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APPLICATION OF ROTARY INERTIA TO DISPLACEMENT REDUCTION FOR VIBRATION CONTROL SYSTEM

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SUMMARY

The main conventional methods for controlling the seismic response of structures is to either change stiffness or to provide damping. The authors have developed a method of improving the safety of structures by providing added mass to these conventional methods and putting it into practical use. This paper firstly discusses seismic response characteristics provided by added mass computations. The paper then describes a device and its performance in which added mass and viscous damping force is provided. Finally details are given about the seismic response characteristics of a base-isolated structure to which this device is actually applied, showing a comparison of the results with and without added mass.

INTRODUCTION

In the 1980's base-isolation and seismic damping technologies had been studied and developed, and the use of these technologies has spread as a result of 1995 Hyogo-ken Nanbu Earthquake, Akagi [1], Shimotori [2]. Many of the base-isolation and seismic damping systems adopted to date have been achieved by intentionally adjusting the displacement-dependent stiffness or the velocity-dependent damping coefficient, Saito[3].

This paper theoretically analyzes the response characteristics of a single lumped mass structure (base-isolation structure) where a GMD device (GYRO/MASS-VISCOUS damper) is incorporated. In the GMD, an added mass, which is relative acceleration-dependent, is provided to the main mass, which is absolute acceleration-dependent, along with a velocity-dependent viscous damping device ("added mass, viscous damping device"),Kuroda [4], [5]. We also discuss the possibility of applying GMD devices to multi-mass structures.

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This paper explains on the principle and performance of the GMD. The GMD uses a ball-screw to convert axial movement into rotational movement, thereby significantly amplifying the velocity developed around the viscous material and the rotor and achieving high viscous damping force and rotational inertia force. By re-converting the rotational movement into axial movement, it further develops a resistance force that is increased by the same amplified ratio. Lastly the paper provides examples of isolated buildings employing this device.

RESPONSE CHARACTERISTICS OF STRUCTURES WITH ADDED MASS AND VISCOUS DAMPING

Response analysis of a single lumped mass system

Fig. 1 illustrates a model of single lumped mass system with the following elements: Main Mass, **M**, Restoring Force, **k ,** Viscous damping coefficient of the structure and the device, **C** and Added mass, **m.**

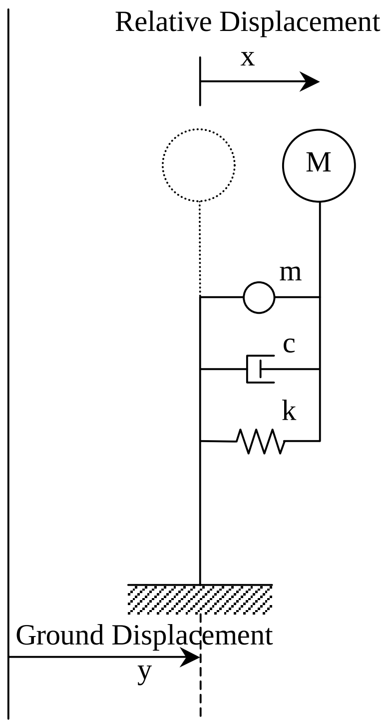


Figure1.
Single lumped mass system

Equation (1) is an equation of motion when the structure is subjected to earthquake ground acceleration.

$$M(\ddot{x}+\ddot{y}_0)+m\ddot{x}+c\dot{x}+kx=0 \tag{1}$$

Equation (2) and equation (3) are transformed versions of equation (1).

$$(M+m)\ddot{x}+c\dot{x}+kx=-M\ddot{y}_0 \tag{2}$$

$$\ddot{x}+\frac{c}{M+m}\dot{x}+\frac{k}{M+m}x=-\frac{M}{M+m}\ddot{y}_0 \tag{3}$$

Equation (4) is the equation of motion in the case without added mass.

$$\ddot{x}+\frac{c}{M}\dot{x}+\frac{k}{M}x=-\ddot{y}_0 \tag{4}$$

It is clear by comparing equation (3) and equation (4), that the added mass m will cause the following:

(1) The natural circular frequency drops by $\sqrt{\frac{M}{M+m}}$ times.

(Natural period extends $\sqrt{\frac{M+m}{M}}$ times longer.)

(2) The damping factor drops by $\sqrt{\frac{M}{M+m}}$ times.

