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DEVELOPMENT AND MODELING OF VARIABLE DAMPING UNIT FOR ACTIVE VARIABLE DAMPING SYSTEM

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ABSTRACT

An Active Variable Damping (AVD) System incorporating a variable damping unit (VDU) is proposed as an active seismic response control system. The VDU, which consists of a variable hydraulic damper and a damping force controller, can control a large damping force, although it consumes only a small amount of electric power and requires only a small amount of external energy. The characteristics of the VDU are affected by the control gains of the damping force controller, and it is important to regulate the gains to achieve maximum VDU performance under actual conditions. It is also important to incorporate the characteristics of the VDU for application analysis. This paper outlines the AVD System and the VDU, and the results of performance tests on a scale-model VDU. Loading conditions of the tests were determined from the results of an application analysis of a high-rise building, to evaluate the performance under actual conditions and to investigate the optimal control gains. The experimental model of the VDU showed stable characteristics under non-stationary conditions. In addition, an analytical model of the VDU, which can reflect the effect of control gain, is proposed. The appropriateness of this model is confirmed by numerical simulation.

KEYWORDS

Seismic response control, Velocity feedback, State-regulator theory, Hydraulic damper, Analytical model

INTRODUCTION

In recent years, there has been a lot of research and development on active seismic response control systems. Most of those developed to date, however, are intended for protection against moderate earthquakes and winds. Relatively, few are aimed at ensuring structural safety under large earthquakes. The authors have already demonstrated through application analysis the effectiveness of the Active Variable Damping (AVD) System as a response control system for high-rise buildings under large earthquakes(1)(2). The AVD System equipped with the Variable Damping Unit (VDU), which consists of a variable hydraulic damper and a damping force controller, can control a large damping force, although it consumes only a small amount of electric power and requires only a small amount of external energy. The authors have developed a scale-model VDU (maximum force is 20tf) and reported the results of basic performance tests(3). Furthermore, a seismic response control experiment by a large shaking table was performed on a three-story steel-frame structure with a mini-scale VDU (maximum force is 2tf)(4). The results of these experiments confirmed the response reduction effect, indicating its applicability to actual buildings. It was also clarified that the response characteristics of the VDU were affected by the control gains of the damping force controller.

Dynamic loading tests were conducted to evaluate the performance of the VDU under actual conditions and to investigate the optimal control gains of the damping force controller. The experimental model is a 20tf-scale VDU(3) modified for this experiment. The construction parts are replaced with those for an actual VDU, except for the cylinder diameter. The loading conditions, determined by application analysis for a high-rise building, are very close to actual conditions. Moreover, an analytical model of the VDU is constructed to prepare the response analysis program incorporating the effect of the characteristics of the VDU, The appropriateness of the proposed model is investigated by the simulation analysis.

This paper, (1) outlines the AVD System and the VDU (2) reports the results of newly conducted performance tests on the 20tf-scale VDU (3) and presents the analytical model of the VDU and the results of simulation analysis.

OUTLINE OF AVD SYSTEM

The AVD System consists of a control computer, velocity sensors and a VDU. To suppress the structural response, the damping force generated by the VDU approximates the optimal control force calculated by the control computer. Velocity feedback control based on the optimal regulator theory has been chosen from various available control rules through the past application analysis[1][2][4]. The composition of the system used in the shaking table experiment[4] shown in Fig.1 is basically the same as an actual high-rise building.

