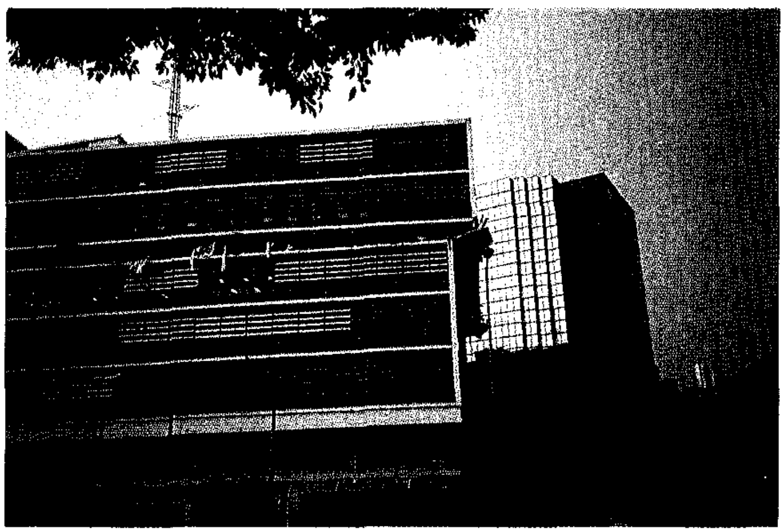
Seismic Isolation Control

for A Buildinglike Structure

Hidekazu Nishimura and Akihito Kojima



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Minimizing the damage to buildings from large earthquakes is very important in maintaining urban function, especially if buildings contain critical facilities. Although passive isolation systems have been used in civil structures, if earthquakes of such great magnitude occur that these systems are ineffectual, an active seismic isolation system may be useful. This article discusses the design method of an active vibration isolator for a multi-degree-of-freedom structure such as a tall building. The controlled variables are selected based on minimization of interaction between a controlled structure and its base. The controller design employs the well-known μ-synthesis approach—considered one of the most robust control methods for parameter variations of the controlled structure. Based on experiments on our laboratory structure and on simulations of an actual building, a controller is designed for an active vibration isolator whose passive elements are installed in parallel with the active element. We show that the proposed design method is useful for seismic isolation of tall buildings.

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Introduction

Structural control to protect civil structures from earthquakes has attracted worldwide attention [1]. Active or hybrid mass damper systems have been implemented in high-rise buildings or bridge towers while under construction. However, the main purpose of these systems is reduction of the wind-induced response, and they are not effective for large seismic disturbances due to actuator force or stroke limitation. On the other hand, a seismic isolation rubber bearing consisting of rubber sheets and steel plates is very effective in civil structures that are subject to seismic disturbances, and such passive isolation systems have been in practical use. Recent studies [2]-[5], how-

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ever, have examined isolation systems in which active actuators are used to isolate or absorb vibration on the transfer path of earthquakes. For buildings that contain important facilities and must continue to function if earthquakes occur, an active seismic isolation system may be useful if the passive isolation system alone cannot prevent destruction by earthquakes.

In a recent paper [6], we discussed a design method for a controller that exhibits robustness to the model uncertainties of the base of a building. We also described a vibration isolation method that minimizes the interaction between the controlled structure and its base by an absolute velocity feedback control strategy that is known as a sky-hook damper [7]. If the interaction between the controlled structure and its base ideally becomes zero, vibration isolation might be perfectly achieved and the designed controller also might be robust for the parameter variation or nonlinearity of the base. Our experimental results, corresponding to the results of μ-analysis for the parameter variation of the base, showed that the controller design method did not need to take into account the base dynamics. To date, however, there have been no reports of studies on design methods of vibration isolation for suppressing the interaction between a controlled buildinglike structure and its base.

Although the experimental results for a three-degree-of-freedom structural model showed the efficiency of the proposed design method, simulations for an actual tall building are necessary to put the active vibration isolation method to practical use.

