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Active vibration control for high-rise buildings

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ABSTRACT: An active dynamic vibration absorber (DVA) driven by an AC servo motor through a ball screw is developed in this study. The facilities of this DVA are smaller than the usual ones controlled by a servo hydraulic actuator. The optimization of the controller is performed taking account of the dynamic characteristics of the active DVA driven by a speed control driver. By carrying out digital computer-controlled type tests and numerical calculations using a 4-story, 11-ton weight model frame structure, it is demonstrated that the active DVA, with the absorber's mass ratio to the structure only 0.5%, can reduce the response of every story, not only displacement but also acceleration, to 1/3 compared with uncontrol. As a result, the usefulness and feasibility of application of this active DVA in high-rise buildings have been made clear.

1. INTRODUCTION

An active vibration control system which actively controls vibrations in medium and small-scale earthquakes and under strong winds has been developed for the purpose of maintaining functional properties and improving residential conditions of high-rise buildings.

Among features of this system are included that, ① from the standpoints of saving space occupied by the apparatus and its accessory equipment, and effectiveness of multi-mode control, an active dynamic vibration absorber which drives added mass supported by linear bearings with an AC servo motor through a ball screw is utilized, and ② as the control technique, upon giving consideration to the dynamic characteristics of the AC servo motor[1), 2)], the probabilistic optimum control theory for a multi-degree-of-freedom vibration system has been employed.

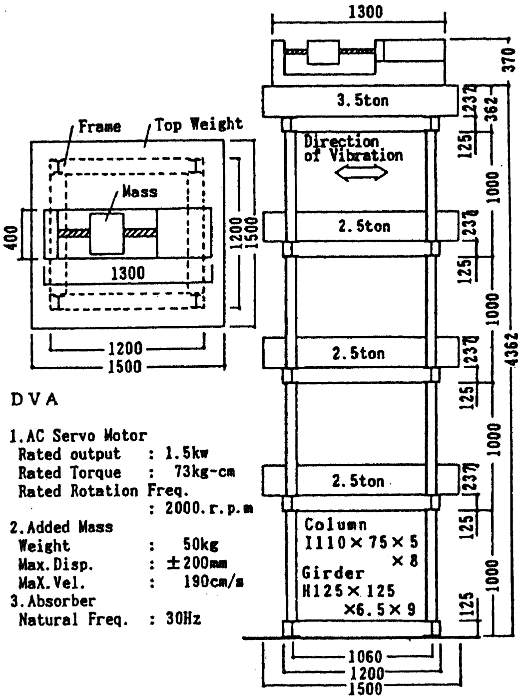
This paper gives an outline of the vibration control system and describes the results of vibration control experiments by the feedback system conducted using a model building.

2 EXPERIMENTATION MODEL

2.1 Specifications of experimentation model

The specifications of a 4-storied structure equipped with an active dynamic vibration absorber (DVA) at its top-most part and the DVA are shown in Fig. 1. and Photo. 1. The total weight of the main structure is approximately 11 ton and the mass of the active DVA 50 kg (mass ratio ≒ 0.5%).

The base of the structure is attached rigidly to a shaking table, and because of this, rocking occurs influenced by the rigidity of the shaking



DVA

1.AC Servo Motor
Rated output : 1.5kw
Rated Torque : 73kg-cm
Rated Rotation Freq. : 2000.r.p.m
2.Added Mass
Weight : 50kg
Max.Disp. : ±200mm
MaX.Vel. : 190cm/s
3.Absorber
Natural Freq. : 30Hz

Fig.1 Model structure and absorber setup table. When the degrees of freedom of rocking is included, the 4-storied structure has five degrees of freedom and the natural frequencies from primary to quinary are 1.86 Hz, 6.19Hz, 10.0 Hz, 13.1 Hz, and 27.3 Hz, respectively. The damping factor of the primary mode is approximately 0.5 %.

2.2 Dynamic characteristics of AC servo motor

A conceptional drawing of the composition of the active DVA used in these experiments is given in Fig.2. The AC servo motor used as the actuator has a rated output of 1.5 KW in view of balance of the dynamic vibration absorber mass and the control force required, and is driven by a driver which provides speed control by minor loop.

