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# A design method and development of damping amplifier system for passive response-controlled structure

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ABSTRACT: In order to increase building safety and reduce occupant discomfort under earthquake motions or wind forces, there is increasing interest in the development of response control systems.

This paper describes the design of a passive damping system which, using a simple lever-based mechanism, amplifies the damping effect on structures.

To investigate the effectiveness of this system, a fundamental test was carried out. The test used a 3-story steel-frame model on a shaking table to determine the response characteristics of a structure fitted with this system. This test demonstrated that the response of the structure was significantly reduced.

Dynamic analyses were carried out on a 10-story steel structure to compare its behavior with and without the system under seismic forces. Results show that if the damping coefficient of the structure is tuned to 0.2 using the system, the maximum response displacements and accelerations are reduced by up to about 40% and 20% respectively. Similarly, the maximum base shear force on the structure is also reduced by about 30%, thus allowing structural members to be reduced in size.

To determine the most efficient damping level for a given building, a sample structure fitted with the system was analyzed by using a Maxwell model, from which response results obtained for various levels of assumed damping.

In conclusion, it is evident that this damping amplifier system offers a practical and cost effective solution to the response control of buildings subject to seismic and wind forces.

## 1. INTRODUCTION

Buildings suffer from vibration as a result of external dynamic disturbances such as seismic or wind forces. Response-controlled systems have been proposed and investigated and some have been put to practical effect.

Those systems installed in buildings to control vibration can be roughly classified as passive types, in which the damping effect is obtained without supplying energy to the system, and active types, in which energy is supplied in the form of an external force to control the vibration. While the active type has the advantage that it can cope in a more flexible way to unforeseen external disturbances such as earthquake motions, many problems need to be solved before putting such a system into practical use. These include the time lag arising in the feedback system, the extra energy that has to be input from outside and the higher initial cost, also running cost. With regard to the passive type, although the response of the buildings depends on the external disturbance, one advantage is that a significant effect can be expected using a relatively simple system.

This paper summarizes the results of experiments and analyses on the effectiveness of a passive response-controlled system in which a large damping effect is achieved by multipling the damping resistance using the lever principle.

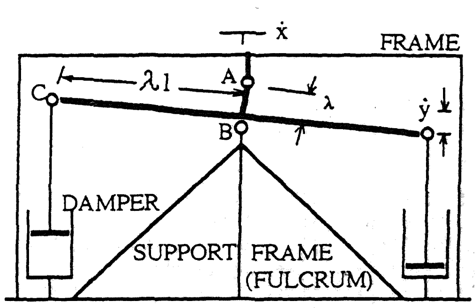



Fig. 1 Schematic Illustration of System

## 2. OUTLINE OF RESPONSE-CONTROLLED SYSTEM

Fig. 1 is a conceptual outline of the damping amplifier system. The system is designed to increase the small damping resistance of the building by using the principle of the lever. The system comprises an inverted T-shaped lever with supporting framework and a pair of dampers.

Defining the length ratio of the lever arms as $\lambda$ ($\lambda$=BC / AB : Fig. 1), a horizontal story deflection x is converted to the dampers as an up-and-down movement y, which is $\lambda$ times larger due to the action of the lever ($y = \lambda \cdot x$, $\dot{y} = \lambda \cdot \dot{x}$ ).

If the damping coefficient for each damper is $C_y$, its resultant force is $C_y \cdot \dot{y} = C_y \cdot \lambda \cdot \dot{x}$. For equilibrium, the equivalent damping coefficient at point A, $C_x$ is given by $C_x \cdot \dot{x} = 2\lambda C_y \cdot \dot{y}$ That is,

$$C_x = 2\lambda^2 \cdot C_y$$

In other words, $C_x$ is amplified by $2\lambda^2$ times $C_y$.

## 3. SHAKING TABLE TESTS OF MODEL BUILIDNG

To check the vibration characteristics of a structure fitted with this damping amplifier system, a shaking table test was performed using a structural model(Photo.1).

