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# HYBRID DAMPER FOR A SEISMIC ISOLATION DEVICE FOR EQUIPMENTS AND MACHINES

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## ABSTRACT

Several types of seismic isolation devices for equipments and machines have been developed. One of the functions required for these devices is to reduce the acceleration responses of the objects. The objective is to avoid the structual or machinery damages and falling down of the object. Another one is to keep the relative displacement between the isolated object and floor within a specified range. The purpose of this function is to prevent from making contact with the adjacent equipments, machines or walls during earthquakes. In this paper, the results of the numerical analyses and shaking table tests of a new type of hybrid damper for the seismic isolation device for equipments and machines are described. This hybrid damper is contracted as a combination of a rotary friction brake damper (semiactive damper) with a rotary damper with magnetic damping (passive damper).

## KEYWORDS

Damper; hybrid damper; piezoelectric actuator; isolation; seismic motion; simulation; semiactive damper; vibration control; shaking table test; magnetic damping.

## INTRODUCTION

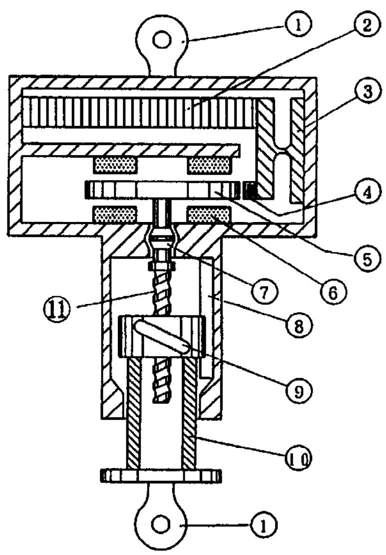
Recently, several types of seismic isolation devices for equipments and machines have been put to practical use. Seismic isolation devices for equipments and machines are generally composed of a bottom support which has small horizontal stiffness such as a laminated rubber bearing and dampers which are designed to suppress movements of an isolated object suitably. The dampers which are now successfully used to seismic isolation devices are passive dampers such as elasto-plastic dampers using steel bars, lead dampers, friction dampers and viscous dampers.

Although the maximum acceleration of an equipment or machine during an earthquake can be reduced satisfactorily by such a passive base isolation system, there is a concern that very large relative displacement over permissible deformation of rubber bearings occurs (Shimosaka *et al*, 1988). It is showed that a controllable friction damper (a semiactive damper) is effective in order to control such a large relative displacement (Fujita *et al*, 1991).

In this paper, a new type of hybrid damper which will enable us to achieve satisfactory reduction in both response acceleration and relative displacement is proposed. The damper utilizes a ball screw, a piezoelectric (PZT) actuator and rare–earth magnets. The PZT actuator generates a controllable friction force (a semiactive damping force) and rare–earth magnets generate an eddy–current force (a passive damping force). An experimental hybrid damper was constructed and its resisting force characteristics were measured. In order to confirm the effects of the hybrid damper, seismic responses of the isolated object installed on the 5th story of a 7–story non–isolated building are numerically analyzed and are measured by use of the electrohydraulic–type shaking table.

## CONSTRUCTION OF THE HYBRID DAMPER

The hybrid damper which is proposed in this paper is shown in Fig.1. In this damper a force and a linear motion between an isolated object and a floor during earthquakes is transferred to a torque and a rotary motion of an aluminium brake disk[ ⑤ ] by a ball screw mechanism[ ⑨ , ⑪ ] with a very high efficiency. The rotary movement of the aluminium disk is suppressed by a braking force caused by a brake mechanism[ ③ , ④ ] with a PZT actuator[ ② ] and by an eddy current force generated between the aluminium disk (conductor disk) and rare–earth magnets[ ⑥ ]. The frictional braking force is controlled corresponding to the relative displacement or relative velocity response between the isolated object and the floor and the magnetic damping force varies in proportion to rotating speed of the aluminium disk.