This article shows that by using the criterion function for the purpose of suppressing the interaction between the controlled structure and its base, a controller with the desired performance can be designed even without precisely knowing the base dynamics. Using simulations, we can verify that a controller based on the proposed methodology can improve the vibration isolation performance of the passive-isolated structure. An 11-story building is used as the controlled object in these simulations to examine the feasibility of the active seismic isolation method for tall buildings. The purpose of this study is to design a controller for vibration isolation to seismic responses. Assuming that the active vibration isolator consists of a linear actuator and passive elements of a spring and a damper, the design problem consists of both tuning the passive elements and designing the controller for the actuator. This study applies a robust control theory based on the structured singular value method, that is, μ-synthesis, to the controller design, since the output controller obtained by μ-synthesis is generally more robust than the output controller including the Kalman filter or the observer obtained by the linear quadratic Gaussian method or the pole assignment method. The robust performance is verified for the parameter variations of the passive elements caused by their nonlinearity [8]. Although nonlinear control methods also may be useful in combination with nonlinear passive elements, it is difficult to correctly identify a nonlinearity such as a hysteresis property and to design the controller taking into account that property. The results show that the proposed design method is useful to achieve the appropriate isolation performance to seismic inputs for tall buildings.

Dynamic Model

The controlled structure used for this study is an n-story towerlike structure with a one-degree-of-freedom base, as shown in Fig. 1. Although the actual base of a buildinglike structure has complicated nonlinearity and is not known precisely, we assume that the base is a vibration system that consists of a mass m_0, a spring k_0, and a damper c_0. The assumption does not affect the interaction between the controlled structure and its base (see (6) at the end of this section). The spring k_1 and the damper c_1 are treated as the passive elements that are installed in parallel with the active vibration isolator symbolized by u_s in Fig. 1.

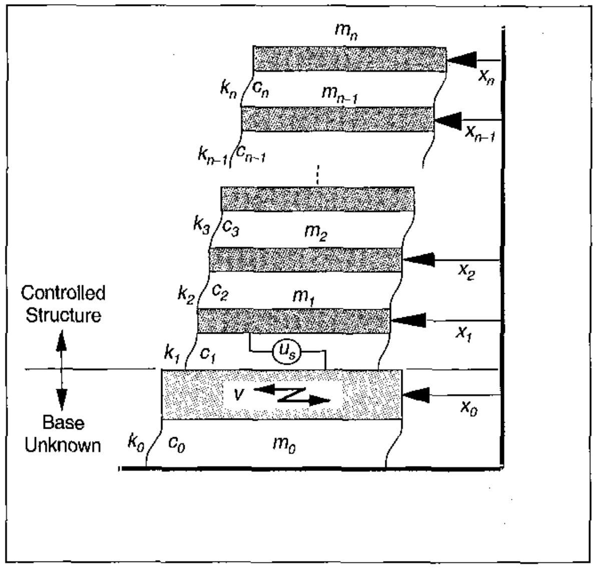

Fig. 1. Dynamic model of structure.

In Fig. 1, u_s indicates a control force, v indicates a disturbance force input, and x_i indicates a displacement of each mass ($i = 0,...,n$) referred to the absolute coordinate system. In this study, an absolute displacement or an absolute velocity means a displacement or a velocity referred to the absolute coordinate system, respectively.

The governing equations of motion of the n-degree-of-freedom structure with its base dynamics can be expressed as follows:

$$m_0\ddot{x}_0 + c_0\dot{x}_0 + k_0x_0 - c_1(\dot{x}_1 - \dot{x}_0) - k_1(x_1 - x_0) = -u_s + v, \quad (1)$$

$$\begin{aligned} &m_1\ddot{x}_1 + c_1(\dot{x}_1 - \dot{x}_0) + k_1(x_1 - x_0) \\ &-c_2(\dot{x}_2 - \dot{x}_1) - k_2(x_2 - x_1) = u_s, \end{aligned} \quad (2)$$

$$\begin{aligned} &m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) \\ &-c_3(\dot{x}_3 - \dot{x}_2) - k_3(x_3 - x_2) = 0, \end{aligned} \quad (3)$$

$$\vdots$$

$$\begin{aligned} &m_{n-1}\ddot{x}_{n-1} + c_{n-1}(\dot{x}_{n-1} - \dot{x}_{n-2}) + k_{n-1}(x_{n-1} - x_{n-2}) \\ &-c_n(\dot{x}_n - \dot{x}_{n-1}) - k_n(x_n - x_{n-1}) = 0, \end{aligned} \quad (4)$$

$$m_n\ddot{x}_n + c_n(\dot{x}_n - \dot{x}_{n-1}) + k_n(x_n - x_{n-1}) = 0. \quad (5)$$

