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ISOLATION TABLE COMPOSED OF CIRCULAR ARC BEAM AND MAGNETIC DAMPING

HARUO SHIMOSAKA[1), TOSHIHARU ARAKAWA[2),
NAOTO ABE[3), and KOTARO WATANABE[3)

1)Department of Mechanical Engineering
2)Department of Architecture
3)Department of Precision Engineering
School of Science and Technology, Meiji University
1-1-1 Higashimita Tama, Kawasaki 214 Japan

ABSTRACT

A three-dimensional isolation table which consists of circular arc beams and viscous/magnetic/aerodynamic damping has been developed. Circular arc beams as spring units have not only simple shape but also even stiffness in every horizontal direction. But they cannot support heavy weight. In this paper a two-dimensional isolation table employing four spring units composed of circular arc beams, a magnetic damper and supporting struts with free bears on the top is proposed in order to be able to support much heavier weight than the former one. A trial isolation table being made, its frequency and seismic responses were investigated by employing an electro-hydraulic type shaking table. The experimental results were compared with the calculated results.

KEYWORDS

Isolation table; magnetic damping; circular arc beam; frequency response; seismic response.

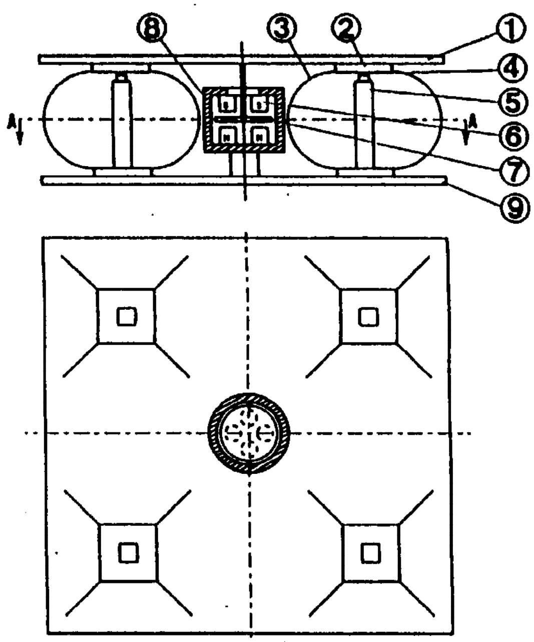
INTRODUCTION

Ohmata *et al* (1990,1993) have reported details in the three-dimensional isolation tables with viscous and aerodynamic dampers and in the two-dimensional isolation tables with magnetic dampers. That is to say, static characteristics and theoretical analyses for isolation have been reported. The circular arc beams and devised dampers can give the isolation tables even stiffness and viscous damping coefficient in the horizontal plane. But the circular arc beams cannot support heavy weight. Less than one hundred kilograms can be allowed on the table.

In this paper the two-dimensioanl isolation table employing four spring units composed of circular arc beams , a magnetic damper and supporting struts with free bears on the top is proposed in order to be able to support much heavier weight than the former one. The rare-earth magnet type magnetic damper is installed at the center underneath the table. The trial isolation table being made, its frequency and seismic responses were measured by employing an electro-hydraulic type shaking table. The experimental results were compared with the calculated results.

CONSTRUCTION OF THE ISOLATION TABLE

The isolation table consists of four spring units and a damper as shown in Fig.1. The table board① is supported by four spring units which have even stiffness in every horizontal direction. The spring unit is composed of four circular arc beams ③ and a simple strut ⑤ having a free bear ④ on the top which can allow heavier weight. The magnetic damper ⑥ installed at the center underneath the table board has even damping in horizontal plane, and acts like a kind of a viscous damper, which means that damping is proportional to velocity.



①Table board ②Plate ③Circular arc beam ④Free bear
⑤Strut ⑥Rare-earth magnet ⑦Copper disk ⑧Case ⑨Base board
Fig.1 Conceptional sketch of the isolation table

VISCOUS DAMPING AND STIFFNESS

Fig.2 shows one of the spring units. Four circular arc beams are diagonally attached on the square plates. Ohmata *et al* (1990) showed that the spring unit has even stiffness in horizontal plane as in Eq. (1), where *EI* is flexural rigidity and GIp is torsional rigidity of the semi-circular arc beam.