In this study, the frequency response of velocity ν of the DVA mass in relation to input voltage u to the speed control driver of the AC servo motor was experimentally investigated, and this was approximated by the following quadratic equation :

$$\frac{V(s)}{U(s)} = \frac{-\beta}{S^2 + \alpha_1 S + \alpha_2} \tag{1}$$

where,

$V(s) = L[\nu(t)]$, $U(s) = L[u(t)]$

provided that $L[\cdot]$: Laplace transform

Accordingly, the equation of motion of the active DVA including the speed control driver can be approximated as follows :

$$\dddot{x}_a(t) = -\alpha_1 \ddot{x}_a(t) - \alpha_2 \dot{x}_a(t) - \beta u(t) \tag{2}$$

provided that x_a is relative displacement of active dynamic vibration absorber mass.

2.3 Formulation of mechanical model

The mechanical model of this experiment is shown in Fig.3. With relative displacement vector of the structure $\boldsymbol{x}_s = \boldsymbol{y}_s - \mathbf{e} z$, and the relative displacement of the DVA as $x_a = y_a - \Delta^T \boldsymbol{y}_s$, the state form equation of this total system including the characteristics of the DVA will be as in Eq.(3), where a newly defined state vector expression as in Eq.(4) is considered.

$$\dot{\boldsymbol{x}}(t) = A\boldsymbol{x}(t) + B u(t) + D \ddot{z}(t) \tag{3}$$

Where, $\mathbf{e}^T = [\,1\ 1\ 1\ 1\ 0\,]$, $\Delta^T = [\,1\ 0\ 0\ 0\ 0\,]$

$$\boldsymbol{x}^T(t) = [\,x_a(t),\ \dot{x}_a(t),\ \ddot{x}_a(t),\ \boldsymbol{x}^T_s(t), \dot{\boldsymbol{x}}^T_s(t)\,] \tag{4}$$

where, $\boldsymbol{x}^T_s(t) = [\,x_4, x_3, x_2, x_1, \theta\,]$

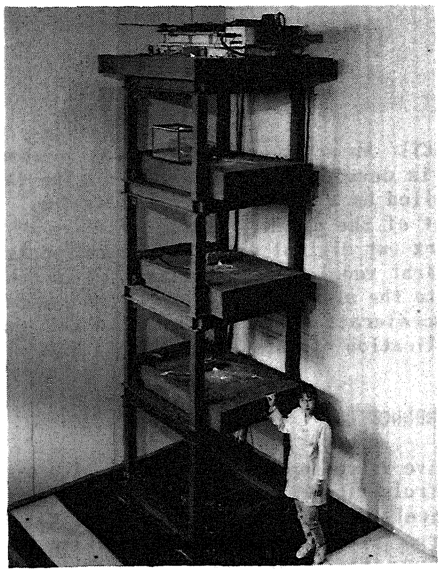


Photo.1 Experimentation model

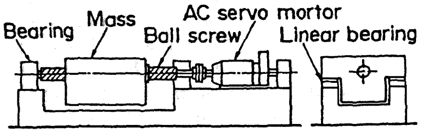


Fig.2 Schematic of active dynamic vibration absorber

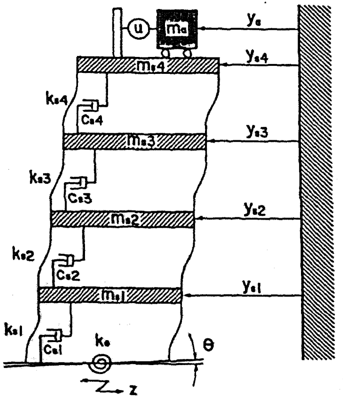


Fig.3 Model of primary structure

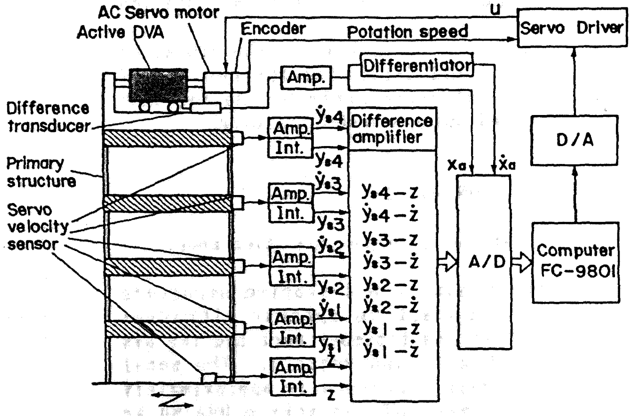


Fig.4 Schematic of control system

3 OPTIMIZATION OF ACTIVE DVA

With the relative displacement of the main structure made objective functions, and further, with the stroke of the DVA mass and input voltage to the AC servo motor as restrictive conditions, the quadratic form evaluation criterion may be expressed as the evaluation functions of the following equation:

Evaluation Function: Relative Displacement

$$J_d(u) = E\,[x^T Q\ x + r u^2] \qquad (5)$$

provided that, E[·] expresses the mathematical expectation. Where x is the state vector, u is the control vector, and Q, r, express weight coefficient matrices.

The optimum control law for minimizing the evaluation function equations (5), control force vector u may be given as follows by feedback gain vector F using the solution of the algebraic Riccati equation:

$$u(t) = F\,x(t) \qquad (6)$$

For realization of the optimum control laws (6), it will be necessary for feedback of all state quantities, but in this study, it was considered that the state quantity of rocking and the quantity of acceleration of the DVA mass would not be fed back, and control was made reduced-order by recalculating feedback gain based on the quasi-optimization method¹⁾ using output of feedback control proposed by Nishimura et al.

4 COMPOSITION OF VIBRATION CONTROL SYSTEM

The composition of the vibration control system is shown in Fig.4. This system is composed of various sensors, a dynamic vibration absorber, and a control panel governing the entire system, where a computer FC-9801 is accomodated inside.

The relative displacements of the structure from the foundation are determined by integrating the velocity signals obtained from velocimeters installed at the individual stories and the foundation, and transforming them into displacement signals and taking the differences. Relative velocities of the structure are similarly determined from velocity signals.

The relative displacement of the DVA mass is detected using a differential transducer, and its relative velocity is obtained passing this through a differential analyzer.

These detected quantities are analog-to-digital transformed at sampling period T = 5 ms and sent to the computer, and after operation of the control law in the computer, they are impressed on the AC servo motor through a digital-to-analog transducer and speed control driver. The rotating force of the AC servo motor is transmitted to a ball screw to cause the added mass supported by linear bearings to be horizontally displaced to produce the control force required for the control system.

5 VIBRATION CONTROL EXPERIMENTS BASED ON DISPLACEMENT EVALUATION FUNCTION

5.1 Experimentation method

As forced vibration experiments, sinusoidal excitation experiments to investigate the frequency amplification characteristics of response accelerations of the structure against input acceleration, and non-stationary random wave excitation experiments using El Centro NS seismic wave to investigatethe responses to seismic wave input were carried out.

The El Centro wave was applied in real time with the maximum value as approxiamtely 50 gal, and to eliminate the influences due to the dynamic characteristics of the shaking table and the structure, the waveform itself applied to the shaking table was compensated by digital signal treatment using high-speed Fourier transform.

In determination of weight coefficients Q and r, Q was made constant, and aiming for the damping factor of the foundamental vibration mode(h_1) becoming around approximately 15 %,the weight coefficient r (r = 2E-0.7) concerning control force was selected.

Hereafter, the uncontrol experiment and control experiment at r = 2E-0.7 will be referred to as CASE D.0 and CASE D.1, respectively.

Further, aiming for the above mentioned mode damping factor to be about 3 %, a control experiment with weight coefficient made r = 2E-0.6 and with control force made smaller will be referred to as CASE D.2.

5.2 Sinusoidal input experiment results

The acceleration frequency response amplification factor and the phase difference of the third story for the input acceleration in the sinusoidal input experiments are shown in Fig.5.

Cases of control by active DVA (CASE D.1, r = 2E-0.7) are indicated by ○ marks, and cases of uncontrol (CASE D.0) by △ marks.

It may be comprehended from Fig.5 that by exerting control, resonance has been suppressed well in the primary and secondary modes. With regard to the primary mode, whereas a response amplification of approximately 100 times had been indicated with uncontrol, this was held to approximately 4.0 times through control, while in the secondary mode, approximately 12 times was held to 1.0 time.