From (1) for the base mass m_0 equipped with the active vibration isolator and (2) for the first-story mass m_1 of the controlled structure, the interaction between the controlled structure and its base is expressed by the term

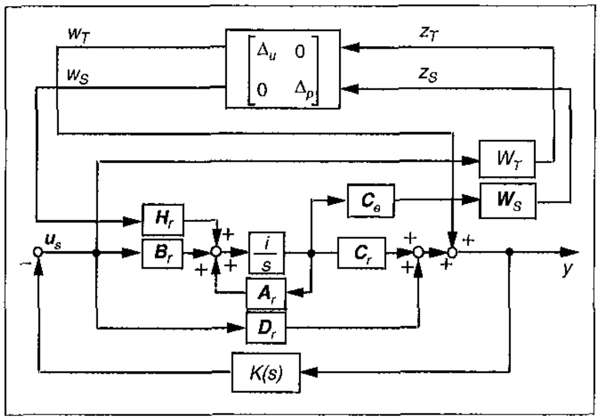

Fig. 2. Generalized plant.

$$c_1(\dot{x}_1-\dot{x}_0)+k_1(x_1-x_0)-u_s. \quad (6)$$

Controller Design

Selection of Controlled Variables

From (6), we can introduce the following necessary condition to suppress the interaction between the controlled structure and its base:

$$|c_1(\dot{x}_1-\dot{x}_0)+k_1(x_1-x_0)-u_s|\rightarrow \min, \quad (7)$$

where $\cdot \rightarrow \min$ means an operation of minimizing.

From (2), the following conditions satisfy the condition (7):

$$|\ddot{x}_1|\rightarrow \min, |x_2-x_1|\rightarrow \min, \text{and} |\dot{x}_2-\dot{x}_1|\rightarrow \min. \quad (8)$$

Therefore, when we select the acceleration $\ddot{x}_1$ of the first story of the controlled structure and the relative displacement x_2-x_1 between the first story and the second story as controlled variables, the interaction (6) will be suppressed equivalently, even without precisely knowing the base dynamics.

Design by μ-Synthesis

The generalized plant to which μ-synthesis [10] is applied is shown in Fig. 2 where the matrices of the controlled structure A_r, B_r, C_r, D_r, and H_r are those of the system without taking into account the base dynamics. Thus, the shaded part of Fig. 1 can be regarded as a rigid body that is subjected to an acceleration input. Here, we design the controller without explicitly taking into account the parameter variations of the controlled structure and the base dynamics, because the control performances did not depend on these values. The design problem related to the parameter variations should be further examined.

The acceleration $\ddot{x}_1$ of the first story of the controlled structure and the relative displacement x_2-x_1 between the first story and the second story are weighted by a frequency weighting function W_S and their controlled vector is defined as z_S. In frequency ranges higher than the controlled frequency range, we add the unstructured uncertainty Δ_p to the controlled object to maintain robust stability. The controlled scalar value z_T is weighted by a frequency weighting function W_T.

For the transfer function G_{zw} from $w=[w_T \;\; w_S]^T$ to $z=[z_T \;\; z_S^T]^T$, the block structure Δ_1 is defined as follows:

$$\Delta_1=\{\text{diag}(\Delta_p,\Delta_u);\ \Delta_p,\Delta_u \in C\}, \quad (9)$$

and to minimize the structured singular value as the general criterion for stability robustness and the robust performance, we have to obtain the controller:

$$\dot{x}_c = A_c x_c + B_c y \quad (10)$$

$$u_s = C_c x_c + D_c y \quad (11)$$

that satisfies the following:

$$\sup_\omega \mu_{\Delta_1}[G_{zw}(j\omega)] \le 1, \quad (12)$$

where $\mu_{\Delta_1}[G_{zw}(j\omega)] = \dfrac{1}{\min\{\bar{\sigma}(\Delta_1):\det(I-G_{zw}\Delta_1)=0\}}$.