① Rod end
② PZT
③ Flexure hinge
④ Brake shoe
⑤ Brake disk
⑥ Rare–earth magnet
⑦ Thrust bearing
⑧ Slide guide
⑨ Ball nut
⑩ Load column
⑪ Screw shaft

Fig. 1. Hybrid damper

## ANALYTICAL MODEL

In calculating responses of the building during an earthquake, it is assumed that motions of the isolated object do not affect the building vibration, because the former mass is extreamly small compared with the later mass. If a 7–story building and the ground are subjected to a horizontal acceleration input $\ddot{z}$ as shown in Fig.2(a), the equations of motion of the analytical model are given by the following expressions:

$$m_1\ddot{y}_1+c_1(\dot{y}_1-\dot{z})+c_2(\dot{y}_1-\dot{y}_2)+k_1(y_1-z)+k_2(y_1-y_2)=0$$

$$m_i\ddot{y}_i+c_i(\dot{y}_i-\dot{y}_{i-1})+c_{i+1}(\dot{y}_i-\dot{y}_{i+1})+k_i(y_i-y_{i-1})+k_{i+1}(y_i-y_{i+1})=0$$

$$\vdots$$

$$m_7\ddot{y}_7+c_7(\dot{y}_7-\dot{y}_6)+k_7(y_7-y_6)=0 \qquad (1)$$

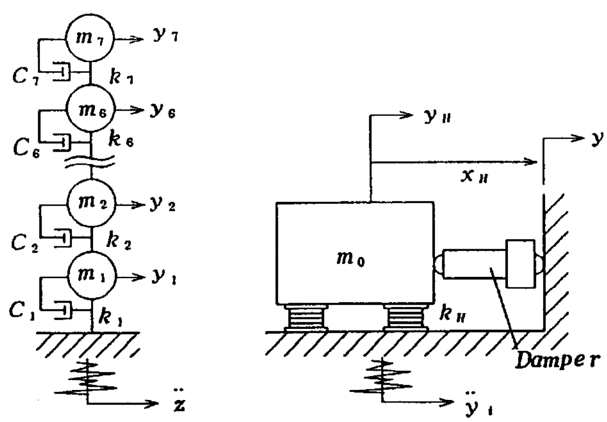
Table 1. Building model

| Story | Mass ( × $10^3$kg) | Stiffness ( × $10^3$kN/m) |
|---|---|---|
| 7 | 568 | 761 |
| 6 | 400 | 873 |
| 5 | 424 | 1323 |
| 4 | 433 | 1323 |
| 3 | 433 | 1364 |
| 2 | 461 | 1593 |
| 1 | 461 | 1587 |

where $y_i$ is the absolute displacement of the ith mass, and $m_i$ ,$c_i$ ,$k_i$ are the mass, damping coefficient and stiffness of the ith story respectively. The values of $m_i$ and $k_i$ are also shown in Table 1. Suppose an isolated object are installed on the ith story of the 7-story non-isolated building model. Input acceleration to the isolated object is given from $\ddot{y}_i$ in the Eq.(1) according to the above assumption. Then the equation of motion of the isolated system in Fig. 2(b) is given by

$$m_0\ddot{x}_H+k_Hx_H+F_s=-m_0\ddot{y}_i \tag{2}$$

where $m_0$ is the mass of the object, $k_H$ is the horizontal stiffness of the rubber bearing, $x_H$ is the relative displacement to the floor and $F_s$ is the resisting force of the hybrid damper.




(a) Building (b) Isolated object and damper

Fig. 2. Analytical model

## RESISTING FORCE OF THE HYBRID DAMPER

The damping torque generated by eddy current induced between the rare-earth magnets and the conductor disk (aluminium disk) is given by

$$T_M = n B^2 h A \alpha s^2 \dot{\theta} / \rho = C_\theta \dot{\theta} \tag{3}$$

where $n$ : number of magnetic fluxes, $B$ : magnetic flux density
$h$ : thickness of the conductor disk, $A$ : area of a magnetic flux
$\alpha$ : dimensionless damping parameter decided by the shape of both the magnetic flux and the conductor
$s$ : distance from the center of the disk to that of each magnetic flux
$\theta$ : rotational angle of the screw shaft and the conductor disk
$\rho$ : the resistivity of the conductor
$C_\theta$ : equivalent coefficient to the torsional damping

