled actuators are added to a passively controlled mega-sub building. For the passive control, β and h_s are set to the optimal values for minimizing the displacement of the bottom mega mass, while for the active control, the actuator feedback force is designed to minimize the acceleration of the top sub mass.

The equations of motion for the hybrid controlled mega-sub building can be expressed as a state-space form

$$\begin{aligned} \dot{X}(t) &= AX(t) + Hf_a(t) + BF(t) \\ Y(t) &= CX(t) + Ef_a(t) + DF(t) \end{aligned} \tag{7}$$

where, $f_a(t) = -GX(t)$ = actuator control force vector with G = feedback control gain matrix
A, B, C, D, E, H = coefficient matrices

Applying the optimal control theory, the feedback control gain G can be obtained to minimize the following objective index

$$J = \int_{-\infty}^{\infty} \{Y^T(t)QY(t) + Rf_a^2(t)\}dt \tag{8}$$

where Q and R are the weighting matrices whose elements are assigned according to the relative importance attached to the responses and to the control force. Since the active control is used mainly for reducing the acceleration of the sub structures, those elements corresponding to the acceleration of the sub masses in the Q matrix are heavily weighted.

DEMONSTRATION OF EFFECTIVENESS

In order to investigate the effectiveness of the mega-sub control method in reducing the seismic response of a high-rise building, numerical simulation using an example building is performed, and the effectiveness is compared with the cases without control and with the conventional TMD control. The frequency response functions of these buildings controlled differently are also evaluated for comparison. The example building is assumed to be a 200-meter high steel structure and the total mass of the building $m_T = 4.9 \times 10^7$ kg. The mega structure is discretized as three concentrated equal masses, to each of which a sub mass is attached. The analytical models of those buildings with their structural parameters are shown in Fig. 4. Throughout the optimization procedure described earlier, it is found that tuning the frequency of the sub structure to the fundamental frequency of the mega structure ω_{m_1} can generate optimal responses, and the optimal parameter values are $\beta_{opt} = 0.54$ and $h_{sopt} = 0.18$ for minimizing the displacement of the bottom mega mass.

The following cases are simulated, using the ground motions generated from the El Centro (1940 NS) earthquake by matching the response spectrum specified in UBC.
Case 1. Passively Controlled Mega-Sub Building: The mass ratio of a sub mass to a mega mass is $\mu = 1$ and each mega mass m_m and each sub mass m_s are both equal to $m_T / 6$. β and h_s are set to their optimal values. Other parameters are shown in Fig. 4.
Case 2. Hybrid Controlled Mega-Sub Building: An actuator is added between the top mega mass and the top sub mass of the passively controlled mega-sub building described in Case 1. The feedback control gain is designed to minimize the acceleration of the top sub mass in the along wind direction.
Case 3. Conventional Building (Without Control): The whole building is descretized to three concentrated masses with each mass m_b = $m_T / 3$. Other parameters are given in Fig. 4.
Case 4. TMD Controlled Conventional Building: A tuned mass damper is added on the top of conventional building described in Case 3. The mass ratio of the damper mass to the building's total mass is μ=0.01. The frequency ratio between the mass damper and the building (fundamental mode) is set to β_{opt} = 0.9901, while the damping ratio of the mass damper is h_{sopt} = 0.0493 which are the optimal values to minimize the response velocity of the building under wind loads (Feng and Mita, 1995).

Figure 5 shows the frequency response functions of the buildings under seismic loads. Although both passive mega-sub control and TMD control reduce the response magnitude of the first mode, only the former can reduce that of higher modes. This is a substantial advantage for the passively control mega-sub building, because seismic loads have much wider and higher frequency range than wind loads, and the higher modes have significant contribution to the building responses to seismic loads. The time histories of the target responses, stroke (the relative displacement between the top mega and top sub masses, or the relative displacement between the mass damper and the building) and the actuator force (normalized by the total building weight) are computed up to 40 seconds, but shown 20 seconds in Figs. 6 and 7. The input ground motion is the El Centro earthquake modified to match the design spectrum for the soil type III. It is noted that the dynamic parameters and the control gains used under seismic loads are the same as those designed against wind loads. Figure 6 demonstrates that the passively controlled mega-sub building behaves extremely well under the seismic load, compared with the conventional building without control and with TMD control. Figure 7 shows that the hybrid control can further reduce the response acceleration without requiring large damper stroke space and actuator force. Similar observations can be made from the simulation results using the input ground motions with their response spectra matched to the design spectra for the type I and type II soils. The maximum responses of all the buildings under earthquake with different characteristics are tabulated in Table 1. This numerical example has confirmed that the mega-sub controlled building, designed to optimally suppress the wind responses, also performs extremely well under seismic loads.