(3) The input acceleration to the system drops by $\frac{M}{M+m}$ times.

Based on equation (3), equation (5) is obtained.

$$\ddot{x}+2h\omega_0\dot{x}+\omega_0{}^2x=-\frac{1}{1+\alpha}\ddot{y}_0 \tag{5}$$

where $\omega_0=\sqrt{\frac{K}{M+m}}$ 、 $2\mathrm{h}\omega_0=\frac{\mathrm{c}}{\mathrm{M+m}}$ 、 $\alpha=\frac{m}{M}$

The complex amplitude C is obtained by adopting $x=ce^{ipt}$ as a particular solution for the complex harmonic ground motion of $y_0=a_0e^{ipt}$

$$c = \frac{1}{1+\alpha} \cdot \frac{a_0 p^2}{\omega_0{}^2 - p^2 + 2h\omega_0 pi} \tag{6}$$

Therefore, the relative displacement x、 relative velocity $\dot{x}$ and relative acceleration $\ddot{x}$ are obtained as follows:

$$x = \frac{1}{1+\alpha} \cdot \frac{a_0 p^2}{\omega_0{}^2 - p^2 + 2h\omega_0 pi} e^{ipt} \tag{7}$$

$$\dot{x} = \frac{1}{1+\alpha} \cdot \frac{a_0 p^3}{\omega_0{}^2 - p^2 + 2h\omega_0 pi} e^{i\left(pt+\frac{\pi}{2}\right)} \tag{8}$$

$$\ddot{x} = -\frac{1}{1+\alpha} \cdot \frac{a_0 p^4}{\omega_0{}^2 - p^2 + 2h\omega_0 pi} e^{ipt} \tag{9}$$

Naturally, it is $\frac{1}{1+\alpha}$ times the response of $\ddot{x} + 2h\omega_0 \dot{x} + \omega_0{}^2 x = -\ddot{y}_0$

The absolute acceleration, $\ddot{Y} = \ddot{x} + \ddot{y}_0$ is shown as follows:

$$\ddot{Y} = \ddot{x} + \ddot{y}_0 = -\frac{1}{1+\alpha} \cdot \frac{a_0 p^4}{\omega_0{}^2 - p^2 + 2h\omega_0 pi} e^{ipt} + \ddot{y}_0 \tag{10}$$

Therefore, the magnification of the absolute acceleration, $\frac{\ddot{Y}}{\ddot{y}_0}$ is presented as follows:

$$\frac{\ddot{Y}}{\ddot{y}_0} = 1 + \frac{1}{1+\alpha} \cdot \frac{p^2}{\omega_0{}^2 - p^2 + 2h\omega_0 pi} = 1 + \frac{\left(\frac{p}{\omega_0}\right)^2}{(1+\alpha)\left\{1 - \left(\frac{p}{\omega_0}\right)^2 + 2h\left(\frac{p}{\omega_0}\right)i\right\}} \tag{11}$$

That is, the magnification of the absolute acceleration is the value by adding 1 to the magnification of the relative acceleration.

Equation (11) is translated as follows:

$$\frac{\ddot{Y}}{\ddot{y}_0} = \frac{(1+\alpha) - \alpha\left(\frac{p}{\omega_0}\right)^2 + 2h(1+\alpha)\left(\frac{p}{\omega_0}\right)i}{(1+\alpha)\left\{1 - \left(\frac{p}{\omega_0}\right)^2 + 2h\left(\frac{p}{\omega_0}\right)i\right\}} = \sqrt{\frac{\left\{1 - \frac{\alpha}{1+\alpha}\left(\frac{p}{\omega_0}\right)^2\right\}^2 + 4h^2\left(\frac{p}{\omega_0}\right)^2}{\left\{1 - \left(\frac{p}{\omega_0}\right)^2\right\}^2 + 4h^2\left(\frac{p}{\omega_0}\right)^2}} e^{-i\theta} \tag{12}$$

Fig. 2 illustrates equation (12) for a range of damping factors.