For computing the controller, we employ D-K iteration [9], [10] using the MATLAB computer-aided control system design tool.

Experimental Results

Experimental Setup

The specifications of the experimental setup are shown in Table 1. The natural frequencies of the first, second, and third modes of the controlled structure are 2.46, 6.98, and 11.68 Hz, respectively. If the damping coefficient c_0 of the base is equal to zero, the natural frequency about the base becomes 9.85 Hz.

A photograph and a schematic diagram of the experimental setup are shown in Figs. 3 and 4, respectively. The acceleration sensor is fixed at the first story, and the active isolator is installed between the base and the first story. The output of the acceleration sensor is fed into the digital signal processor, and the calculation of the controller is performed in the processor every sampling interval $T_d = 1$ ms. The designed controller is digitized by zero-order holding, and the processor is implemented by the digitized controller beforehand. The digitized controller is as follows:

$$x_c(k+1) = A_d x_c(k) + B_d y(k) \quad (13)$$

$$u_s(k) = C_c x_c(k) + D_c y(k) \;, \quad (14)$$

where $A_d = \exp(A_c T_d)$, $B_d = \int_0^{T_d} \exp(A_c\tau)d\tau \cdot B_c$.

Table 1. Specification of Structural System

Base	*Controlled Structure*	*Actuator*
m_0 = 5.0 kg	m_1 = 1.72 kg, m_2 = 1.48 kg	K_f = 2.0 N/A
c_0 = 100 N·s/m	m_3 = 2.34 kg	K_e = 2.0 V·s/m
k_0 = 16000 N/m	$c_1 = c_2 = c_3$ = 0.078 N·s/m	R = 1.5 Ω
	$k_1 = k_2 = k_3$ = 2600 N/m	

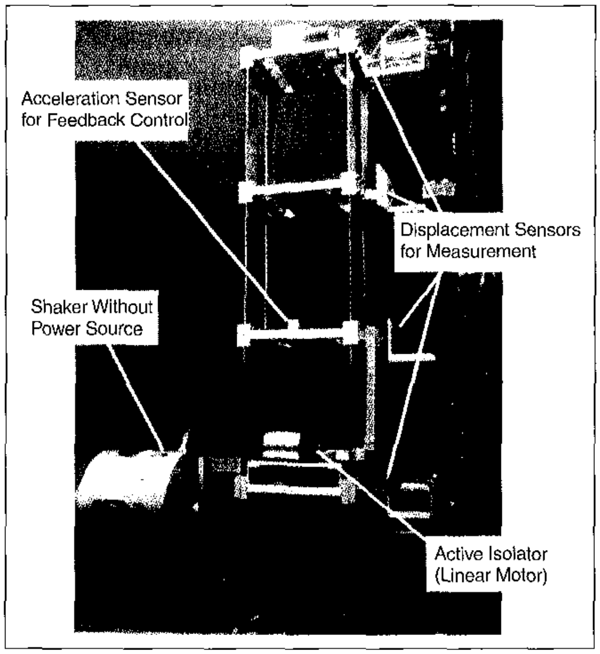

Fig. 3. Experimental setup of structural system.

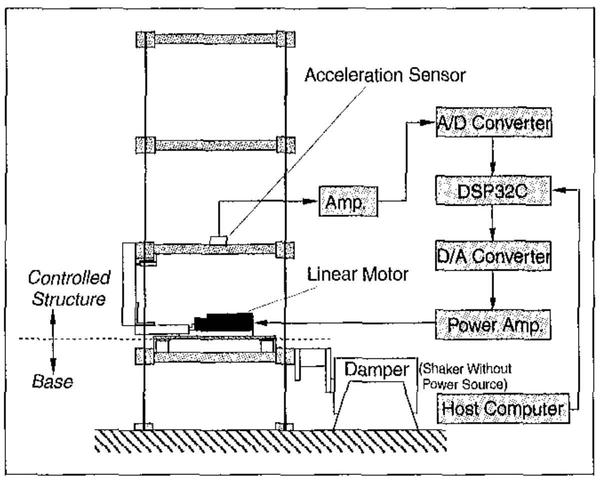

Fig. 4. Schematic diagram of experimental setup.