Fig. 2 shows the tested damping resistance amplifier system, Fig. 3 a rough sketch of the structural model. The lever length ratio, $\lambda$, was made adjustable by changing the pivot position, i.e. the length of A-B in Fig. 1. The dampers used in this system were of a fluid-filled type, with one attached to each end of the lever. The steel structural frame consisted of three-story in a three-dimensional layout with a bay. Each story was fitted with the damping system as shown in Fig. 2.

Fig. 4 shows the frequency response curve resulting from a uni-directional sine wave step sweep excitation in the horizontal direction.

This figure shows that the primary response ratio of the top of the frame when excited by the sine wave was reduced to about 1/10 by installing the damping system, and the secondary and tertiary peaks almost disappeared. Thus there is a tendency for not only the primary, but also higher orders to be controlled.

Fig. 5 shows the response at the top of the structural model during a seismic wave excitation and Table 1 is a comparison of maximum response values. The results confirm that the maximum response acceleration was reduced to about 1/2 of that in a model without the system.

Fig. 6 is a comparison of acceleration response as calculated in a simulation. A two-dimensional column and beam model including damping resistance was also analyzed.

The analysis model of the system is shown in Fig. 7, and the damping force was modeled by using the result of element test ( refer to REFERENCE ). Measured and simulated results correlate well.

## 4. SEISMIC RESPONSE OF STRUCTURE WITH DAMPING SYSTEM

### 4.1 Analysis model

Seismic responses were analyzed on model frames representing a 10-story steel building(Photo 2) with the damping devices fitted and on a typical rigid frame structure without the devices. Effects of the system were examined by comparison. Fig.8 shows a typical floor plan. The damping characteristics of the damper were designed to be proportional to the rigidity of 4th story. In other words, assuming that $C_i = \alpha \cdot K_4$ and the constant of proportionality $\alpha = 2h/\omega_0$.

The response was compared in the two models. For the seismic wave, EL CENTRO 1940 (NS component) and TAFT 1952 (EW component) were used as the example and the maximum acceleration was set up at 256 gal and 248gal respectively (25 cm/s: velocity).

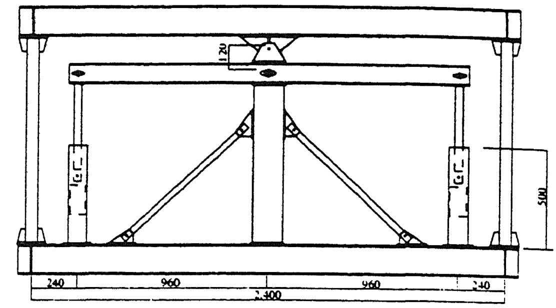



Fig. 2 Test Specimen of Damping Resistance Amplifier System

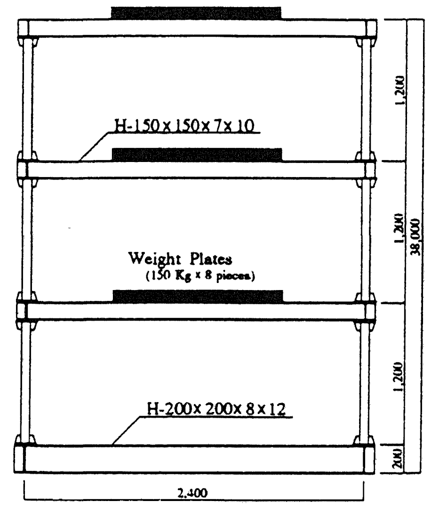



Fig. 3 Structure Model (shaking table test)

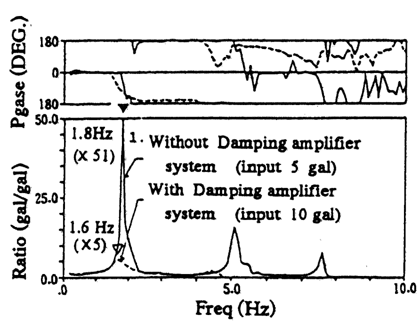



Fig. 4 Frequency Response at the Top of the Model

A coefficient of damping was assumed for each story, so the damping was additive, and cases of 5%, 10%, 20%, 30%, 40% and 50% damping were analyzed. An inherent damping of the building was assumed to be proportional to the rigidity of each story [ $C_0 = 0.02 \cdot (2K/\omega_0)$ ].