As shown in Fig. 2, the absolute acceleration can be 0(zero) when the damping factor h=0. By using equation (12), it follows that:

$$\left\{1 - \frac{\alpha}{1+\alpha}\left(\frac{\mathrm{p}}{\omega_0}\right)\right\} = 0 \tag{13}$$

When substituting $\alpha = \frac{m}{M}$、 $\omega_0 = \sqrt{\frac{\mathrm{K}}{M+m}}$ into the equation (13), equation (14) is obtained as follows:

$$m = \frac{k}{p^2} \tag{14}$$

Equation (14) indicates that “in a structure of a simple lumped mass subject to harmonic ground motion, $y_0 = a_0 e^{ipt}$, absolute acceleration response can be 0(zero) with added mass, $m = \frac{k}{p^2}$.

Also, in equation (12), the absolute acceleration response approaches $\frac{\alpha}{1+\alpha}$ by making $\frac{p}{\omega_0}$ infinite. This means that while the response of absolute acceleration approaches 0 (zero) with zero added mass (α=0)when the natural period is prolonged, it approaches 1 (that is, the same as the ground acceleration) with added mass increased ($\alpha \to \infty$). When damping is increased, the response amplitude drops at the resonance point, ($\frac{p}{\omega_0}=1$), whereas the minimum response amplitude increases. Hence, when added mass is applied to isolated structures, it is a practical approach to adopt the values within the following range: $\alpha \leq 0.2$、$h \leq 0.20$.

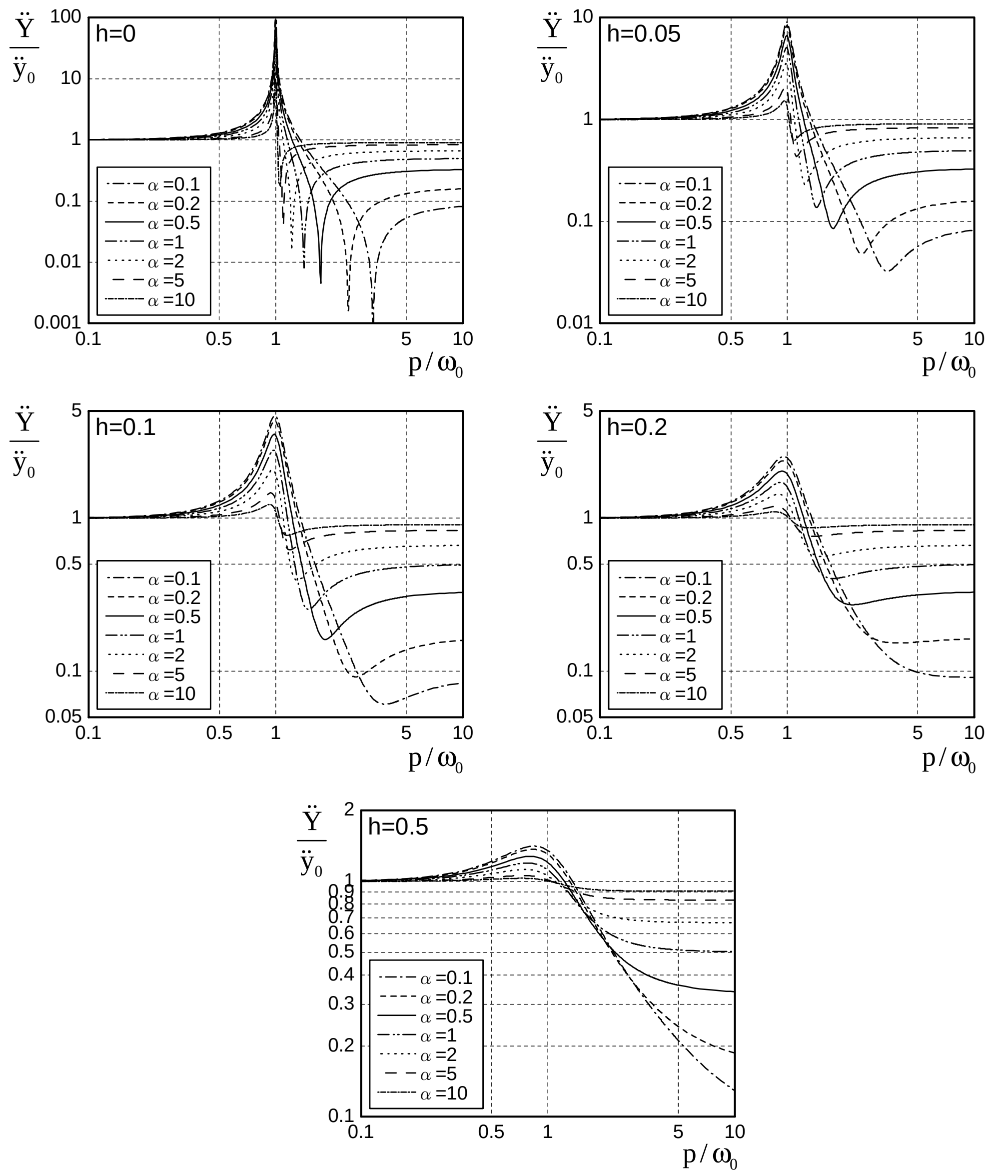
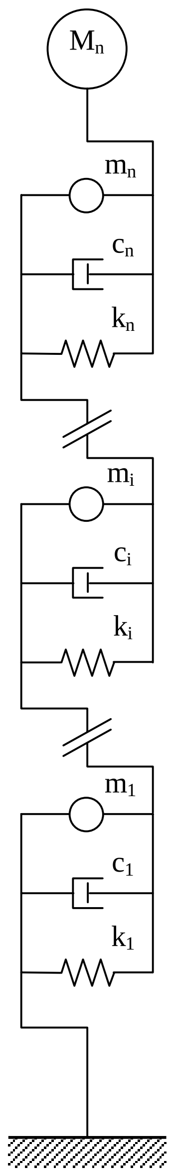


