Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VIII)

SE-13

ACTIVE DYNAMIC VIBRATION ABSORBER FOR SEISMIC RESPONSE CONTROL

Hidekazu NISHIMURA , Kazuo YOSHIDA and Taro SHIMOGO

Department of Mechanical Engineering, Faculty of Science and Technology,
Keio University, Kohoku-ku, Yokohama, Japan

SUMMARY

For a vibration control of a multi-degree-of-freedom structure subjected to earthquake-like nonstationary random inputs, an active dynamic vibration absorber (active DVA) with a feedforward link is synthesized by the linear optimal stochastic control theory. By carrying out theoretical calculations and experiments the usefulness of the active DVA for seismic response control was examined. And it was demonstrated that the performance of the active DVA with a feedforward link is superior to a feedback link alone type.

INTRODUCTION

Tuned mass dampers which consist of an auxiliary mass, a spring and a damper have been installed to reduce the wind induced vibration of a structure such as a tall building. The tuned mass damper have been also examined to reduce the seismic response of a structure (Ref. 1). Active mass damper which is controlled by an active element such as a hydraulic actuator have recently been proposed and examined to overcome the performance of a tuned mass damper (Ref.2). In this study such an active mass damper is termed an active dynamic vibration absorber (active DVA).

Since a ground excitation is often possible to be detected, not only a state feedback control but also a feedforward control of input disturbance becomes able to be performed by using the optimal stochastic control theory. From these viewpoints, in this study, for a vibration control of a multi-degree-of-freedom structure subjected to earthquake-like nonstationary random inputs, an active DVA with a feedforward link is synthesized. The usefulness of the active DVA is examined by theoretical calculations and experiments.

STRUCTURAL MODEL

A 3-degree-of-freedom structural model is dealt with as a building-like structural model, on the top of which an active DVA is mounted, subjected to ground excitation as shown in Fig.1. The active DVA used in the experiment possesses such a mechanism that an auxiliary mass is driven by a linear motor. Using the following state variables including the current i in an armature coil of a linear motor,

$$x_r=[x_a \quad \dot{x}_a \quad x_s^T \quad \dot{x}_s^T \quad i]^T, \quad z_d=[\dot{z} \quad \ddot{z}]^T, \quad x_s=[x_{s1} \quad x_{s2} \quad x_{s3}]^T,$$

we have the following state equation of the mathematical model.

$$\dot{x}_r = A_r x_r + B_r u + D_r z_d, \tag{1}$$

$$A_r = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -(1/m_a+\Delta^T M_s^{-1}\Delta)k_a & -(1/m_a+\Delta^T M_s^{-1}\Delta)c_a & \Delta^T M_s^{-1}K_s & \Delta^T M_s^{-1}C_s & (1/m_a+\Delta^T M_s^{-1}\Delta)K_f \\ 0 & 0 & 0 & I & 0 \\ M_s^{-1}\Delta k_a & M_s^{-1}\Delta c_a & -M_s^{-1}K_s & -M_s^{-1}C_s & -M_s^{-1}\Delta K_f \\ 0 & -K_e/L_a & 0 & 0 & -R_a/L_a \end{bmatrix},$$

$$B_r^T = [0 \quad 1/L_a], \quad D_r^T = [0 \quad -e_s \quad 0],$$

where u is the voltage input to the linear motor, $\ddot{z}$ denotes the acceleration of the ground excitation, superscript T denotes a transpose of matrix, and

$x_s = y_s - e_s z$, $x_a = y_a - y_{s3}$, $e_s^T = [1\ 1\ 1]$, $\Delta^T = [0\ 0\ 1]$,
y_s : absolute displacement vector of primary structure;
M_s : mass matrix of primary structure;
K_s : stiffness matrix of primary structure;
C_s : damping matrix of primary structure;
L_a : inductance of linear motor; R_a : resistance of linear motor;
K_e : induced voltage constant; K_f : thrust constant.

The other constants and variables are shown in Fig.1.