5.3 Seismic wave input experiment results

The results of non-stationary random wave excitation experiments using El Centro NS

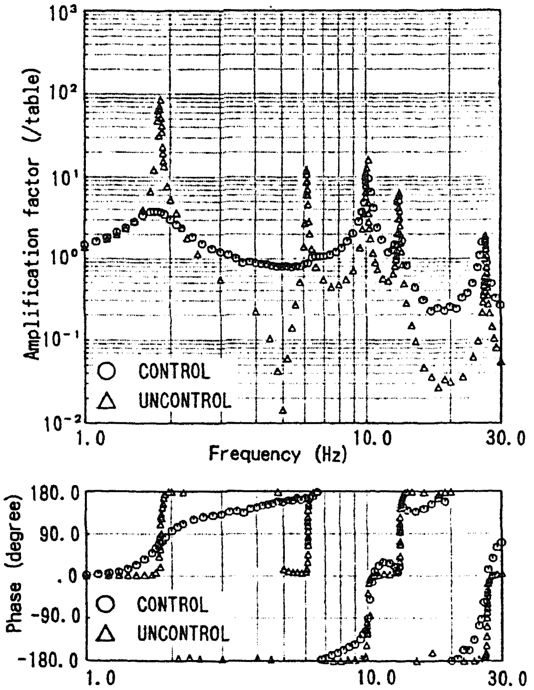


Fig.5 Frequency response functions of third story acceleration to input acceleration

waves are shown in Table 1 and Fig.6 and 7.

Table 1 gives comparisons of maximum response values and RMS responses in CASES D.0, D.1, and D.2, while Figs.6 and 7 respectively show the response waveforms at the third-story location and responses of the DVA mass in CASE D.0 and CASE D.1.

According to Table 1 and Figs.6 and 7, in spite of the DVA's mass ratio being low at 0.5%, large vibration control effects have been obtained on both acceleration and displacement responses of the various stories.

Further, since compensation of the input waveform was not sufficient, there is a slight difference in input between uncontrolled and controlled, but when numerical corrections are made based on frequency response functions under identical input conditions, the maximum response value in CASE D.1 will be approximately 1/4 in terms of displacement and approximately 1/3 in terms of acceleration compared with the uncontrol experiment of CASE D.0.

5.4 Simulation analysis results

The results of simulation analyses of uncontrol (CASE D.0) and control (CASE D.1) experiment are given in Table 2. In case of