The output of the controller is fed into the linear motor through the amplifier. The active isolation system consists of the linear motor and the linear slide bearing. The shaker is used as a damper for the base. Since the shaker also has a certain nonlinearity, such as friction force, the experimental setup includes uncertainties about the base dynamics, and the base is assumed to simply have one degree of freedom in the mathematical model.

Experimental Results

Fig. 5 shows the frequency response functions of the interaction with the disturbance input to the base of the structure. The solid line indicates the controlled case by the designed controller and the broken line indicates the uncontrolled case. From Fig. 5, we can verify that the vibration isolation performance achieved by the controller is obtained using controlled values of the acceleration $\ddot{x}_1$ and the relative displacement $x_2 - x_1$. We also confirm that the experimental results coincide with the simulation results.

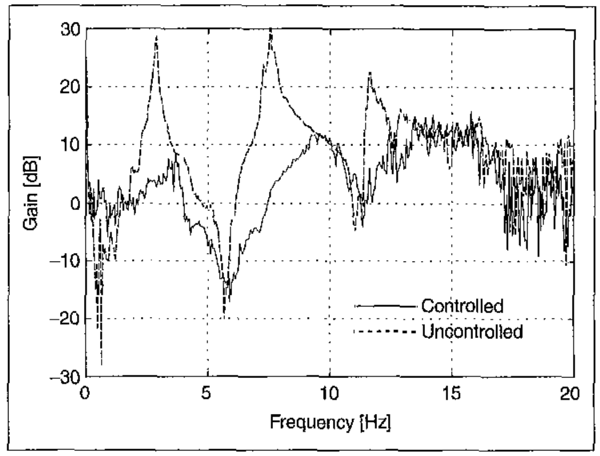

Fig. 5. Experimental results of frequency response $(c_1(\dot{x}_1 - \dot{x}_0) + k_1(x_1 - x_0) - u_x)/v$.

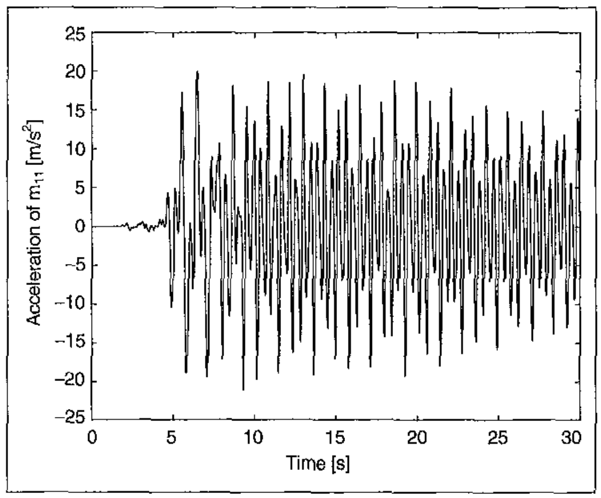

Fig. 6. Seismic response $\ddot{x}_{11}$ *of nonisolated structure.*

Simulations for the 11-Story Building

This section describes the 11-story building used to study the feasibility of practical use of the active vibration isolator. The specifications of the nominal structure that is not isolated are shown in Table 2. The base dynamics are assumed to be negligible. Fig. 6 shows the time-history response against the Hyogoken-nanbu earthquake (with maximum amplitude of 8.18 m/s^2 reduced by 60%), which was recorded at Kobe Kaiyo Kishoudai in the N-S direction. Fig. 6 shows the acceleration of the top of the structure. The maximum amplitude of the acceleration of the top mass exceeded 20 m/s^2, and this structure needs at least the passive isolation device to protect the facilities included.