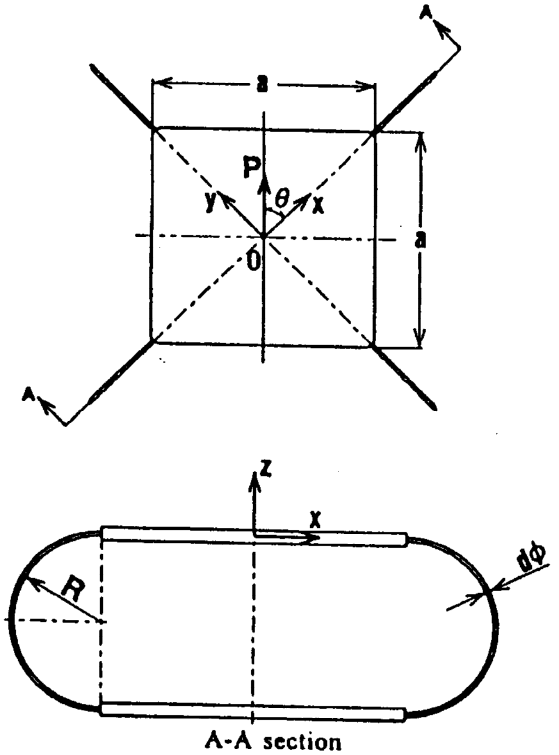


Fig.2 Spring unit

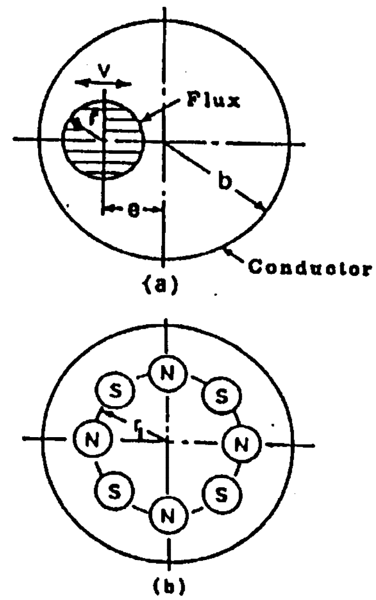


Fig.3 Magnetic fluxes and a conductor

$$k_H = \frac{P}{\sqrt{2}\xi(3\pi RF_{y_1} - 4RF_{z_1} - 2\pi M_{x_1})} \tag{1}$$

where

$$\left.\begin{aligned}
&\xi = \frac{R^2}{2EI} \\
&F_{y_1} = \frac{B_5}{2\sqrt{2}}P \\
&F_{z_1} = \frac{P}{2\sqrt{2}} \cdot \frac{B_1B_5B_7 + B_3B_4 - B_3B_5(3\pi + B_4)}{B_3B_6 - B_2B_7} \\
&M_{x_1} = \frac{RP}{2\sqrt{2}} \cdot \frac{B_1B_5B_6 + B_2B_4 - B_2B_5(3\pi + B_4)}{B_2B_7 - B_3B_6}
\end{aligned}\right\} \tag{2}$$

where

$$\left.\begin{aligned}
&B_1 = -2(4R + \sqrt{2}\pi a) &&, \ B_2 = 2(\pi R + 2\sqrt{2}a) \\
&B_3 = 2(4R + \sqrt{2}\pi a) &&, \ B_4 = (1+3\epsilon)\pi - \frac{16\epsilon^2}{(1+\epsilon)\pi} \\
&B_5 = \frac{2\epsilon\{\pi^2(1+\epsilon) - 8\epsilon\}}{\pi(1+\epsilon)(B_4 - \pi\epsilon)} &&, \ B_6 = \frac{\pi}{\sqrt{2}R}(1+\epsilon)a - 4 \\
&B_7 = -\pi(3+\epsilon) &&, \ \epsilon = \frac{EI}{GI_p}
\end{aligned}\right\} \tag{3}$$

As we have four spring units in the isolation table, the stiffness of the isolation table is expressed in Eq. (4).