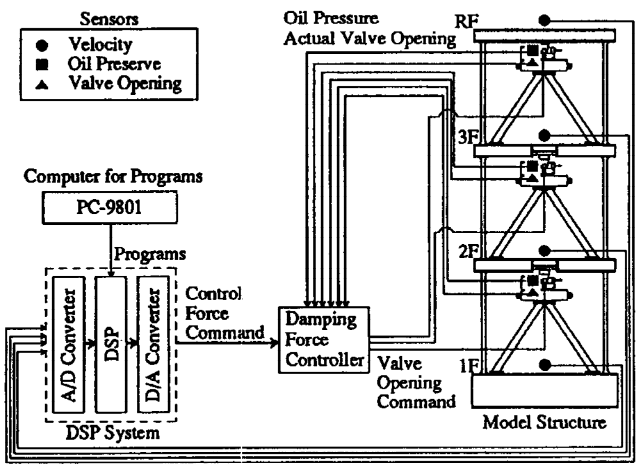


Fig.1 Control Setup for Shaking Table Experiment

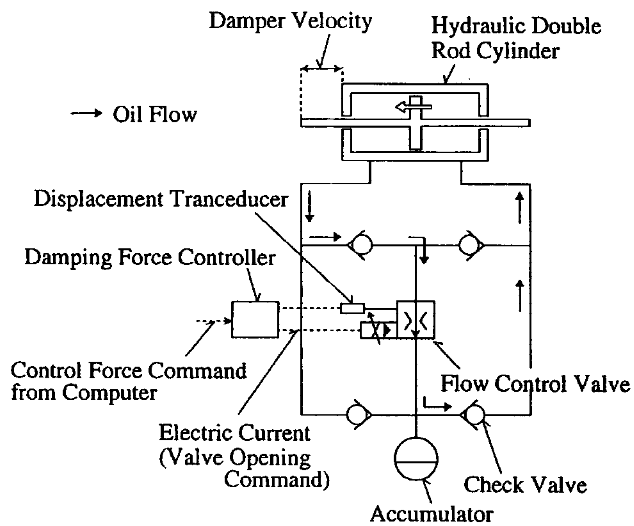


Fig.2 Hydraulic Circuit of Variable Hydraulic Damper

VARIABLE DAMPING UNIT (VDU)

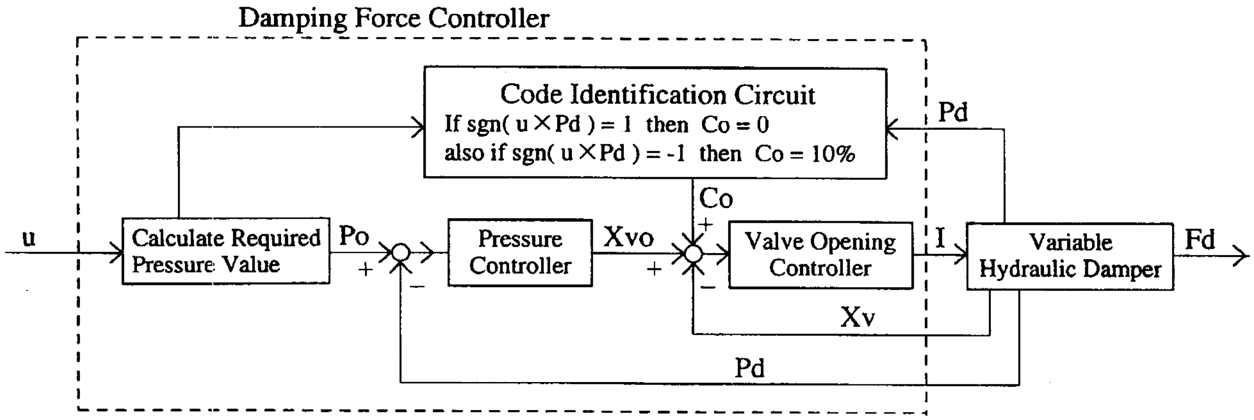
The VDU consists of a Variable Hydraulic Damper and a Damping Force Controller.

Variable Hydraulic Damper (VHD)

The hydraulic circuit of the VHD, which requires no external source of hydraulic pressure, is shown in Fig.2. It consists of a double-rod cylinder, a piston, a flow control valve for controlling the valve opening level, four check valves, and an accumulator. The hydraulic flow, produced by the piston motion, generates hydraulic resistance when the fluid passes through the flow control valve. This resistance works as the damping force between the piston and the cylinder. By controlling the opening level of the flow control valve, the damper can easily control a large damping force, which is the major feature of this damper. The four check valves keep the flow unidirectional at the flow control valve at all times. The accumulator supplements the momentary compression of the oil. Thus, the VHD can control damping forces of 100 to 200tf, while consuming only tens of watts of electric power.