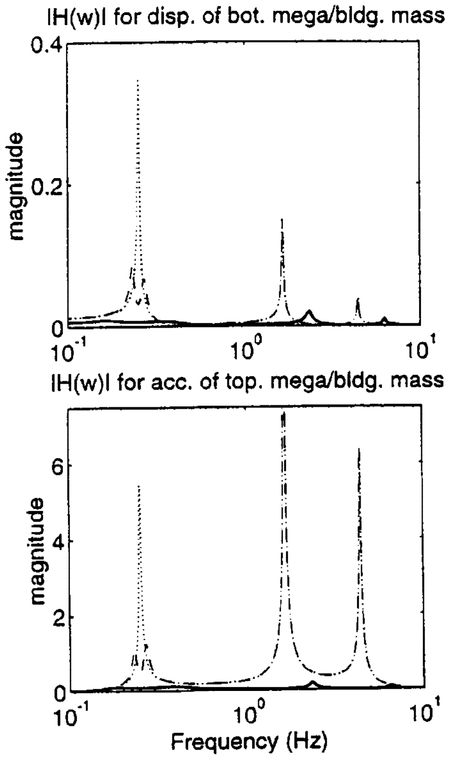

Fig. 5 Frequency Response Functions

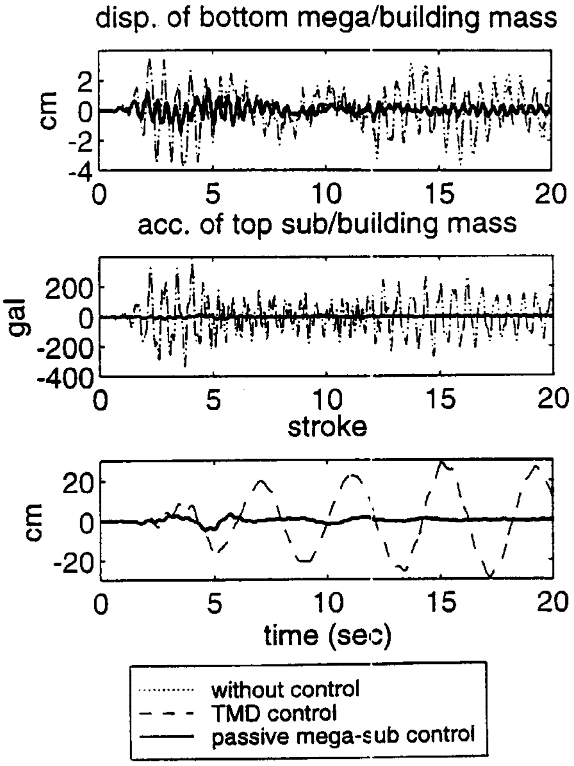

Fig. 6 Response Time Histories (I)

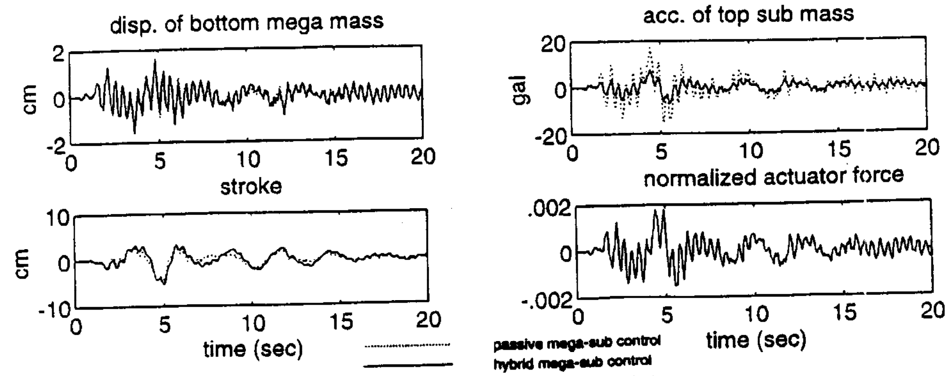

Fig. 7 Response Time Histories (II)

Table 1. Max. Response of Buildings Excited by Simulated Ground Motions

	without contl.	TMD contl.	passive mega-sub contl.	hybrid mega-sub contl.
		TYPE I SOIL		
disp. of bot. mega/bldg. mass (cm)	3.02	2.72	1.25	1.34
acc. of top sub/bldg. mass (gal)	277	277	11.8	4.81
stroke (cm)	-	13.1	2.21	2.58
normalized contl. force.	-	-	-	.0014
		TYPE II SOIL		
disp. of bot. mega/bldg. mass (cm)	3.53	3.54	1.27	1.40
acc. of top sub/bldg. mass (gal)	352	352	14.6	5.92
stroke (cm)	-	17.7	3.15	3.45
normalized contl. force	-	-	-	.0014
		TYPE III SOIL		
disp. of bot. mega/bldg. mass (cm)	3.73	3.73	1.47	1.61
acc. of top sub/bldg. mass (gal)	391	390	17.1	7.64
stroke (cm)	-	28.9	4.72	5.26
normalized contl. force.	-	-	-	.0018

CONCLUSION

The excellent performance of the passively and hybrid controlled mega-sub buildings under seismic loads have been demonstrated. Through the time and frequency domain analysis of the seismic response of the buildings controlled by different methods, it is found that (1) the passive mega-sub control can effectively reduce the building vibration in all the modes, which cannot be achieved by the TMD control; and (2) with the help of actuators, a certain target response can be further reduced without requiring much power and stroke of the actuator.

ACKNOWLEDGE

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