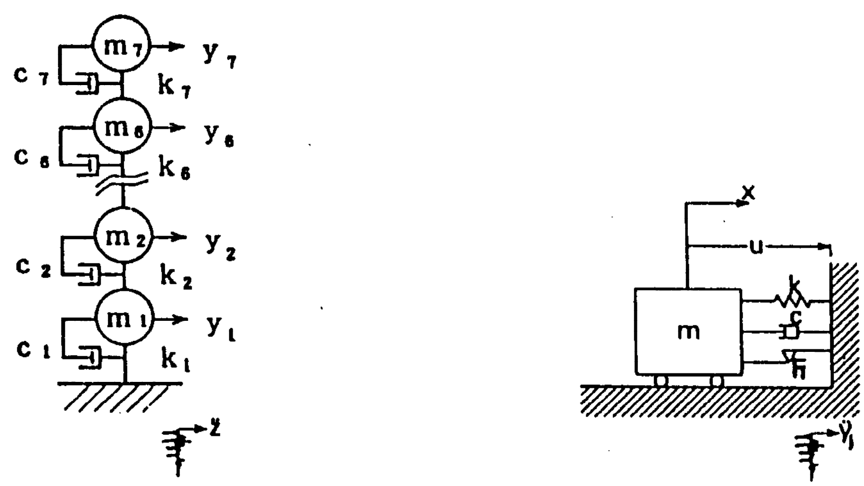
$$k=4k_H \tag{4}$$

Fig.3 (a) shows magnetic damper which consists of a conductive circular plate and uniform magnetic flux eccentrically located, where r is eccentricity, b is radius of the conductive circular plate, and v is relative velocity of the conductive circular plate. Nagaya *et al* (1984) have analytically obtained viscous damping coefficient, which is simply expressed in Eq. (5), where B is magnetic flux density, h is thickness of the conductive circular plate, and Co is dimensionless damping coefficent. Co, whose values have been shown by Nagaya *et al* (in the Tab.3, 1984), depends on the values of e/b and r/b. Multiple magnetic fluxes of oposite polarity alternatively located can give larger magnetic damping what has been shown by Ohmata *et al* through the experiment (1989) and Nagaya *et al* through theoretical analysis (1991). Overall damping coefficient of the isolation table can be obtained by adding each value calculated through Eq. (5).

$$c=(B^2 h\pi r^2/\rho)c_0 \tag{5}$$

SEISMIC RESPONSES OF AN ISOLATION SYSTEM

A model of a seven storied RC building, which is designed in modern normal way, is shown in Fig.4 (a) (Ohmata *et al*, 1991). The isolation table is assumed to be equipped at the j-th floor. Mass and stiffness of the building are shown in Tab.1. Values of parameters related to the isolation table are listed in Tab.2. Eigen frequencies of the building through the first to the third mode are 1.82Hz, 4.81Hz, and 7.84Hz respectively. A 3% damping ratio is assumed to the first mode.



(a) Building

(b) Isolation table

Fig.4 Analytical model

Equation of motion of the building is written in Eq. (6), where m_j, c_j, and k_j denote mass, viscous damping and spring constant of the j-th floor respectively, and x_j is relative displacement to the ground.

$$\begin{aligned}
&m_1\ddot{x}_1+c_1\dot{x}_1+c_2(\dot{x}_1-\dot{x}_2)+k_1x_1+k_2(x_1-x_2) \\
&\qquad =-m_1\ddot{z} \\
&m_j\ddot{x}_j+c_j(\dot{x}_j-\dot{x}_{j-1})+c_{j+1}(\dot{x}_j-\dot{x}_{j+1})+k_j(x_j-x_{j-1}) \\
&\qquad +k_{j+1}(x_j-x_{j+1})=-m_j\ddot{z} \quad (j=2\sim6) \\
&m_7\ddot{x}_7+c_7(\dot{x}_7-\dot{x}_6)+k_7(x_7-x_6)=-m_7\ddot{z}
\end{aligned} \tag{6}$$

Tab.1 Mass and stiffness of the building

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

Tab.2 Parameters of the isolation table

Mass m	100 kg
Stiffness k	1.034 kN/m
Damping coefficient c	120 Ns/m
Friction force Fo	49 N

The floor response at the j-th floor is employed as an input to the isolation table as shown in Fig.4(b). Equation of motion of a machine mounted on the isolation table can be written in Eqs. (7) and (8), because Coulomb friction between the free bears and the table board works.

(1) Phase I (stick by friction)

$$u=const.\ ,\ \dot{u}=0\ ,\ \ddot{u}=0 \tag{7}$$

(2) Phase II (in motion under friction)

$$m\ddot{u}+c\dot{u}+ku+F_0\cdot sign(\dot{u})=-m\ddot{y}_j \tag{8}$$

The condition for switching from Phase I to Phase II can be given in an inequality (9).

$$|m\ddot{y}_j+ku|>F_0 \tag{9}$$

The condition for switching from Phase II to Phase I can also be written in an inequality (10).

$$\dot{u}=0\ ,\ |m\ddot{x}+c\dot{u}+ku|\leq F_0 \tag{10}$$

The notations appeared among Eqs. (7) and (10) are as follows; m is overall mass of the machine and the table board, k is overall stiffness of the four spring units, c is damping coefficient of the magnetic damper, Fo is Coulomb friction between the free bears and the table board, and u is relative displacement of the table board to the j-th floor.