Figure2. Response magnification of single lumped mass with added mass, m

Response in multi lumped mass systems

Equation (15) is the equation of motion for a multi lumped mass system without added mass



Figiure3.
Lumped mass system model

$$[M]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M]\{1\}\ddot{y}_0 \tag{15}$$

$[M]$: mass matrix (diagonal matrix)

$[C]$: damping matrix

$[K]$: stiffness matrix

$\{\ddot{x}\}$: response acceleration vector

$\{\dot{x}\}$: response velocity vector

$\{X\}$: response displacement vector

$\ddot{y}_0$: ground acceleration

Equation (16) is the equation of motion for a multi lumped mass system with added mass as illustrated by Fig. 3:

$$([M]+[m])\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}=-[M]\{1\}\ddot{y}_0 \tag{16}$$

This is based on the added mass matrix $[m]$ (lumped mass system, triple diagonal matrix)

$$[m]=\begin{bmatrix} m_n & -m_n & & & & & \\ -m_n & m_n+m_{n-1} & -m_{n-1} & & & & \\ & & \ddots & & & & \\ & & -m_{i+1} & m_{i+1}+m_i & -m_i & & \\ & & & & \ddots & & \\ & & & & & -m_2 & m_2+m_1 \end{bmatrix}$$

By substituting $[Mm]=[M]+\{m\}$, equation (16) is transformed to equation (17),

$$\begin{aligned}[Mm]\{\ddot{x}\}+[C]\{\dot{x}\}+[K]\{x\}&=-[M]\{1\}\ddot{y}_0\\ &=-[Mm]\{\eta\}\ddot{y}_0\end{aligned} \tag{17}$$

with the following condition:

$$\{\eta\}=[Mm]^{-1}[M]\{1\} \tag{18}$$

$\{\eta\}$ is designated as the reduction factor of input-motion.

From equation (18), the equation (19) is obtained:

$$\begin{aligned}&[M]\{1\}=[Mm]\{\eta\}=([M]+[m])\{\eta\}\\ &\therefore [M]\{1-\eta\}=[m]\{\eta\}\end{aligned} \tag{19}$$

Equations (20) through (23) correspond to equilibrium on the top floor, n, middle floor, i, and the first floor, 1:

$$M_n(1-\eta_n)=m_n(\eta_n-\eta_{n-1}) \tag{20}$$

$$M_i(1-\eta_n)=-m_{i+1}(\eta_{i+1}-\eta_i)+m_i(\eta_i-\eta_{i-1}) \tag{21}$$

$$M_1(1-\eta_1)=-m_2(\eta_2-\eta_1)+m_i\eta_1 \tag{22}$$

Equations (20) through (22) with added masses m_n, m_i, m_1 correspond to equations (23) through (25) respectively.

$$m_n = \frac{M_n(1-\eta_n)}{\eta_n - \eta_{n-1}} \tag{23}$$

$$m_i = \frac{\sum_{k=i}^{n} M_k(1-\eta_k)}{\eta_i - \eta_{i-1}} \tag{24}$$

$$m_1 = \frac{\sum_{k=1}^{n} M_k(1-\eta_k)}{\eta_1} \tag{25}$$

Equation (26) shows the conditions necessary to maintain the added mass m_i as a positive value and η as 1 or less.

$$\eta_i \geq \eta_{i-1} > 1 \tag{26}$$

As $\eta_i - \eta_{i-1} << 1$ is the limiting condition derived from equation (24), and as the added mass is the linear sum of the main mass above the floor, structures with more floors require more added mass.