This study tuned the spring k_1 and the damper c_1 for the passive vibration isolator. The values of the stiffness k_1 and the damping coefficient c_1 are 0.3 k_2 and 50 c_2, respectively.

The controller of the active isolator is designed for the model reduced by the balanced realization method [11] that truncates the modes whose controllability and observability gramians are

Table 2. Specifications of Simulation Model		
Mass [kg]	*Stiffness* [N/m]	*Damping* [Ns/m]
$m_i = 44.2\times10^3$ $(i = 1,2,\cdots,10)$	$k_1 = 91.6\times10^6$, $k_2 = 91.6\times10^6$	$c_1 = 18.3\times10^3$, $c_2 = 18.3\times10^3$
$m_{11} = 54.2\times10^3$	$k_3 = 88.3\times10^6$, $k_4 = 89.2\times10^6$	$c_3 = 17.7\times10^3$, $c_4 = 17.8\times10^3$
	$k_5 = 79.1\times10^6$, $k_6 = 73.1\times10^6$	$c_5 = 15.8\times10^3$, $c_6 = 14.6\times10^3$
	$k_7 = 66.1\times10^6$, $k_8 = 58.0\times10^6$	$c_7 = 13.2\times10^3$, $c_8 = 11.6\times10^3$
	$k_9 = 48.8\times10^6$, $k_{10} = 38.1\times10^6$	$c_9 = 9.8\times10^3$, $c_{10} = 7.6\times10^3$
	$k_{11} = 25.5\times10^6$	$c_{11} = 5.1\times10^3$

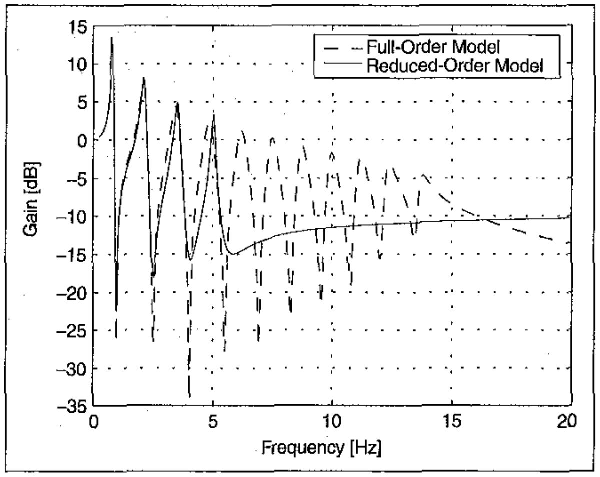

Fig. 7. Frequency response by model reduction.

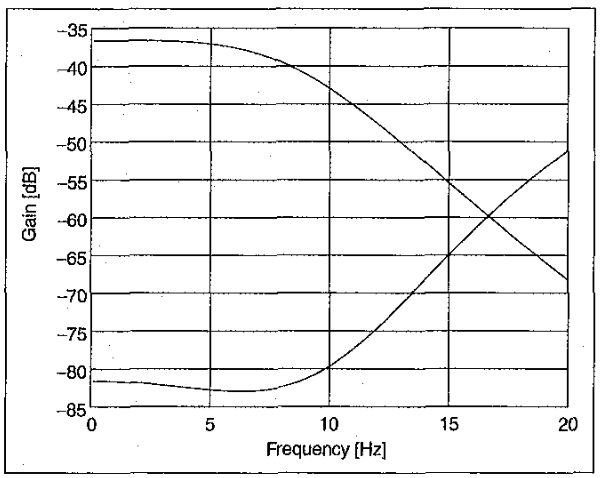

Fig. 8. Frequency weighting functions W_S and W_T in the bad case.

relatively smaller than the other modes. The solid line in Fig. 7 shows the frequency response function of the acceleration $\ddot{x}_1$ to the input acceleration $\ddot{x}_0$ for the reduced-order model; modes 1 through 4 corresponding to those of the full-order model are indicated by the broken line.