SIMULATION OF THE SEISMIC RESPONSE

El Centro NS and Akita NS whose maximum acceleration is normalized at 0.5, 1, 2 m/s^2 are employed as a seismic input. The isolation table is assumed to be installed at the 5th floor. That is, the floor response at the 5th floor is employed as the input to the isolation table. Specification is shown in Tab.4. Tab.3 shows the maximum values of the floor response at the 5th floor, acceleration on the table board and the relative displacement.

Tab. 3 Maxima of the response

Max. input acc.		El Centro NS			Akita NS		
$\ddot{z}$ (m/s^2)		0.5	1.0	2.0	0.5	1.0	2.0
Nonisolated	$\ddot{y}$ (m/s^2)	1.08	2.16	4.33	1.49	2.98	5.97
Isolated	$\ddot{x}$ (m/s^2)	0.64	0.80	1.18	0.75	1.00	2.07
c=120 (Ns/m)	u (mm)	11.4	26.8	45.0	19.4	39.4	83.5

The maximum acceleration on the table board reduced to as much as 1/2 ~ 1/3 of the floor response. The maximum relative displacement is 40 ~ 90 mm when the ground motion is normalized at 2 m/s^2.

EXPERIMENT

The isolation table is sketched in Fig.5. Specification is listed in Tab.4. 16pairs of Sm_2Co_{17} magnet with 20 mm diameter are employed. Load-displacement of single unit in the direction of θ =0°, 15°, 30°, and 45° are plotted in Fig.6. Fig.6 shows that the spring unit has even stiffness in horizonntal plane, and that the result obtained by the experiment coincides with the calculated one.

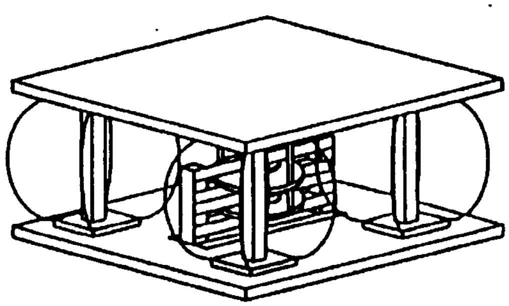


Fig.5 Experimental isolation table

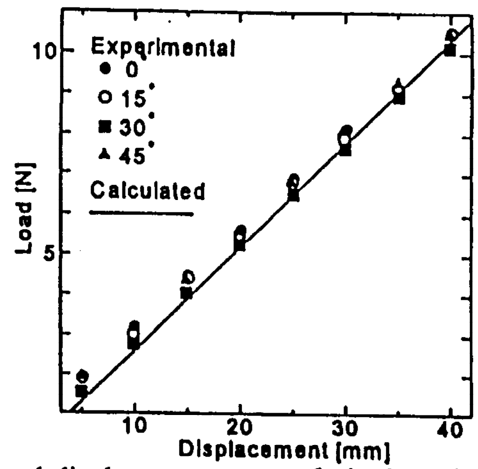


Fig.6 Load-displacement curve of single spring unit

Tab.4 Experimental condition of the isolation table

Table board	Circular arc beam	Rare-earth magnet	Copper disk
Material A2017	Material SUP6	Material Sm_2Co_{17}	Material C1220BE
Length of a side *a*	Diameter *d* 3mm	Thickness 5mm	Diameter 2*b* 220mm
1000mm	Radius *R* 150mm	Gap 3mm	Thickness *h* 4mm
		Number of pairs 16	Resistivity ρ $1.68\times10^{-2}\Omega$m

Magnetic flux density vs gap measured by Gauss meter is shwon in Fig.7.