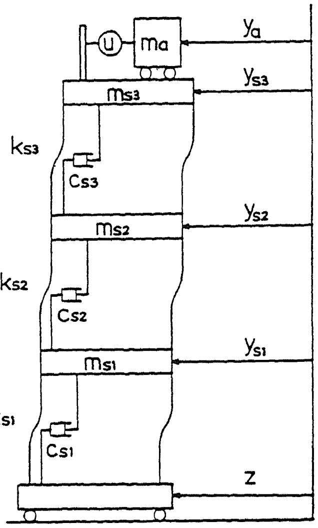

Fig.1 Model of a Primary Structure with an Active DVA

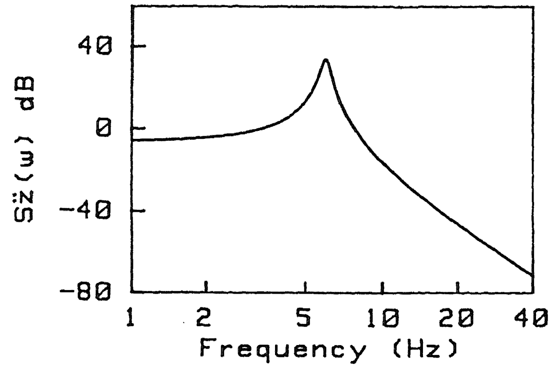

Fig.2 Power Spectral Density of the Input Disturbance

In order to consider the case of an seismic excitation, the input disturbance to the system is assumed to be a Gaussian amplitude modulated random process and to possess the following power spectral density function shown in Fig.2,

$$S_{\ddot{z}}(\omega) = S_w / (\omega^4 + 2\omega_d^2(2\zeta_d^2 - 1)\omega^2 + \omega_d^4). \tag{2}$$

Choosing the following state vector for the augmented system including disturbance states,

$x = [x_r^T \quad z_d^T]^T$,

we have the augmented state equation:

$$\dot{x} = Ax + Bu + DE_v w, \tag{3}$$

$$A = \begin{bmatrix} A_r & D_r \\ 0 & A_d \end{bmatrix}, \quad B = \begin{bmatrix} B_r \\ 0 \end{bmatrix}, \quad D = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad A_d = \begin{bmatrix} 0 & 1 \\ -\omega_d^2 & -2\omega_d\zeta_d \end{bmatrix}, \quad E_v = t/t_p \exp(1-t/t_p),$$

$$E[w(t)]=0, \quad E[w(t)w(\tau)]=2\pi S_w\delta(t-\tau)$$

where $E[\cdot]$ is a mathematical expectation and $\delta(t)$ is the Dirac's delta function.

OPTIMIZATION OF ACTIVE DVA

Criterion function The objective function is the mean squared relative displacement of the primary structure. Since there are practically constraints with respect to the relative displacement of the auxiliary mass and the input voltage to the actuator, these constraints have to be taken into consideration in the criterion function. The criterion function are described in the following quadratic form by using the state vector,

$$J(u) = E[x^TQx + ru^2], \quad Q = \begin{bmatrix} Q_{11} & 0 \\ 0 & 0 \end{bmatrix}, \quad Q_{11} = \left[\begin{array}{cc:c} q_a & 0 & \mathbf{0} \\ 0 & 0 & \\ \hdashline \mathbf{0} & & \mathbf{I} \end{array}\right]. \tag{4}$$

Optimal control law The optimal control law which minimizes the criterion function (4) is obtained as follows:

$$u(t) = F_b x_r + F_f z_d, \quad F_b = -B_r^T P_{11}/r, \quad F_f = -B_r^T P_{12}/r, \tag{5}$$

where the first term of right side is a feedback link of state variables of system, the second term is a feedforward link of input disturbance and P and P are obtained as the unique solution of the following matrix Riccati algebra equation:

$$\begin{aligned} &P_{11}A_r + A_r^T P_{11} + Q_{11} - P_{11}B_r B_r^T P_{11}/r = 0, \\ &P_{11}D_r + P_{12}A_d + A_d^T P_{12} - P_{11}B_r B_r^T P_{11}/r = 0. \end{aligned} \tag{6}$$

From above equations (5) and (6), it is seen that the feedforward link is determined by the characteristics of input disturbance to the system and the feedback link.

EXPERIMENTAL PROCEDURES

A photograph of the primary structure used in the experiment is shown in Fig.3. The active DVA is mounted on the 3rd story of the structure. The specifications of the primary structure and the active DVA are shown in table 1. The table 1 also includes the specification of input disturbance. Figure 4 is a schematic of the experimental apparatus showing the signal flow of the control system of an active DVA.