Damping Force Controller (DFC)

A block diagram of the DFC is shown in Fig.3. It consists of a pressure controller, a valve opening controller and a code identification circuit. Since the valve opening level is controlled by the DFC based on the pressure difference between the two chambers of the cylinder, the influence of oil temperature and excitation frequency can be eliminated. The code identification circuit prevents a damping force from being generated when the directions for the control force command and the damper velocity is different.



u	: Control Force Command	Fd	: Damping Force
Po	: Pressure Command	Pd	: Pressure Difference between two chambers
Xvo	: Valve Opening Command	Xv	: Actual Valve Opening
I	: Electric Current	Co	: Output from Code Identification Circuit

Fig.3 Block Diagram of Damping Force Controller

The DFC has some control gain for regulating the characteristics of the VDU. The shaking table experiment showed that the structural response, especially the acceleration response, was greatly affected by the damping force overshoot. Therefore, regulating the control gain is very important to provide maximum VDU performance under actual condition. It is also important to incorporate the effect of the DFC control gain in modeling the VDU.

PERFORMANCE TEST ON REMODELED 20TF-SCALE VDU

Dynamic loading tests were conducted to evaluate the characteristics of the VDU and investigate its optimal gains under actual conditions.

Test Specimen

The experimental model is a 20tf-scale VDU(3) modified for this experiment. The construction parts are replaced with those for an actual VDU (maximum force is assumed to be 100tf) except for the cylinder diameter. To meet the conditions for pressure and flow rate around the valves, the loading force is set to 1/5 and the velocity between the piston and the cylinder is set to 5 times. The experimental model is specified in Table 1.

Table 1 Specifications of Experimental model of VDU

Cylinder Section	Outer Diameter	φ125mm
	Inner Diameter	φ80mm
	Piston Stroke	±100mm
	Piston Area	7250mm^2
	Rated Pressure	300kgf/cm^2
Flow Control Valve Section	Diameter	φ22mm
	Rated Pressure	315kgf/cm^2
	Power Consumption	30W
Check Valve Section	Diameter	φ32mm
	Rated Pressure	300kgf/cm^2

Experimental Method

The setup of the experimental model of the VDU and the hydraulic actuator are shown in Fig.4. The load is operated by the hydraulic actuator under displacement control. The test conditions are determined by a preliminary control response analysis on a model high-rise building incorporating the AVD System. The optimal control gain of the VDU is investigated first by the sinusoidal wave test, and the seismic response wave loading test is conducted to confirm the appropriateness of the gain fixed by the sinusoidal test.The model building is a 26-story steel-frame structure approximately 100m high, and the VDU is assumed to be installed on the 1st to 16th floor of the building, as shown in Fig.5. The 1st period is about 3.0sec. In the control response analysis, relative-velocity feedback and absolute-velocity feedback were adopted in the control method, and the values of feedback gain were determined by the parameter study. El-Centro(NS) and Hachinohe(NS) were selected for input waves.