Added mass and viscous damping device

Figure 4 illustrates a device (GMD) that produces a large damping force and mass inertia force by using a rotary ball screw. Damping force is developed through the following mechanism: The rotary ball-screw converts axial movement into rotary movement, thereby the axial movement velocity is amplified and applied to the viscous material. A large damping force is developed within the viscous material through this conversion. The obtained damping force is further amplified through reverse conversion of the rotary movement into axial movement. The mass inertia force is developed by the following mechanism: From the axial movement and rotary movement conversion mentioned above, axial acceleration is converted into rotational acceleration. The developed rotational acceleration acts upon the mass of the rotor thereby producing a large rotational inertia moment. The reverse conversion from the rotational inertia moment into axial movement further develops even larger mass inertia.

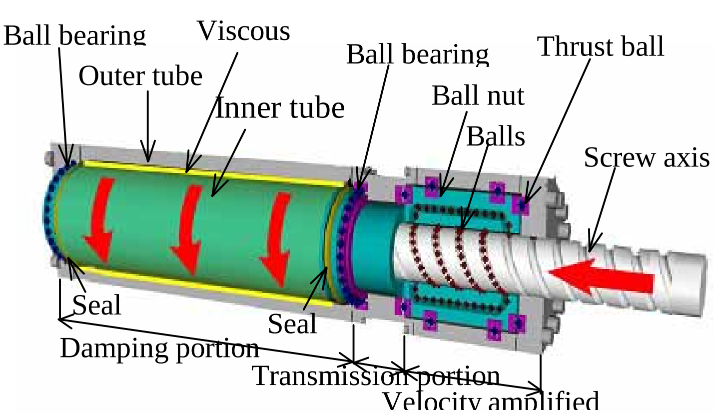


Figure 4. Gyro/Mass-Viscous damper (GMD)

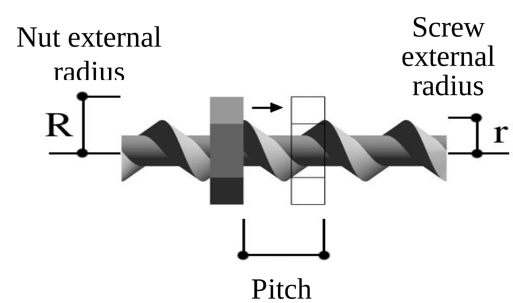


Figure 5. Relation of Screw pitch and Nut

Figure 5 illustrates the relationship between the screw and the nut at the ball screw. One turn of the nut is an equivalent of one lead or pitch. The circumference of the nut moves by $2\pi R = \pi D$ (R:Nut external radius, D:Diameter) for 1 pitch of the screw. That is, the velocity at the external circumference of the nut is amplified 2πR/p times (=ϕ : amplification rate) against the axial velocity. When this amplified velocity is applied to the viscous material, a large viscous resistance is obtained. The obtained viscous damping force is further amplified by 2πR/p times (=ϕ : amplification rate) in the course of the reverse conversion into axial movement. The viscous damping force, Q_n, is expressed by equation (27) below.

$$Q_n = \phi \cdot \nu \cdot \frac{\phi V_n}{dy} \cdot A = \nu \phi^2 \cdot \frac{V_n}{dy} \cdot A$$

ϕ: Amplification factor=$2\pi R/p$
ν: Apparent viscosity
V_n: Axial velocity
A: Area facing viscous material
dy: Clearance

As one turn of rotational (angle) acceleration (2πx radius) equals 1 pitch, it equals axial acceleration x 2π/p and acts upon the rotor's moment of inertia. The rotational moment of inertia is increased by 2π/p and developed as a resisting force. Thus, the inertia resistance in the axial direction is expressed as follows (Equation 28).