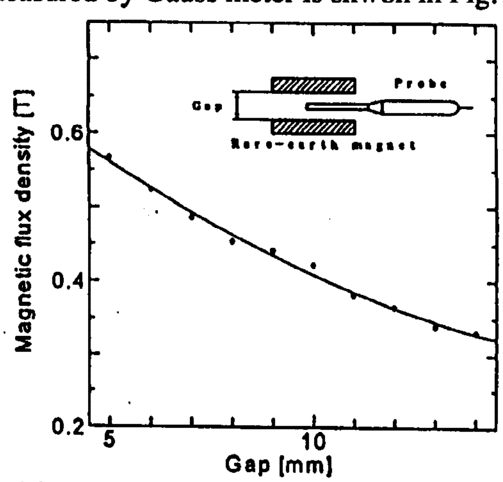


Fig.7 Magnetic flux density of the magnet

A mass of 56 kg is put on the table board. The isolation table system is mounted on the electro-hydraulic type shaking table. Resonanse curves under sinusoidal excitation with an 30 mm amplitude is shwon in Fig.8. Fig.8 tells that three resonanse curves in the direction of θ =0°, 30°, and 45°coincide with each other and that theoretical resonanse curve is alomost the same as the one obtained by the experiment. The resonanse frequency of the isolation table can be said to be low enough to isolate a machine from an earthquake.

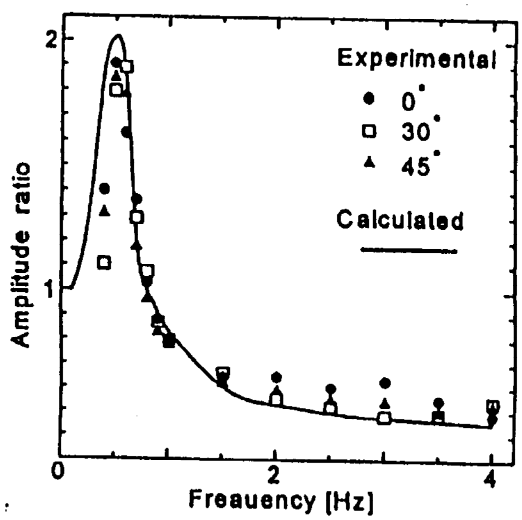


Fig.8 Resonanse curves

El Centro NS and Akita NS normalized at maximum 2 m/s^2 were directly input to the isolation table. The result of th eexperiment and the calculation are listed in Tab.5. The response waves to Akita NS are shown in Fig.9. Tab.5 and Fig.9 show that the maximum acceleration is reduced to as much as half of the maximum input and that the isolation table is effectively working against the earthquakes.

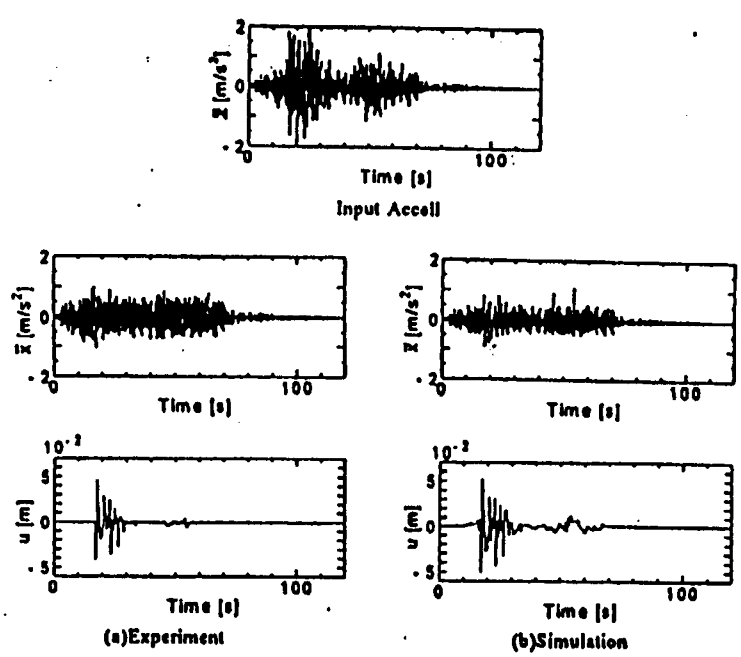


Fig.9 Response waves (Akita NS)

Tab.5 Maxima of the response

Input acceleration	El Centro NS (Max.=2 m/s^2)		Akita NS (Max.=2 m/s^2)	
	$\|\ddot{x}\|_{Max}$ (m/s^2)	$\|u\|_{Max}$ (mm)	$\|\ddot{x}\|_{Max}$ (m/s^2)	$\|u\|_{Max}$ (mm)
Experiment	0.81	16	1.04	46
Simulation	0.69	17	1.08	51

CONCLUSIONS

The conclusions are as follows:
(1)the four spring units and free bears on the struts allow heavier weight,
(2)the isolation table has even stiffness and damping in every horizontal direction, and
(3)the excitation acceleration can be reduced to half.

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