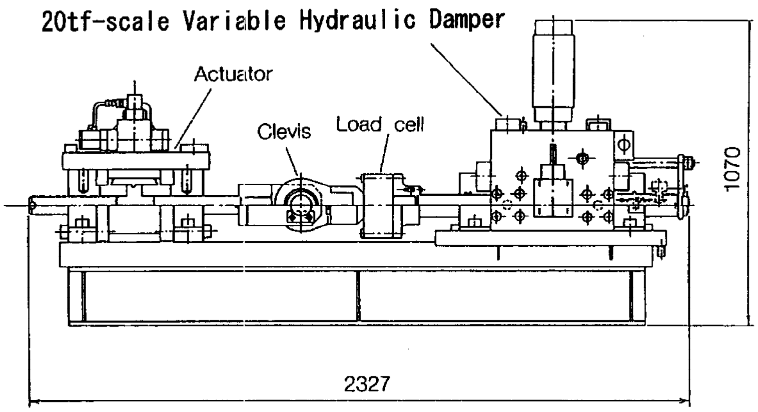


Fig.4 Experimental Setup

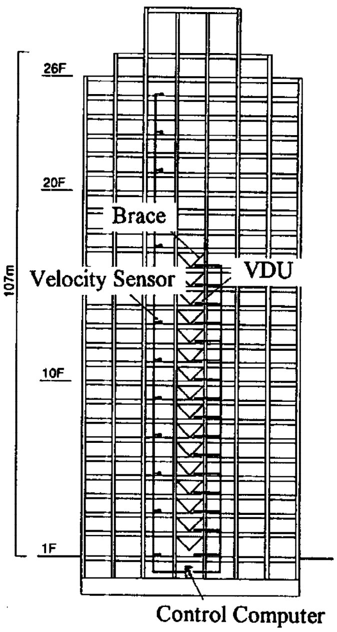


Fig.5 Model High-rise Building

Sinusoidal Wave Test

Fig.6 shows a typical input motion. Since the loading waves are set to imitate transient conditions under earthquakes, the optimal control gain can be investigated roughly by this experiment. The wave conditions are set as follows: (1) The amplitude level of displacement D, velocity V of the device and control force command U are estimated from the results of an application analysis on the model building. (2) An equivalent circular frequency ω is calculated as V/D. (3) A phase difference ϕ between d(t)(or v(t)) and u(t) is set to envelope the command-displacement relation of the results of the response analysis, as shown in Fig.7 as examples. Determined test conditions are shown in Table 2, and a typical test result with the finally fixed control gain is shown in Fig.8.

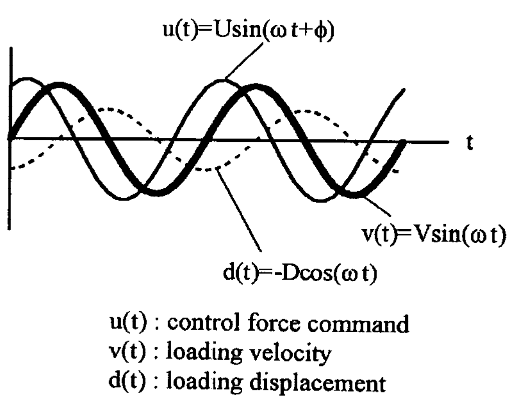


Fig.6 Input Motion

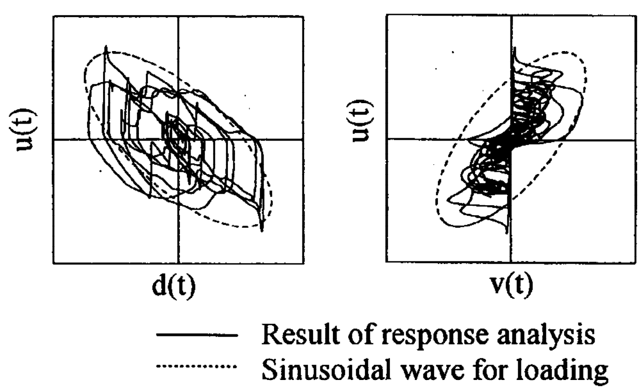
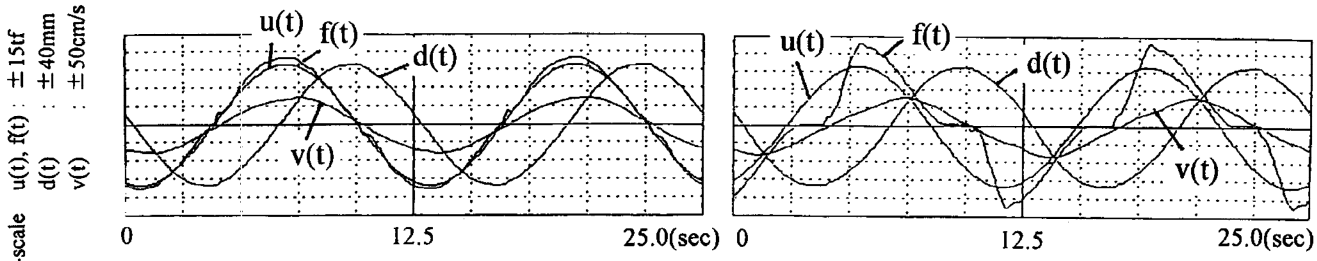