Since the frequency range of the controlled object is limited to 5 Hz, the weighting functions W_S and W_T are selected as shown in

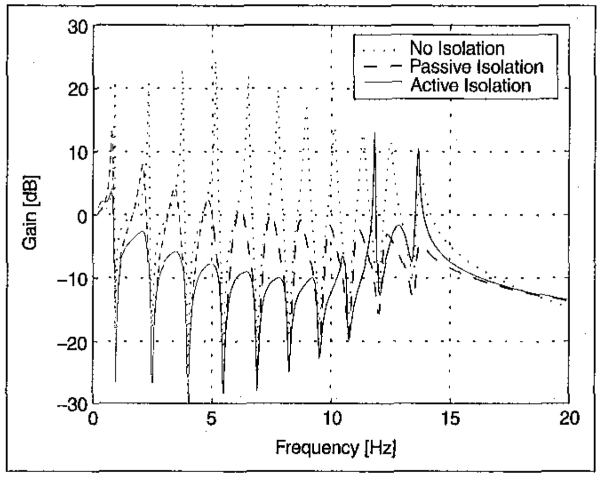

Fig. 9. Frequency response by the controller.

Fig. 8. The adoption of these weighting functions in μ-synthesis results in the controller. Since damping ratios of actual buildings are relatively large and the passive vibration isolator permits the structure above the isolation layer to move in a rigid body, minimization of the relative displacement or velocity between the first and second stories is not necessary for the controlled values.

Fig. 9 shows the frequency response functions of $\ddot{x}_1 / \ddot{x}_0$ for the passive isolation and the active isolation structures as well as that of the nominal nonisolated structure. From Fig. 9, we can verify that the active-isolated structure reduces the transfer of the disturbance input from the base to the upper structure more than the passive-isolated structure in the frequency range from 0 to 10 Hz. The magnitude of the gain also increases more than in the passive-isolated structure in frequency ranges higher than 10 Hz.

Since these phenomena avoid isolation performance in the higher frequency range, the frequency weighting functions are devised so that the controlled object in the full-order model ranges to 15 Hz. This devising of the frequency weighting functions improved the frequency characteristics of the controller. Decrement of the controller gain in the higher frequency range is reduced. Fig. 10 shows the frequency response functions with the improved controller. The accelerations of the lowest mass and the top mass are reduced in all frequency ranges and base isolation is achieved.

Since the passive elements may have a nonlinearity such as a bilinear hysteresis, the controller has to be robust against varia-

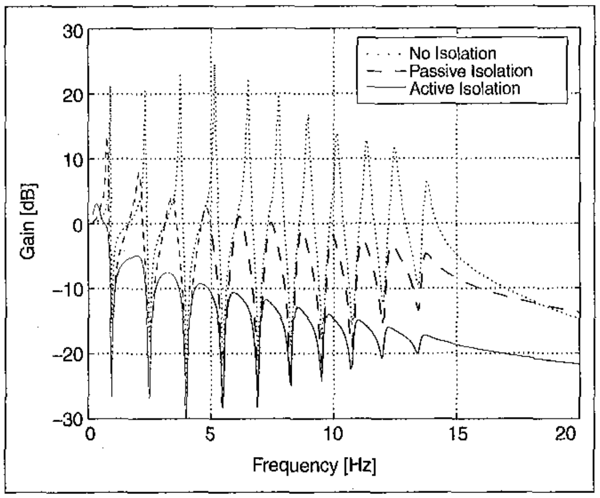

Fig. 10. Frequency response $\ddot{x}_1 / \ddot{x}_0$ by the controller improved.

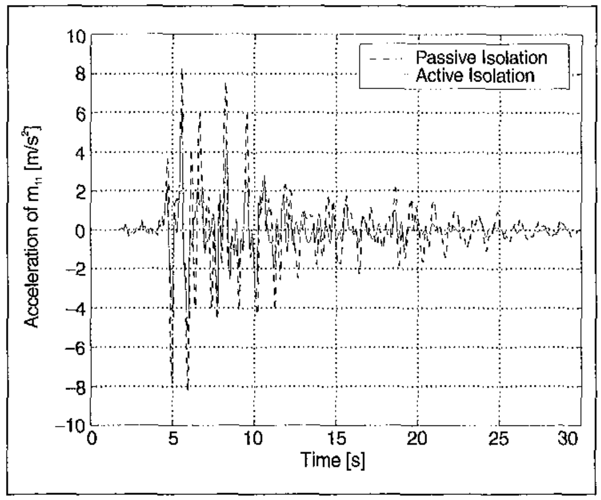

Fig. 12. Robust performance against nonlinearity.