$$\begin{aligned} Ia &= T \cdot \frac{2\pi}{p} \\ &= I\ddot{\theta} \cdot \frac{2\pi}{p} \\ &= I \cdot \frac{2\pi}{p} \cdot Aa \cdot \frac{2\pi}{p} \\ &= \frac{4\pi^2}{p^2} \cdot I \cdot Aa \end{aligned} \qquad (28)$$

T: Torque
$\ddot{\theta}$: Angular velocity
I: Moment of inertia
Aa: Axial velocity

When the rotor is a cylinder, the moment of inertia in equation 28 is described by equation 29.

$$I = \frac{m_t\left(D_2^2 + D_1^2\right)}{8} \qquad (29)$$

M_t: Rotor mass
D_1: Rotor inner diameter
D_2: Rotor outer diameter

When inserting Pitch: 2. 5cm, Outer diameter: 26cm, Inner diameter: 20cm into the equation 29, the equivalent mass $\left(4\pi^2/p^2\right)\cdot I$ is 253,668kg. This (253,668kg) is approximately 850 times the original mass of 300kg.

In addition to the above resistive force, the device is subject to resistive forces from other parts such as the ball-screw, the support bearing, and the seals. The following equations specify the performance of the GMD, derived from various theories and experiments.

$$Pn = \alpha \cdot \lambda \cdot Qn + Ia$$

$$\alpha = 2.6463 \cdot \left(\frac{\phi \cdot Vn}{dy} \right)^{-0.1473}$$

($\alpha \leq 1.0$)

$$\lambda = \frac{1}{\left(1 - \frac{0.005 \cdot (\phi_1^2 + 1)}{\phi_1 + 0.005} - 0.005 \cdot \phi_2 \right)}$$

$$Qn(V) = \phi \cdot \nu(Vn, t) \cdot \left(\frac{\phi \cdot Vn}{dy} \right) \cdot A$$

$$\nu(Vn, t) = \frac{\nu_0}{1 + b \cdot \left(\frac{\phi \cdot Vn}{dy} \right)^{\beta}} \times 10^{-10}$$

$I\alpha$:Inertia force in the axial direction
ρ:Amplification factor from friction
ϕ_1:Rate of velocity amplification at the ball bearing
ϕ_2:Thrust bearing rate of velocity amplification
Q_n:Damper circumferential axial force from viscous damping
V_n:Axial velocity
d_V:Shear clearance
ϕ:Rate of velocity amplification of damper ($=2\pi r_0/\rho$)
A:Effective area $2\pi r_0 L$
p:Pitch
r_B:Outer radius of ball screw
r_{so}:Outer radius of thrust ball bearing ($=r_0$-1)
r_o:Outer radius of internal cylinder
L_e:Effective length
$\nu(\nu_{n.t})$:Apparent viscosity
ν_o:Kinematic viscosity (2.3723x $\nu_t^{0.2963}$) at shear displacement 0&t^{o}C
b:Apparent viscosity constant(0.000846 x $\nu_t^{0.2963}$)
β:Constant of apparent viscosity (0.2793$\nu_t^{0.0768}$)
ν_t:Base kinematic viscosity at t^oC (ν_{25} x $1.02^{(25-t)}$)
ν_{25}:Kinematic viscosity of viscous material (25^{o}C)

Figure 6 shows the relationship between the damping (resistant) force and velocity, figure 7 shows the damping force and displacement of the GMD shown in table 1 under the steady state input wave specified in table 2.

TABLE 1 Specification of Device(GMD)

Cylinder outer radius : r_o	13.2(cm)	Lead length : p	2.5(cm)
Cylinder internal radius : r_o	8.87(cm)	Effective length : Le	73.0(cm)
Ball-screw axial radius : r_B	6.0(cm)	Kinematic viscosity of viscous material(at25 ^{o}C)	300,000(cSt)
Outer radius of thrust bearing : r_{so}	12.2(cm)	Temperature : t ^{o}C	20.0(^{o}C)
Shear clearance: dy	0.25(cm)	Ratio of velocity amplitude at damper : ϕ	33.175

TABLE 2 Specification of Input motion(Steady state Wave, Sine Wave)