Fig.7 Manner of setting phase difference ϕ

Table 2 Test Conditions

	Circular Frequency ω	Displacement D	Control Force Command U	Phase Difference ϕ	Notes Equivalent Control Case
Case-1	1.26~6.3(rad/sec)	±0.5~80(mm)	±0.5~18(tf)	0(deg)	Relative-velocity Feedback
Case-2	1.26~6.3(rad/sec)	±0.5~80(mm)	±0.5~18(tf)	45(deg)	Absolute-velocity Feedback



(a) U=10tf,D=26.7mm,ω=5.0,ϕ=0deg (b) U=10tf,D=26.7mm,ω=5.0,ϕ=45deg

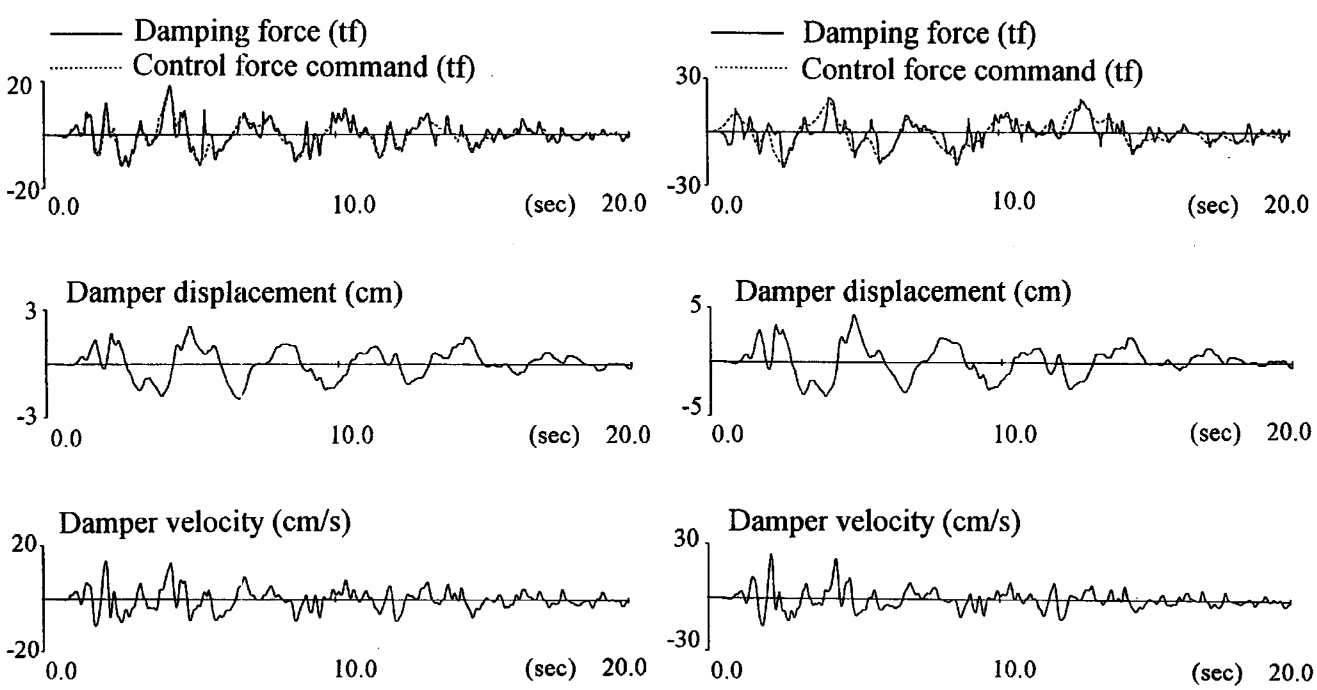
Fig.8 Sinusoidal Test Result

Seismic Response Wave Test

A seismic response wave test is conducted to confirm the appropriateness of the control gain fixed by the sinusoidal wave test under non-stationary conditions. Loading waves of displacement and control force command are just the results of an application analysis on a model high-rise building. The test conditions are:

Control Method :(1) Relative-velocity feedback (2) Absolute-velocity feedback
Input Waves :(1) El-Centro(NS) (2) Hachinohe(NS)
VDU Location :(1) 2nd story (2) 16th story

Some test results are shown in Fig.9 as examples. Compared with the case of relative-velocity feedback, the case of absolute-velocity feedback has severe transient conditions because of the phase difference between the control force command and device velocity. The experimental model, however, shows stable characteristics and generates a damping force which agrees well with the control force command in both cases. The results of the performance test confirm the following: (1) The method of regulating the control gains using a sinusoidal wave is effective.(2) Stable VDU characteristics are achieved under actual conditions.



(a) Relative-velocity Feedback (b) Absolute-velocity Feedback

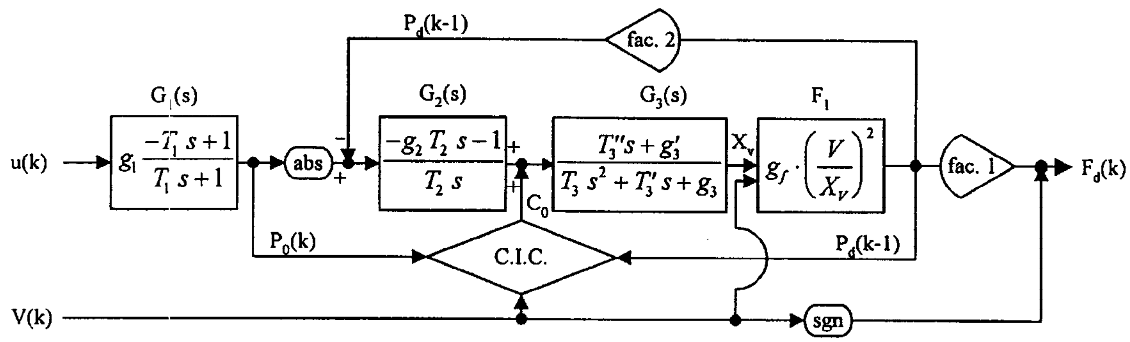
Fig.9 Results of Seismic Response Wave Test for El-Centro(NS) at 2nd Story

MODELING OF VDU

To incorporate the effect of the characteristics of the VDU, its analytical model is constructed as shown in Fig.10. It consists of the 1st order lag element which represents the characteristics of the flow control valve, and transfer functions for controllers and the code identification circuits. The damping force Fd is calculated with this model using control force command u and damper velocity v. The contents of each element are:

$G_1(s)$: calculation of required pressure value
$G_2(s)$: 1st order transfer function for pressure controller
$G_3(s)$: 2nd order transfer function for valve opening controller and flow control valve
F_1 : calculation of pressure difference between two chambers by orifice model

The coefficients of each transfer function can be calculated from the values of the control gain of the DFC, and the cylinder diameter is also used as a parameter. Therefore, the characteristics of any VDU with the same composition, can be simulated by changing the coefficients.



u(k) :Control Force Command of k step
V(k) :Damper Velocity of k step
$F_d(k)$:Damping Force of k step

C.I.C. = Code Identification Circuit
If $sgn(P_0(k) x P_d(k-1))=1$ then $C_0=0$
also if $sgn(P_0(k) x P_d(k-1))=-1$ then C_0=fac. 3

Fig.10 Block Diagram of Analytical Model of VDU

SIMULATION ANALYSES

Simulation of Seismic Response Wave Test on 20tf VDU

A Simulation analysis of device test on 20tf VDU is conducted to confirm the appropriateness of the proposed analytical model of the VDU. In this analysis, a damping force is calculated with the analytical model using the displacement and control force command of the device. The waves of the experimental results are used in this analysis, and the experimental conditions for simulation are the same as for Fig.9. The parameters for the analytical model are shown in Table 3. The time histories of the damping force are shown in Fig.11. It is confirmed that the proposed analytical model represents the characteristics of the VDU under non-stationary conditions.