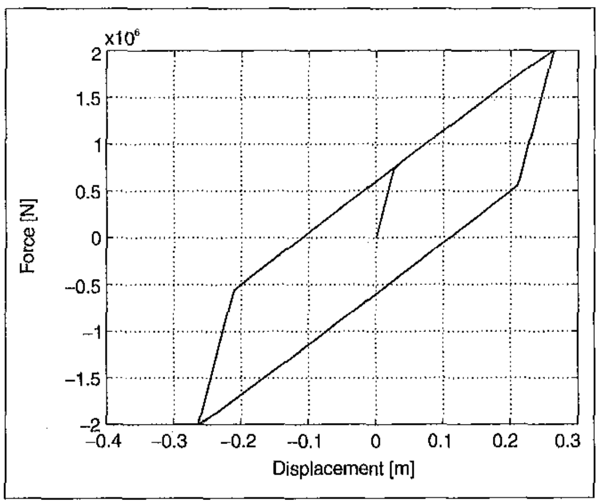

Fig. 11. Hysteresis of the passive isolator.

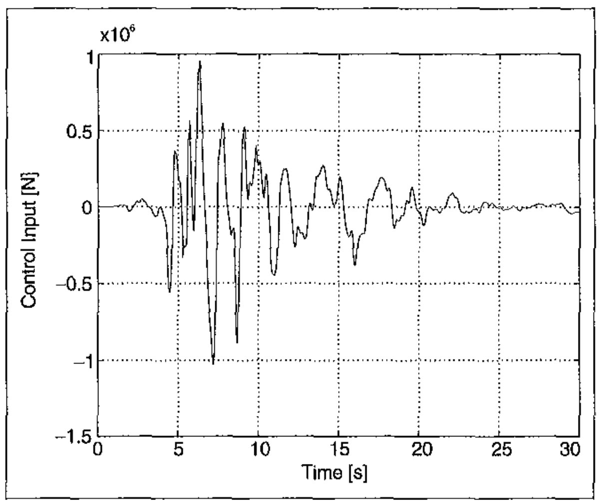

Fig. 13. Necessary input force u.

tions of the properties of the passive elements. Simulations taking into account the hysteresis of the passive elements examined robustness of the controller. The time-history responses to the Hyogoken-nanbu earthquake (with maximum amplitude of 8.18 m/s^2 reduced by 60%) are examined when the passive elements in parallel with the active device have a nonlinearity such as hysteresis. Fig. 11 shows the hysteresis loop caused by sinusoidal force. Fig. 12 indicates the acceleration of the top mass. The broken line indicates the response of the passive isolator with hysteresis, and the solid line indicates the response using the active isolator. From Fig. 12, it is clear that since the bilinear hysteresis absorbs the vibration energy, the robust controller designed for the active isolator does not worsen nominal control performance because the passive element exhibits bilinear hysteresis. Fig. 13 is the control input necessary for the active isolator. The maximum value of the input force is about 1000 kN and the corresponding maximum power is about 150 kW. These maximum values are about half of the necessary quantities for the active seismic isolator with linear passive elements. Hysteresis of the passive elements also contributes to reduction of energy consumption for the active seismic isolator.

Conclusions

This article discussed the design of a controller for an active vibration isolation system using feedback signals of the first-story acceleration. The design was based on μ-synthesis with controlled variables of (i) acceleration of the first story and (ii) the relative displacement between the first story and the second story, if necessary. We have demonstrated by simulations and experiments that the designed controller has sufficient vibration isolation performance and robust performance under the existence of bilinear hysteresis of the passive elements.

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