The braking torque generated by the disk brake is also given by

$$T_C = N \mu P R \,\mathrm{sign}(\dot{x}_H) \tag{4}$$

where $N$ : number of the brake
$\mu$ : coefficient of friction
$P$ : force that a brake shoe exerts on the brake disk
$R$ : radius of the brake disk (aluminium disk)
$\mathrm{sign}(\dot{x}_H)$ : sign function which takes −1 or 1 corresponding to a minus or plus sign of $x_H$

Using the damping torque in Eq.(3) and the friction torque in Eq.(4), the equation of motion of the hybrid damper can be expressed by

$$J \ddot{\theta} + T_C + C_\theta \dot{\theta} = F_s L / (2\pi) \tag{5}$$

where $J$ is the moment of inertia of the brake disk and $L$ is the lead of the ball screw. From the above equation, the resisting force of the hybrid damper is defined by

$$F_s = \beta (T_M + T_C + T_I) \tag{6}$$

in which $\beta = 2\pi / L$, $\theta = \beta x_H$, $T_I = \beta J \ddot{x}_H$ and $T_M = \beta C_\theta \dot{x}_H$.

The resisting torques acting on the brake disk were measured using the experimental apparatus as shown in Fig.3. Figures 4 (a) and 4 (b) show the eddy current torques and the friction torques with the rotating speed respectively. Figure 4 (c) shows the sum of 4 (a) and 4 (b), that is, the total resisting torques of the hybrid damper. It will be seen from Fig.4 that the eddy current torque is directry proportional to the rotating speed and the friction torque is nearly a constant value independent of rotating speed.

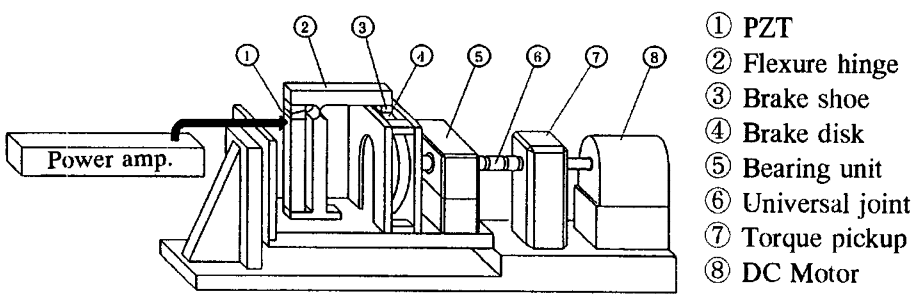
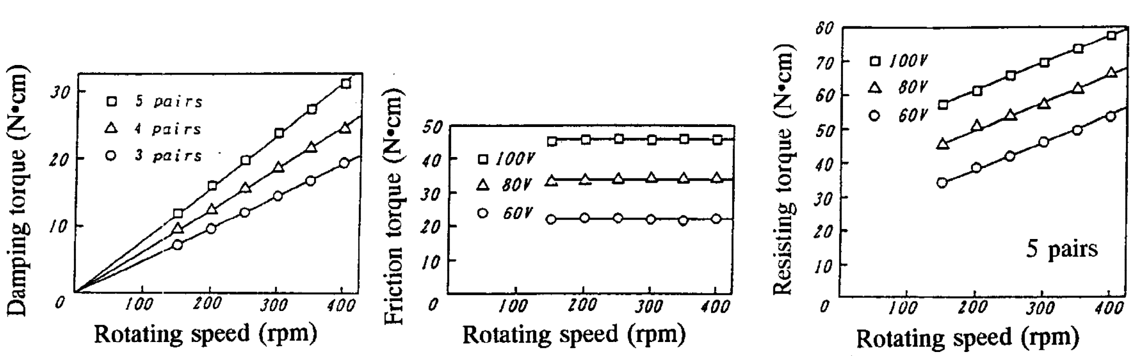



Fig. 3. Experimental apparatus for measuring the resisting torque




(a) Eddy current (b) Disk brake (c) Hybrid damper

Fig. 4. Resisting torque

The hybrid damper was subjected to a sinusoidal displacement of amplitude 5 mm and frequency 1 Hz or 3 Hz in order to measure the relationship between the resisting force and the displacement. The damper is attached between a shaking table and a rigid wall through a load cell. Figure 5 shows the resisting force with the time and the Lissajous' figures of the hybrid damper. It is apparent from Fig.5 that the resisting force of the hibrid damper has the desirable characteristics.