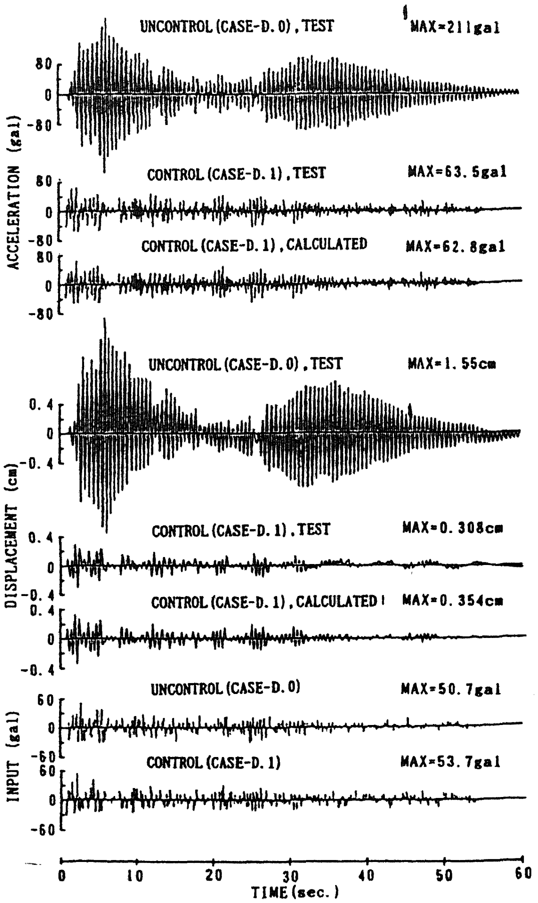


Fig.6 Test and calculated response waveformes of CASE D.0 and CASE D.1

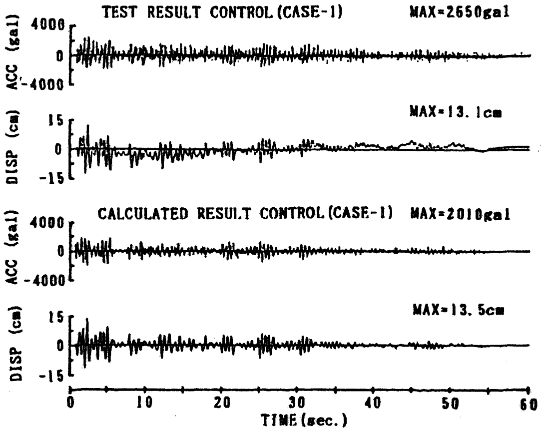


Fig.7 Test and calculated absorber's responses of CASE D.1

Table 1 Comparison of maximum and RMS responses (CASE-D.0, D.1 and D.2)

		CASE-D.0 $h_1 \fallingdotseq 0.5\%$		CASE-D.1 $h_1 \fallingdotseq 15.\%$		CASE-D.2 $h_1 \fallingdotseq 3.0\%$	
		Max.	rms	Max.	rms	Max.	rms
Response Disp. (cm)	4	1.95	0.271	0.383	0.047	0.958	0.077
	3	1.55	0.222	0.308	0.035	0.765	0.049
	2	1.06	0.134	0.203	0.026	0.548	0.038
	1	0.52	0.073	0.110	0.018	0.283	0.021
Response Acc. (gal)	4	235.	41.6	127.	10.9	183.	16.4
	3	211.	32.9	63.5	7.04	108.	9.85
	2	199.	20.6	53.8	5.04	121.	10.5
	1	120.	14.5	57.1	5.42	64.4	9.18
Input ACC (gal)		50.7	---	53.7	---	63.0	---

Table 2 Comparison between test and calucukated results

		CASE-D.0		CASE-D.1		
		Test	Calc.	Test	Calc.	Behaviof of
Response Disp. (cm)	4	1.95	1.75	0.383	0.407	Dynamic Vibration Absorber (Test) Disp. =13.1cm Acc. =2650.gal (Calculated) Disp. =13.5cm Acc. =2010.gal
	3	1.55	1.49	0.308	0.354	
	2	1.06	1.07	0.203	0.257	
	1	0.522	0.570	0.110	0.139	
Response Acc. (gal)	4	235.	251.	127.	85.3	
	3	211.	219.	63.5	62.8	
	2	199.	189.	53.8	50.5	
	1	120.	141.	57.1	44.0	
Input Acc. (gal)		50.7	50.7	53.7	53.7	

the two analyses, measured acceleration records on shaking table were used for input motions.

Simulation analysis results of the response waveforms for the third-story location and responses of the DVA in control experiment are shown together with experimental results in Fig.6 and 7, respectively.

According to Table 2 and Fig.6 and 7, the analytical and experimental results agree well with respect to both structure responses and DVA responses, and the appropriateness of the analysis technique is verified.

6 ENERGY CONSIDERATION

Using earthquake response analysis results of uncontrolled and controlled cases, energy balance such as input energy with vibration and absorption energies is discussed in this chapter. In the analyses, the experimentation structure model, the active DVA and original EL Centro NS wave were used, where only the maximum input acceleration value was reduced to 50 gal. The determination method of weight coefficients Q and r concerning control force was the same as before mentioned experiment one, and aiming for the damping factor of the fundamental vibration mode (h_1) becoming around 2, 5 and 15 %, three weight coefficients were selected.

Hereafter, following accumulated energy expressions are used.

E_I: Input energy to structure

E_V: Vibration energy of structure

E_H: Absorbed energy by structural damping

E_{AMD}: Absorbed energy by DVA

E_{CON}: Control energy of DVA

The caculated response results are shown in Fig.8, Table 3 and 4. Table 3 shows maximum response values of the structure and the DVA.

According to Table 3, response values are a little larger than the experimental ones, although the maximum input accelerations are almost the same. This is because of the power of original record is larger than the vibration table record's power at the experiment.