Since the controller consists of a discrete time controller using a digital computer, we apply the digital control theory to the design of controller. That is, the detected analog state vector $x(t)$ is converted to the digital state vector $x(k)$ in the sampling interval $T = 6$ ms and fed to a digital computer. In the computer, the calculation of discrete time controller is performed, and the control force $u(k)$ is fed to the linear motor through a D/A converter and a power amplifier.

In this study, a stationary random excitation and a nonstationary random excitation are performed. In the experiment of a stationary random excitation, the foundation of structure is excited by using a white noise which is generated from a FFT analyzer on the market. The frequency response function is also measured by the same FFT analyzer. In the experiment of a nonstationary random excitation an artificial earthquake wave form and past real earthquake wave forms i.e. N-S component and E-W component of EL. CENTRO are used. Since this wave form is not always reproduced on the foundation of the structure due to the influence of the dynamic characteristics of the shaker and the tested structure, it becomes necessary to control the shaker. The technique to control the shaker by compensating the input wave itself by digital signal processing using FFT method (Ref. 3) is used in this study. The section relating to the control of shaker are shown by the broken lines in the schematic of the experimental apparatus shown in Fig.4.

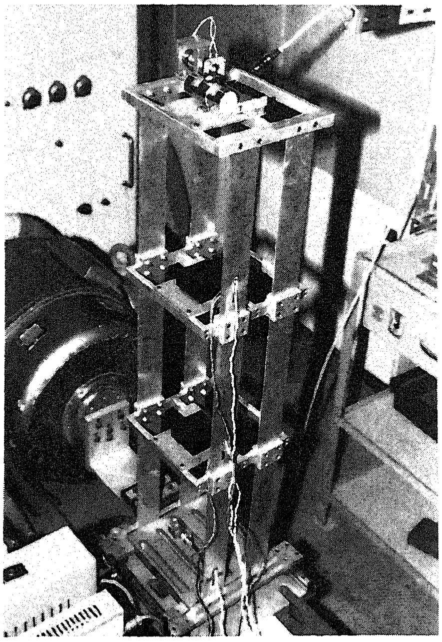

Fig.3 Photograph of the Experimental Apparatus

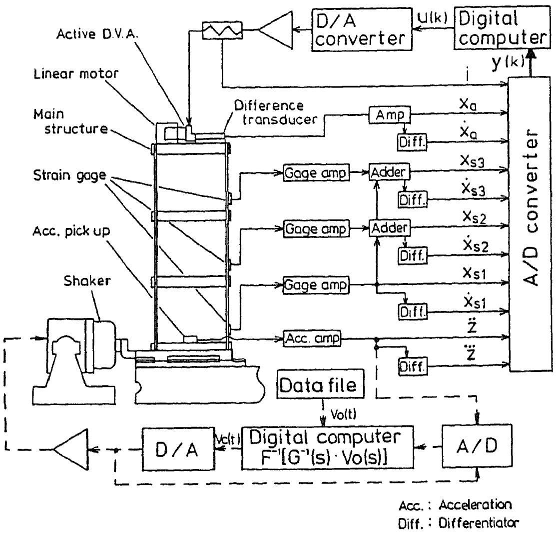

Fig.4 Schematic of the Experimental Apparatus

Table 1 Specifications of Primary Structure, Active DVA and Input Disturbance

primary structure	active DVA	input disturbance
m_{s1}=1.55 kg, m_{s2}=1.77 kg, m_{s3}=1.75 kg, c_{s1}=1.3 N•s/m, c_{s2}=0.3 N•s/m, c_{s3}=0.6 N•s/m $k_{s1}=k_{s2}=k_{s3}$=13000 N/m	m_a=0.123 kg, R_a=3.4 Ω, L_a=0.72 mH K_e=5.0 V•s/m, K_f=2.6 N/A	ω_d=38.3 rad/s ζ_d=0.05

EXPERIMENTAL RESULTS

Stationary random excitation In order to compare the feedback link type control with both the feedback and feedforward links type one, the theoretical calculation results of frequency response function ($x_{s3}/\ddot{z}$) are shown in Fig.5. Figure 5 also includes the frequency response function ($x_{s3}/\ddot{z}$) of the primary structure in the case of uncontrol. From this figure, it is seen that the feedback control can reduce the response in all modes of the structure. Because the resonance frequency of input disturbance is assumed to be equal to the natural frequency of 1st mode of the structure, the control performance of the feedback and feedforward links type is superior to the one of the feedback link type in 1st mode of the structure. Though in the other modes outside of frequency range of input disturbance the performance of feedback control is superior to the one of the control with feedforward link, the whole response of the structure is more effectively reduced by adding the feedforward link.