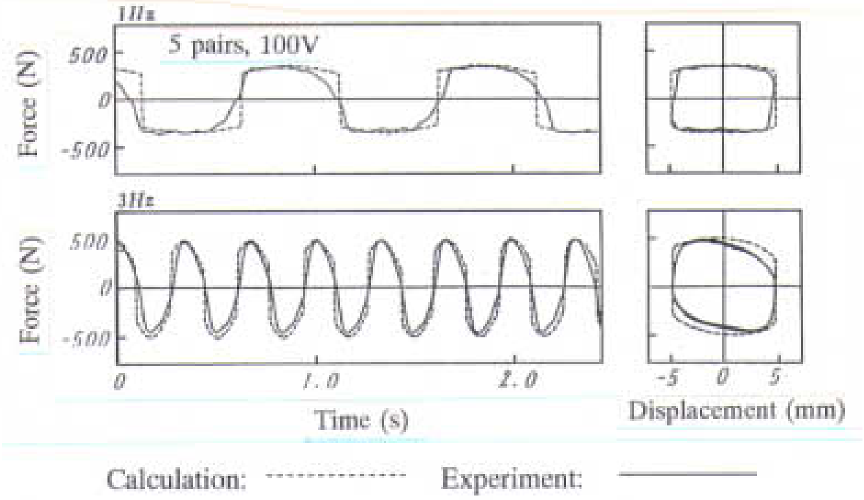



Fig. 5. Resisting force

## SHAKING TABLE TESTS

In order to confirm the effects of the hybrid damper, seismic responses of the isolated object installed on the 5th story of the 7-story non-isolated building are numerically analyzed and are measured by use of the electrohydraulic-type shaking table at Meiji University. Figures (6) and (7) show an external view and the measuring and controling system of the experimental apparatus respectively. In Fig.7, the mass corresponding to an equipment or a machine is mounted on the linear bearings. The combination of the linear bearings and the coil spring is equivalent to the laminated rubber bearings. The hybrid damper and the coil spring are attached in parallel between the mass and the shaking table. The displacement of the mass is measured by the inductance type transducer and the accelerations of the mass and the shaking table are by the piezoelectric type pickup.