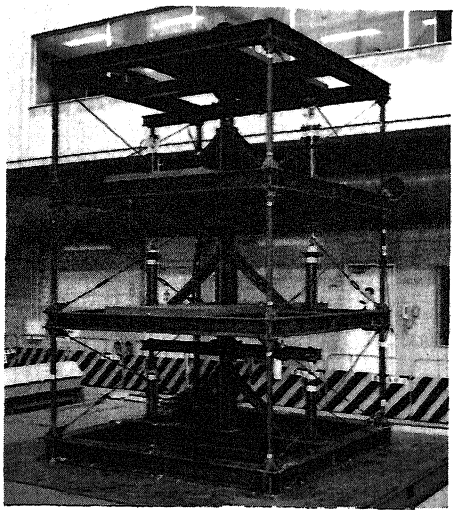


Photo. 1 Test Specimen on shaking table

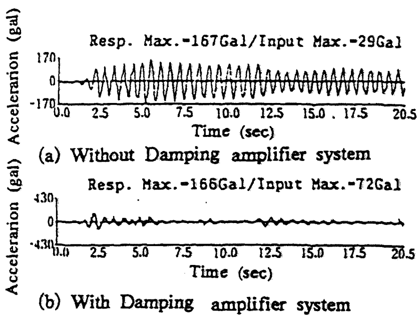



Fig. 5 Response Acceleration at the Top of the Model

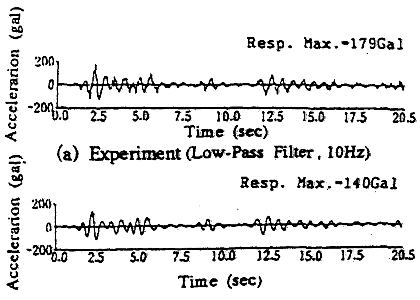



Fig. 6 Comparisons of Experimental Results and Simulated Results for Response Acceleration of Structure Model

Fig. 9 shows the analysis model in which $\lambda$=4.5. Fig. 10 shows a detail of the damping system.

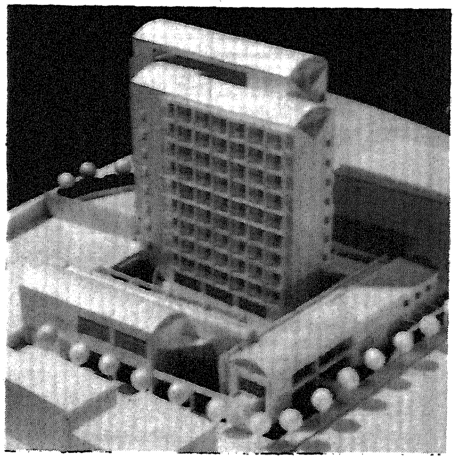


Photo.2 Analysis Building

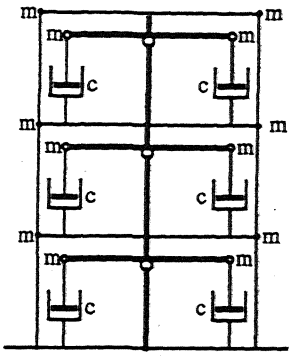



Fig. 7 Analysis Model for 3-story Building

Table. 1 Maximum Response Values

| Type | Maximum Response (gal) | EL CENTRO 1940 NS input | | | HACHINOHE 1968 NS input | |
|---|---|---|---|---|---|---|
| | | 10gal | 30gal | 80gal | 30gal | 80gal |
| Without | Top Acc. | 69 | 165 | | 128 | |
| | (Top / Table) | (4.9) | (5.7) | | (4.6) | |
| | 3rd Fl. Acc. | 56 | 137 | | 107 | |
| | 2nd Fl. Acc. | 43 | 97 | | 67 | |
| | Table Acc. | 14 | 29 | | 28 | |
| With | Top Acc. | 35 | 96 | 165[179] | 70 | 152[150] |
| | (Top / Table) | (2.7) | (3.5) | (2.2) | (2.3) | (2.0) |
| | 3rd Fl. Acc. | 34 | 112 | 278[128] | 76 | 242[141] |
| | 2nd Fl. Acc. | 37 | 96 | 155[104] | 95 | 145[112] |
| | Table Acc. | 13 | 27 | 74 | 31 | 77 |
| | Damper Load (kg) | 3 | 11 | 25 | 6 | 19 |
| | Damper Disp(mm) | 1.3 | 15.4 | 41.8 | 8.9 | 33.0 |