The experimental results of frequency response function of the structure with or without the active DVA are shown in Fig.6. The result in this figure is in agreement with the one in Fig.5, and accordingly it is verified that this method is useful for stationary random vibration control.

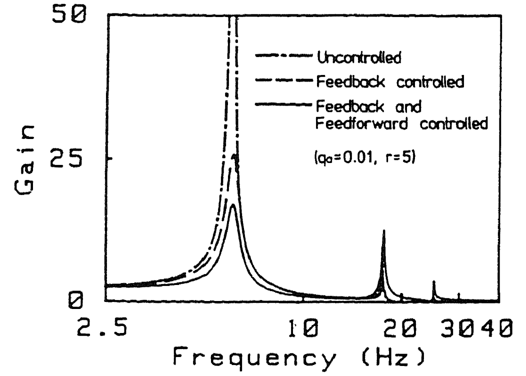

Fig.5 Theoretical Results of Frequency Response Function ($x_{s3}/\ddot{z}$)

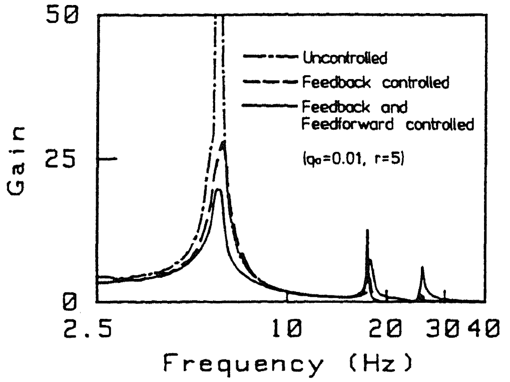

Fig.6 Experimental Results of Frequency Response Function ($x_{s3}/\ddot{z}$)

Nonstationary random excitation The control performances of feedback link type and both feedback and feedforward links type are investigated experimentally for the nonstationary random excitation. Figures 7, 8 and 9 correspond to the cases of EL. CENTRO (N-S), EL. CENTRO (E-W) and the artificial earthquake. In both figures, (a) shows the earthquake input, (b) shows the response (relative displacement) of the 3rd story of primary structure in the case of uncontrol, and (c) and (d) respectively show the responses of the 3rd story in the case of only feedback control and the feedback and feedforward control.

From these figures, it is seen that the active DVA by a feedback control is also useful for the vibration control to a seismic excitation. Furthermore, by adding the feedforward link to the control system, the control performance is improved.

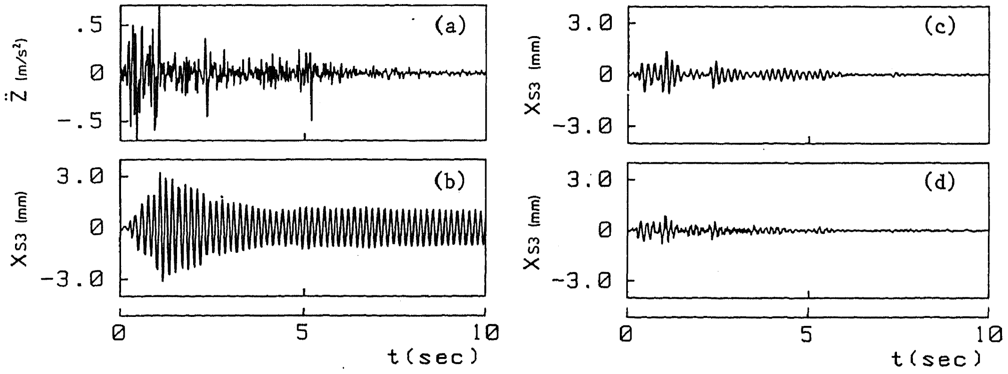

Fig.7 EL. CENTRO (N-S) Earthquake Wave Form $\ddot{z}$ and 3rd Story Response x_{s3} :
(a)Input; (b)Uncontrol; (c)Feedback Control; (d)Feedback and Feedforward Control