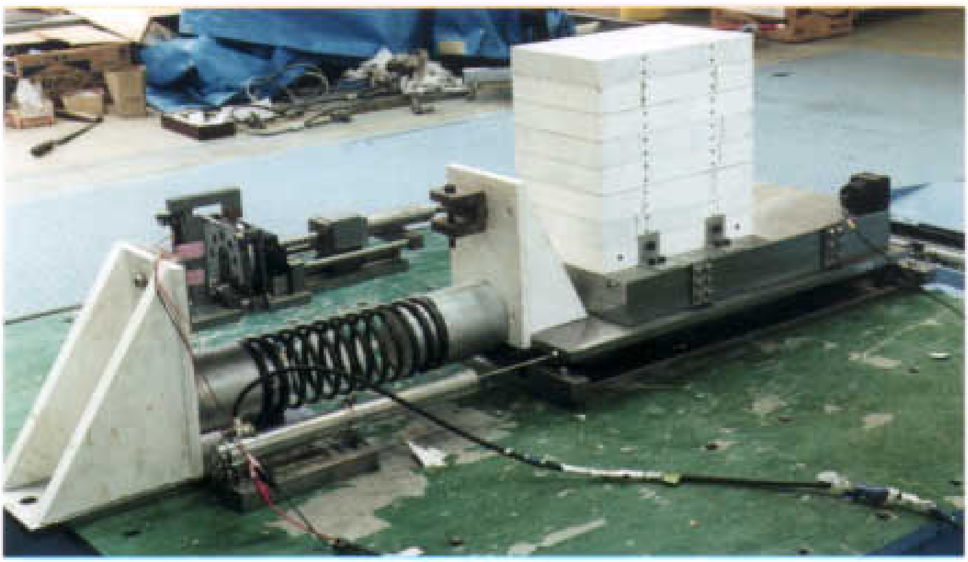


Fig. 6. External view of the experimental apparatus

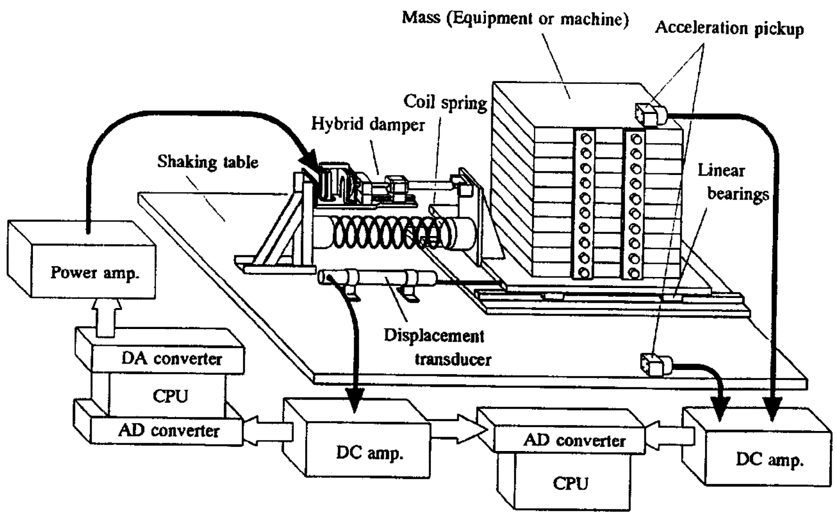
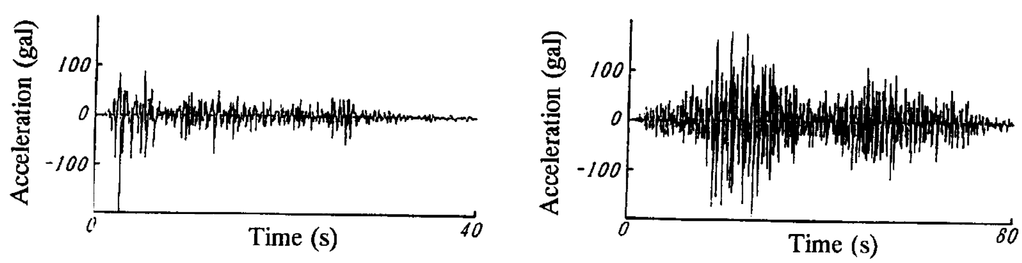



Fig. 7. Measuring and controlling system

The force that a brake shoe exerts on the brake disk is regulated under the following control conditions with reference to the previous report (Ohmata *et al*, 1993).

(a) On–off control corresponding to the relative velocity of the mass
(b) On–off control corresponding to the relative displacement of the mass
(c) Proportional control corresponding to the relative velocity of the mass

The input seismic waves to the 7–story non–isolated building are the El Centro (1940) NS and the Akita (1983) NS normalized to be 200 gal as shown in Fig. 8. As already stated, the acceleration response of the 5th story of the building is used as an input acceleration to the isolated object. The experimental condition of the isolation device in this shaking table test is shown in Table 2.