Table 3 Parameters of 20tf-scale VDU

G1(s)	T1	1.00E-08
	g1	0.276
G2(s)	T2	0.12
	g2	0.59
G3(s)	T3	2.64E-04
	T3'	0.3239
	T3"	0.023
	g3	3.73
	g3'	2.73
F1	gf	0.37
fac1		0.0725
fac2		0.02
fac3		1.5

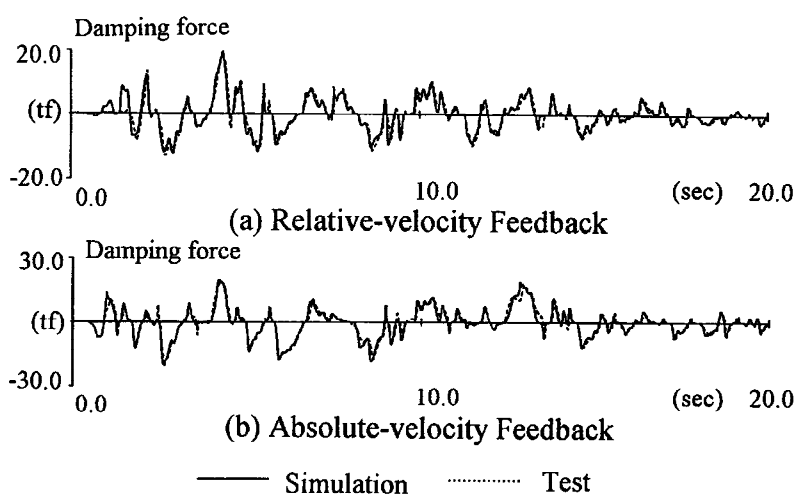


Fig.11 Simulation of Seismic Response Wave Test for El-Centro(NS) at 2nd story

Simulation of shaking Table Experiment

A simulation analysis of the shaking table experiment(4) is conducted using the response analysis program installed with the analytical model of the VDU. In this experiment, relative-velocity feedback was adopted in the control method, and input waves were chosen as shown in Table 4. The analytical model of the 3-story model structure is shown in Fig.12. The parameters for the analytical model of the 2tf-scale VDU is shown in Table 5. The simulation results are compared with the experimental results under El-Centro(NS) at r(weighting coefficient)=700 and r=200(4). The time histories for the top response of the model structure are shown in Fig.13 and the damping force-displacement hysteresis for the VDU installed in 1st story are given in Fig.14. The control force command is large when r=200, making it difficult for the damping force to keep up with the command. Simulation results, however, show good agreement with the test results in both cases. Thus, it is confirmed that the proposed analytical method of the AVD System with the VDU is appropriate.

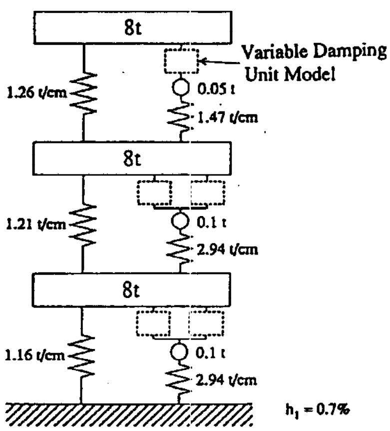


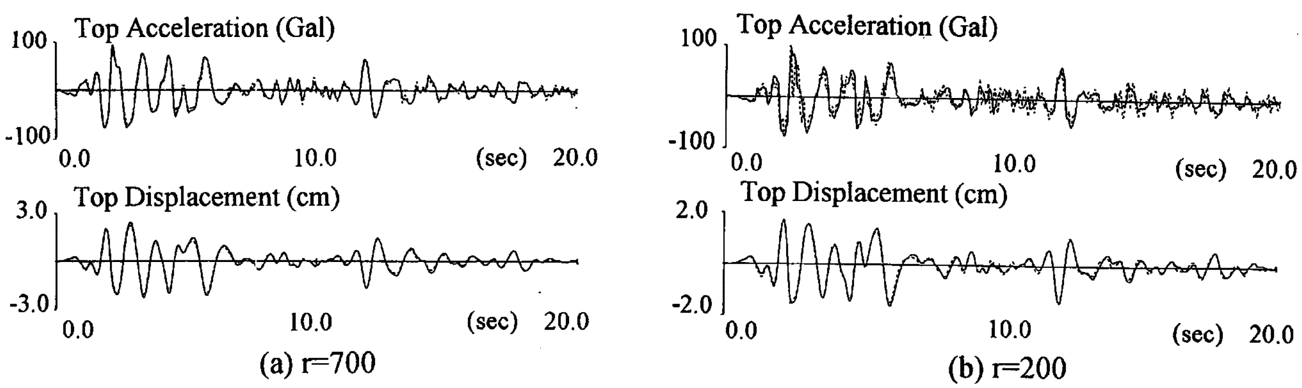
Fig.12 Analytical Model of Model Structure for Shaking Table Experiment