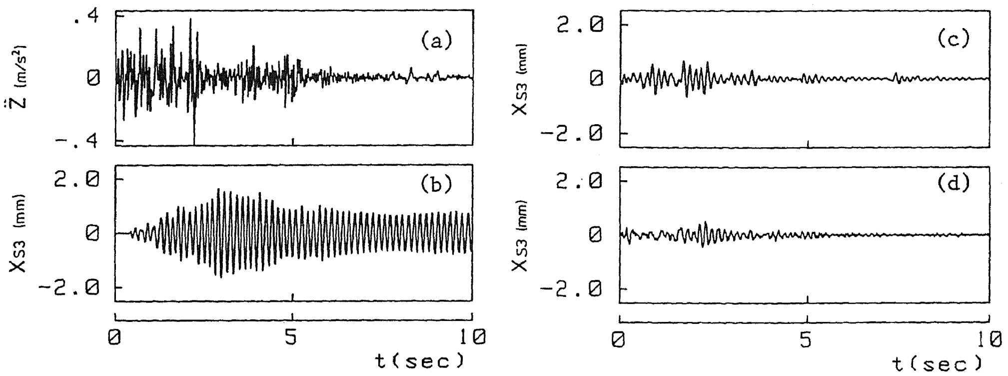

Fig.8 EL. CENTRO (E-W) Earthquake Wave Form $\ddot{z}$ and 3rd Story Response x_{S3} : (a)Input; (b)Uncontrol; (c)Feedback Control; (d)Feedback and Feedforward Control

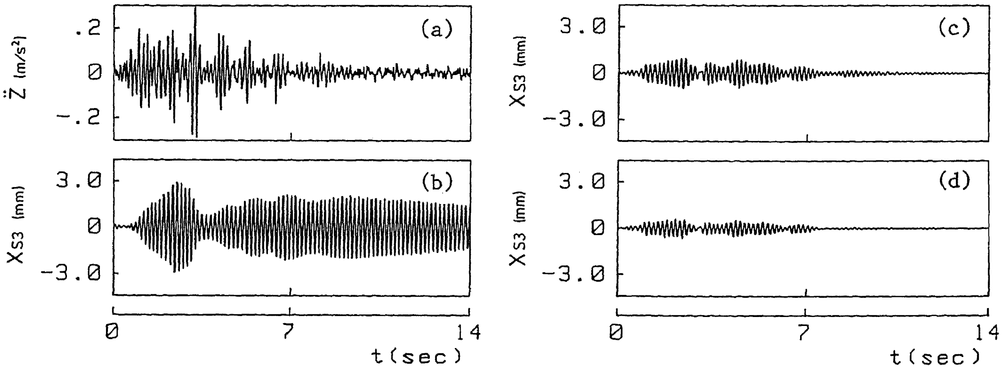

Fig.9 Artificial Earthquake Wave Form $\ddot{z}$ and 3rd Story Response x_{S3} : (a)Input; (b)Uncontrol; (c)Feedback Control; (d)Feedback and Feedforward Control

CONCLUSIONS

By theoretical calculations and experiments it was demonstrated that the active DVA by a feedback control is useful for the vibration control when a structure is subjected to not only a stationary random input but also a non-stationary random input such as a seismic excitation. Furthermore, it was shown that the performance of the active DVA with a feedforward link is superior to that of an feedback link alone type.

From the viewpoint of reliability it might be necessary to simplify a controller in practical use. In this case, a design of a controller using a reduced order model is conceivable, and we will propose an active DVA controlled by using a reduced order model with a feedforward link at a next opportunity.

REFERENCES

1. Chowdhury, A.H., Iwuchukwu, M.D. and Garske, J.J., "The Past and Future of Seismic Effectiveness of Tuned Mass Damper", Structural Control, (Ed. Leipholz, H.H.E.), MARTINUS NIJHOFF PUBLISHERS, 105-127, (1987)
2. Hrovat, D., Barak, P. and Rabins, M., "Semi-Active versus Passive or Active Tuned Mass Damper for Structural Control", ASCE, Vol.109, No.3, 691-705, (1983)
3. Yoshida, K., Shimogo, T. and Nishimura, H., "Optimal Control of Random Vibration by the Use of an Active Dynamic Vibration Absorber", JSME International Journal, Series III, Vol.31, No.2, 387-394, (1988)