4.2 Analysis results

Figs. 11(a)(b), 12(a)(b) and 13(a)(b) show the response of the story due to the difference in additional damping, and Figs. 11(c), 12(c) and 13(c) show the relationship between additive damping with the response at 2nd, 6th and roof level.

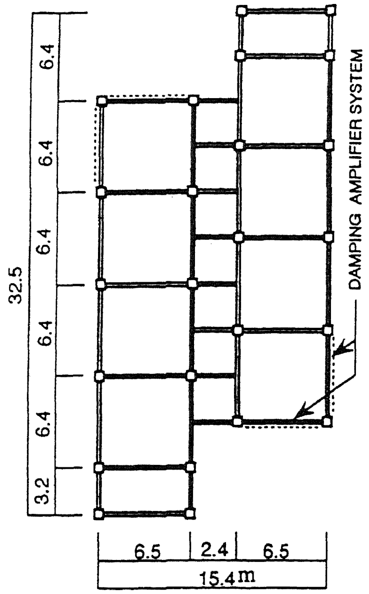



Fig. 8 Plan of Analysis Building

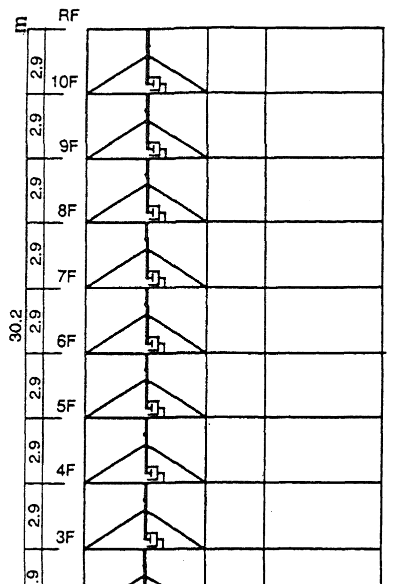



Fig. 9 Frame Model of Analysis Building

Response displacement at the top fell to about 60% when additive damping coefficient was 20% and the response fell to a minimum point when additive damping

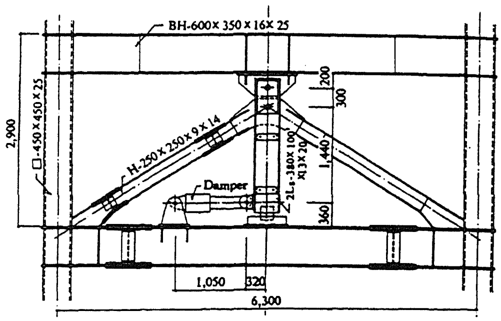



Fig. 10 Detail of The Damping System

coefficient was around 20 to 30% (Figs. 11). The acceleration at the top also decreased to about 70% for additive damping coefficient of 20%, a similar change to that seen in displacement (Figs. 12). However, as additive damping was increased to 50%, the responses no longer decreased.

As can be seen from Figs. 13, the shear force distribution in the story followed the same tendency as the acceleration distribution.

## 5. A DESIGN METHOD OF THE BUILDING WITH THE DAMPING SYSTEM

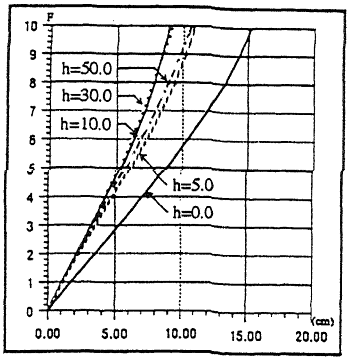
If a damping effect is applied to buildings using this damping system, a very important question of design is how to determine the optimum damping. Although response displacement, velocity, acceleration, and rate of change of acceleration are available as indices, the fact remains that it is not clearly known which is the best index for the representation of vibration level and which factors correlate most closely with human perceptions of vibrations.