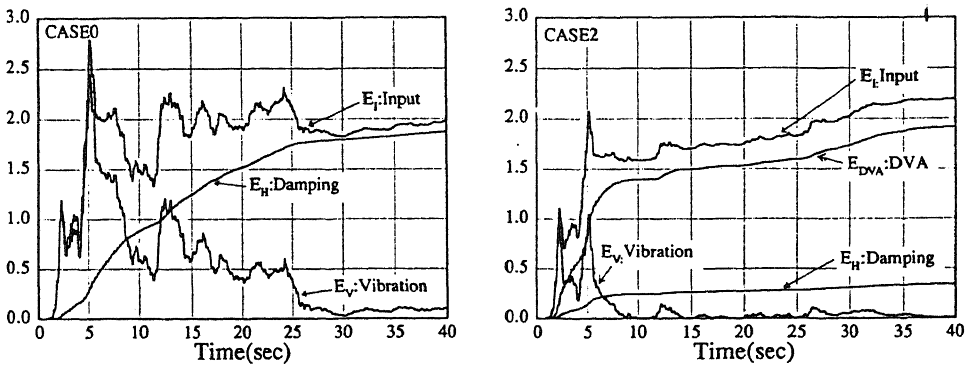
Fig.8 shows time history of the accumulated energies. From the Fig.8 the following equation can be obtained at every moment and as the control force and energy (E_{CON}) increased the vibration energy (E_V) and absorbed energy by damping (E_H) decrease.

$$E_V + E_H + E_{DVA} = E_I \qquad (7)$$

Maximum energy responses are shown in Table 4. From Table 4, although the active control system needs considerably large control energy, the duration time acting maximum power which defined accumulated control energy divided maximum control power is only a few seconds.

7 CONCLUSIONS

The method of optimum design of an active dynamic vibration absorber using an AC servo motor and a ball screw has been presented, along with which the effectiveness has been verified by means of vibration tests. In the past, mass ratios of 1 to 2 % were mainly used in studies of active dynamic vibration absorbers, but it has been ascertained that even with about 0.5 %, equivalent or better vibration control performance can be achieved if optimum control considering high-order modes is realized, and that analytical results can explain experimental results well and there is ample possibility for them to be applied to actual structures.



(CASE 0: Uncontrol) (CASE 2: Control)

Fig.8 Accumulated energy responses

Table 3 Maximum response values (El Centro NS 50gal input)

			Uncontrol	Control		
			CASE-0 $h_1 \fallingdotseq 0.5\%$	CASE-1 $h_1 \fallingdotseq 2.0\%$	CASE-2 $h_1 \fallingdotseq 5.0\%$	CASE-3 $h_1 \fallingdotseq 15.\%$
Structure	Displacement (cm)	4	2.309	1.859	1.512	1.066
		3	1.962	1.578	1.283	0.913
		2	1.394	1.127	0.913	0.656
		1	0.754	0.616	0.500	0.356
	Acceleration (gal)	4	308.6	253.9	210.6	160.3
		3	267.5	234.1	195.7	136.9
		2	217.9	194.3	159.1	107.3
		1	162.4	137.7	117.1	85.92
D V A	Displacement (cm)		0.	6.013	10.04	25.00
	Acceleration (gal)		0.	793.5	1225.	4188.
	Control Force (Kg)		0.	43.8	64.4	214.
	Control Power (Kg·cm/s)		0.	1923.	4178.	28550.
	(KW) = (KN·m/s)		0.	0.188	0.409	2.79

Table 4 Maximum energy responses

		Un-Control	Control		
		CASE-0 $h_1 \fallingdotseq 0.5\%$	CASE-1 $h_1 \fallingdotseq 2.0\%$	CASE-2 $h_1 \fallingdotseq 5.0\%$	CASE-3 $h_1 \fallingdotseq 15.\%$
Structure	E_I:Input to stru. (Kg·cm)	2790.	2412.	2194.	1944.
	E_V:Vibration of stru. (Kg·cm)	2443.	1584.	1046.	590.
	E_H:Absobed by daming (Kg·cm)	1875.	626.	342.	87.5
	E_{DVA}:Absobed by DVA (Kg·cm)	0	1761.	1919.	1914.
D V A	E_{CON}:Control energy (Kg·cm)	0	3833.	7803.	29740.
	(KN·m)	0	0.376	0.765	2.91
	Cont.energy/Cont.power (sec)	0	1.99	1.87	1.04

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