(a) El Centro (1940) NS

(b) Akita (1983) NS

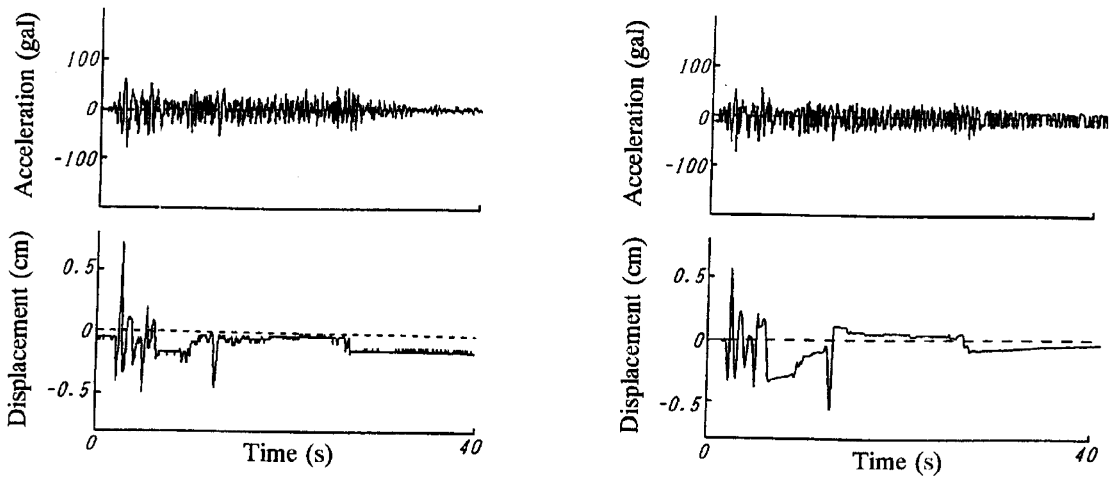
Fig. 8. Input seismic acceleration

Figures 9 shows the response waves of the isolated object when the only eddy current force act on the brake disk, that is, friction brake force $P$=0, and Fig. 10 shows the response waves when the control condition of the hybrid damper is (a). Fig. 11 is under the same condition with the Fig. 10 except that the input wave differs from the El Centro to the Akita. The calculated results are also shown in these figures.

As a result of the seismic response tests, it is revealed that the acceleration response of the object can be reduced to 1/2.5 – 1/1.5 to that of the floor response by the isolation device with the hybrid damper. Also the ability of the hybrid damper in suppressing the relative displacement response satisfies our requirements. From the comparison of Figs. 9 and 10, it is confirmed that the hybrid damper is more effective than the passive damper with magnetic damping to reduce the relative displacement of the isolated object to the floor. Moreover the experimental results agree well with the calculated results.

Table 2. Experimental condition

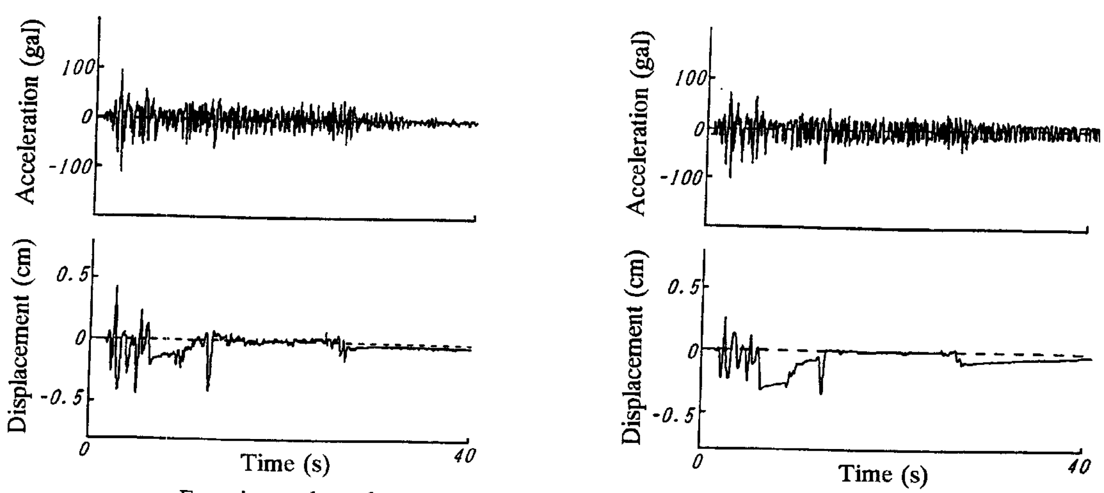
| | | | |
|---|---|---|---|
| Isolated object | | Mass $m_0$ | 300 kg |
| Coil spring | | Stiffness $k_H$ | 7580 N/m |
| Damper | Ball screw | Lead $L$ | 10 mm |
| | PZT | Dimension | 10 × 10 × 108 mm |
| | | Displacement | 78 $\mu$ m/100V |
| | Brake disk | Material | AE0010 |
| | | Thickness $h$ | 3 mm |
| | | Radius of brake disk $R$ | 50 mm |
| | | Moment of inertia $J$ | $9.99 \times 10^{-5}$ kg•m$^2$ |
| | | Coefficient of friction $\mu$ | 0.25 |
| | | Resistivity $\rho$ | $2.82 \times 10^{-8}$ $\Omega$ •m |
| | Magnet | Material | $Sm_2Co_{17}$ |
| | | Number of pairs $n$ | 3 |
| | | Magnetic flux density $B$ | 0.6 T |
| | | Area $A$ | 314 mm$^2$ |
| | | Distance $s$ | 35 mm |