Considering building vibration from the viewpoint of earthquake resistant design, deformation and shear force would be the major indexes; however, it is very difficult to determine at what level of criteria building safety should be taken into account. Leaving this question for next study, we here consider a method for determining the most efficient condition between damping and rigidity.

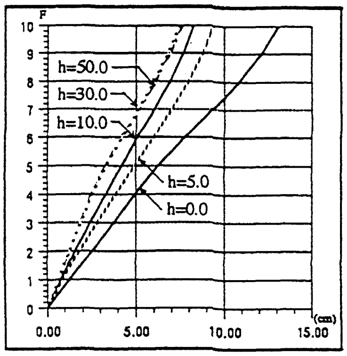
In a system of the type we have proposed, the damping effect is influenced considerably by the rigidity of the damper supports(a lever and support frame). In order to correctly take this effect into consideration, it is necessary to carry out analyses using a frame model, with every frame of a building evaluated as they are. One method of doing this would be a parametric study of vibration for the frame model of each building; however, this would take much time and cost a great deal.

A building equipped with a damping system is transformed into a Maxwell model consisting of a rigidity($K_1$) of the building, the damping coefficient of the damping system ($C_2$), and the rigidity at the damper support ($K_2$), as shown in Fig. 14.

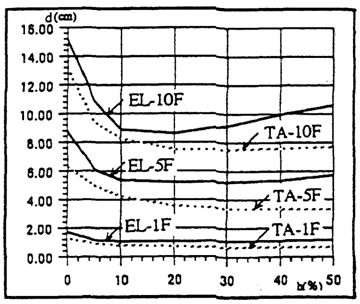
The amplification ratio of displacement obtained by the model is expressed as follows:




(a) (input: EL CENTRO)

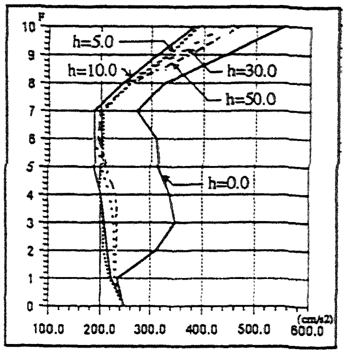



(b) (input: TAFT EW)

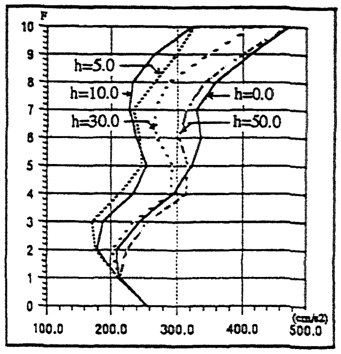



(c) (EL : input EL CENTRO)
(TA : input TAFT EW)

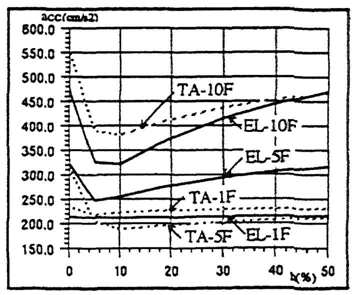
Fig. 11 Maximum Response Displacement (h; %)




(a) (input: EL CENTRO)




(b) (input: TAFT EW)




(c) (EL : input EL CENTRO)
(TA : input TAFT EW)

Fig. 12 Maximum Response Acceleration (h; %)

$$\frac{|X|}{X_s}=\omega_1^2\cdot\left(\frac{\omega_2^4+4h_2^2\,\omega_1^2\,\omega^2}{\omega_2^4(\omega_1^2-\omega^2)^2+4h_2^2\,\omega_1^2\omega^2(\omega_1^2+\omega_2^2-\omega^2)^2}\right)^{1/2}$$

in which

$K_1/M_1=\omega_1^2$, $K_2/M_1=\omega_1^2$, $C_2/M_1=2h_2\,\omega_1$

This equation can be expressed using the parameter $\omega/\omega_1$, as shown in Fig. 15., where the intersection $(B, \beta)$ is a singular point independent of the damping coefficient. Thus, most efficient damping can be obtained by considering the amplification ratio.