Table 4 Input Seismic Waves

	Max.Acc (Gal)	Duration (sec)
El-Centro (1940) NS	120	20
Taft (1952) EW	150	20
Kushiro (1993) NS	125	30
Sendai (1978) NS	120	20
Hachinohe (1968) EW	35	30

Table 5 Parameters of 2tf-scale VDU

G1(s)	T1	0.02
	g1	4.42
G2(s)	T2	0.17
	g2	0.06
G3(s)	T3	1.63E-03
	T3'	0.7845
	T3"	0.41
	g3	3.3
	g3'	2.3
F1	gf	0.0527
fac1		0.022
fac2		0.1
fac3		1



—— Simulation .... Experiment

Fig.13 Simulation Results of Top Response of Model Structure for El-Centro(NS)

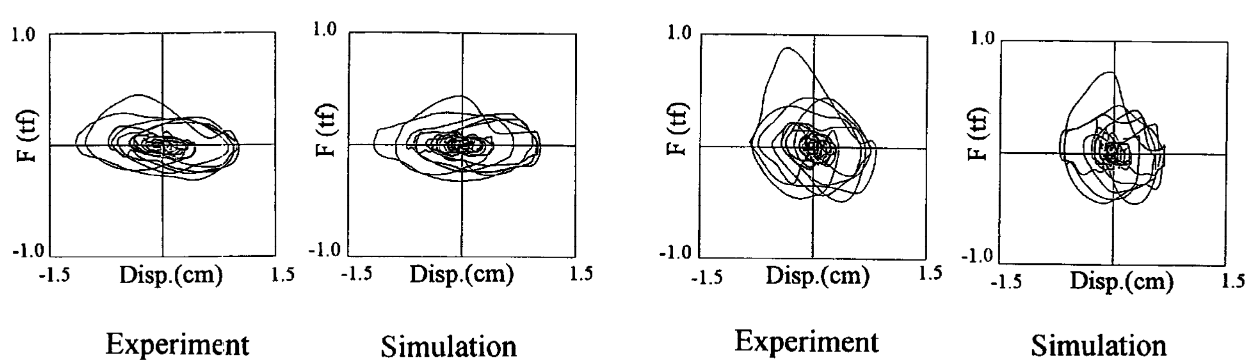


Fig.14 Damping Force-Displacement Hysteresis of 1st Story

CONCLUSION

The concluding remarks of this study are as follows:
(1) Development of the VDU
Performance tests were conducted on the 20tf scale VDU model. The experimental model, whose control gains were determined previously by the sinusoidal wave test, showed stable characteristics and generated a damping force which agrees well with the control force command under earthquake conditions. The construction parts and mechanism of the experimental model were the same as those of the actual VDU except for the cylinder diameter, and the loading conditions were set to meet the conditions for pressure and flow rate around the valve with those of the actual VDU. With the results of the performance tests, the actual VDU is expected to show stable performance under actual conditions.
(2) Modeling of the VDU
An analytical model of the VDU which can reflect the effect of control gains of the damping force controller was developed. The results of simulation analyses of the performance tests and the shaking table experiment, agreed well with the experimental results. Thus, it is confirmed that the proposed analytical method of the AVD System with the VDU is appropriate.
(3) In these circumstances, it is considered that the fundamental study for development of the VDU was completed. An analysis program, incorporating the response characteristics of the VDU, was prepared for more detailed application study for actual buildings.

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