Experimental results

Calculated results

Fig.9 . Responses by the damper with magnetic damping (El Centro)




Experimental results

Calculated results

Fig.10 . Responses by the hybrid damper (El Centro)

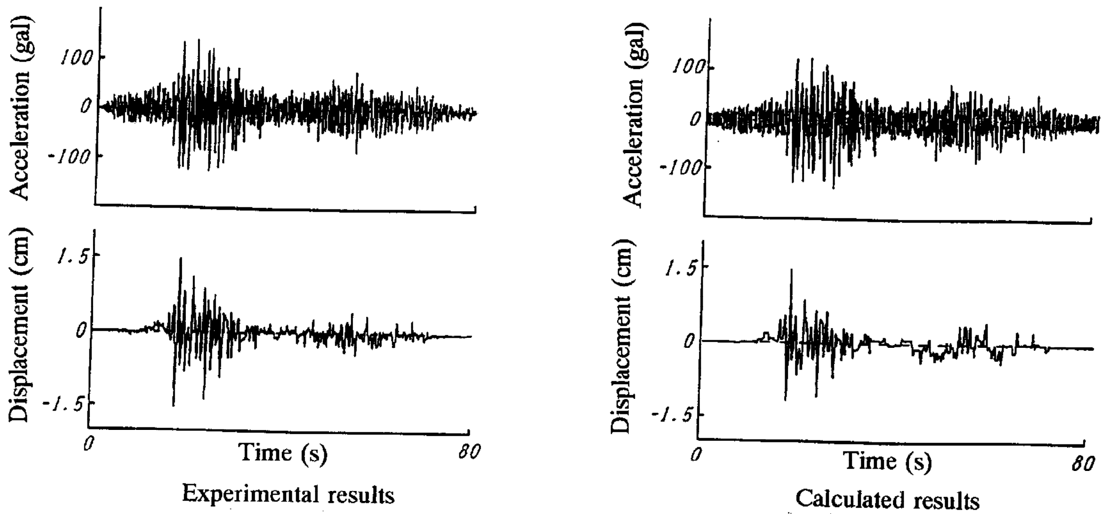



Fig.11 . Responses by the hybrid damper (Akita)

## CONCLUSIONS

The hybrid damper, which is contracted as a combination of a rotary frictional brake damper (semiactive damper) with a rotary magnetic damper (passive damper), was developed and seismic responses of the isolated object installed on the 5th story of a 7-story non-isolated building were numerically analyzed and measured by use of the electrohydraulic-type shaking table.

Remarkable features of the hybrid damper are as follows: (1) The maximum acceleration response of the object can be reduced to 1/2.5 - 1/1.5 to that of the floor response by the isolation device with the hybrid damper. (2) The maximum relative displacement of the object can be reduced to 3/5 compared to the damper with magnetic damping, although the maximum acceleration response is even or increased to 1.25. (3) The hybrid damper is designed to function as a fail-safe damper with the magnetic damping, even if a trouble occurs in the controllable friction damper. (4) The hybrid damper does not make a residual displacement of the isolation device after earthquakes. (5) The experimental results agree well with the calculated results. (6) The hybrid damper using passive magnetic damping and controllable friction damping is effective for seismic isolation device for equipments and machines.

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