By adding inherent structural damping to the model of Fig. 14., the relationship between equivalent damping coefficient and parameters $K_2/K_1$ and $h_2$ is summarized in Fig. 16. Here, equivalent dampings($h_e$) result from maximum displacement response of the model.

For example, let the ratio of the module of rigidity be $K_2/K_1=0.1$, and the damping coefficient of the damping system be $h_2$ = 10%, then it is clear from the figure that the actual damping( $h_e$) is 4%( refer to ◌).

Fig. 17 shows the damper design flow with using the equivalent damping curve.

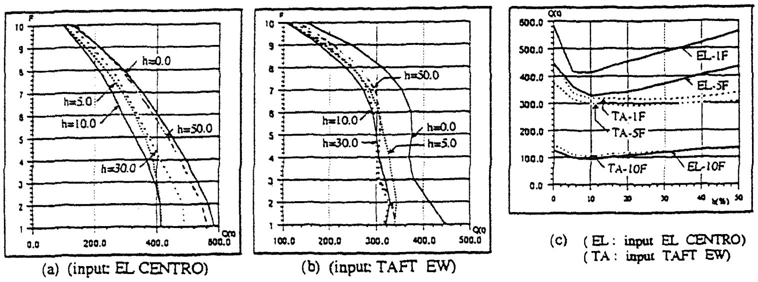



Fig. 13 Maximum Response Shear Force (h; %)

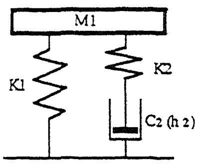



Fig. 14 Maxwell Model

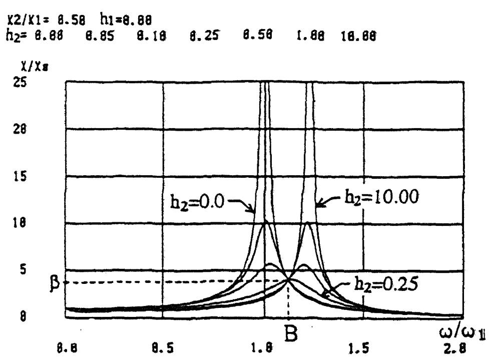



Fig. 15 Response Amplification

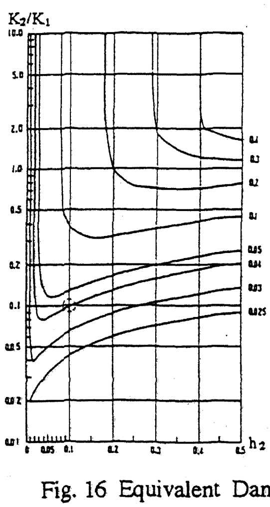



Fig. 16 Equivalent Damping Curve
(structure inherent damping : $h_i = 0.02$)

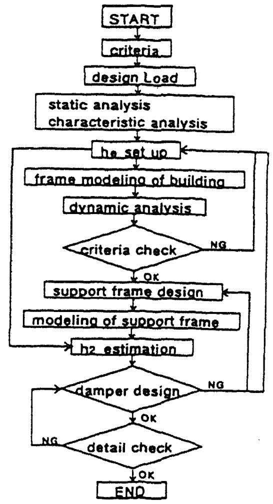



Fig. 17 Damper Design Flow

## 6. CONCLUSIONS

A shaking table test of the frame model demonstrated that by adding suitable damping with the system, the response of the structure could be reduced by a large amount. Adopting the system on more than one floor allows not only the primary mode, but also the higher order responses to be reduced.

The seismic response analyses of a building fitted with the damping system verified that by adding damping of about 0.2 to each story, the displacement, acceleration at the top and the base shear force could be reduced to about 60% to 70% of their values in buildings not fitted with the system. It was also showed that the rigidity of the damper support could also influence the damping effect.

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