Specification of steady wave (sine wave)	symbol	Input value	unit
Input amplitude	δ_o	4.0	cm
Frequency	f	1.0	Hz
Angular frequency	ω	6.28	rad/sec
Maximum velocity	$\omega\delta_o$	25.13	cm/sec
Maximum acceleration	$\omega^2\delta_o$	157.91	cm/sec^2

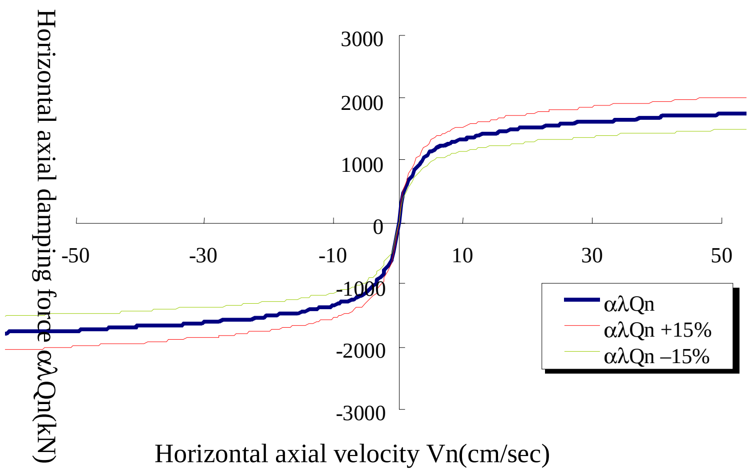


Figure 6. Relationship between axial velocity V_n and damping force $\alpha\lambda Q_n$

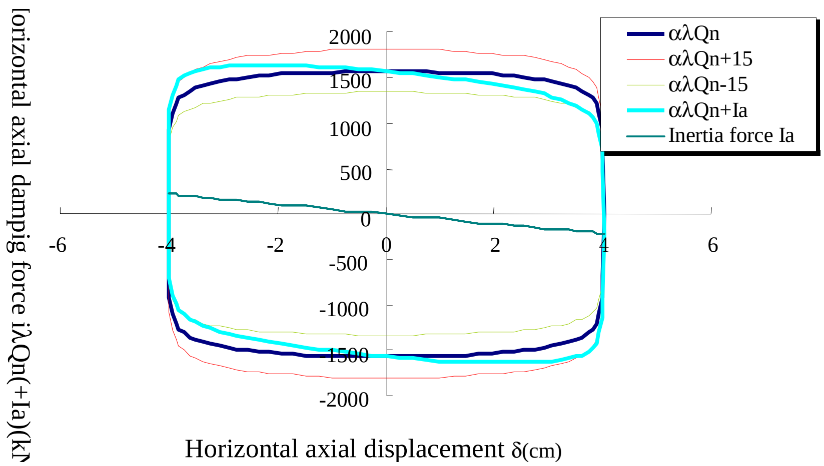


Figure 7. Relationship between axial displacement δ-damping force $\alpha\lambda Q_n$(+Ia)
(characteristics of steady state input wave)

RESPONSE CHARACTERISTICS OF A SEISMICALLY ISOLATED STRUCTURE

Response characteristics of a single-lumped mass system.

Prior to designing a seismic-isolated structure using GMDs, the response of a single-lumped mass system was examined. The superstructure is modeled as a single-degree of freedom lumped mass, the laminated rubber bearing is represented by the elastic spring element, and the viscous damping of the GMD is represented by the dashpot.

In this study, the added mass from the GMD was treated by including it in the lumped mass.

Figure 8 shows the response spectra of several earthquake motions.

The ART-WAVE, among input earthquake motion, is a simulated earthquake motion designed to fit an energy spectrum consistent with VE (equivalent velocity) =150 (cm/s) within a period range of 0.6 seconds or more.

Figure 9 shows the maximum response displacement and Figure 10 illustrates the maximum response absolute acceleration. In both figures the ratio of added mass is on the vertical axis. The maximum displacement in the long period model showed a greater response reduction effect in response to the increase in the added mass, regardless of the damping level.

The dispersion due to the difference in earthquake waves is also smaller in the long period model with added mass. On the other hand, the acceleration response, irrespective of the period difference, showed almost no response reduction in any model. As the added mass increases, the effects of the input earthquake motion dominate, thereby resulting in a slight increase in the absolute acceleration response.

From the above analysis, it was concluded that in order to reduce both the displacement response and the acceleration response in isolated buildings with GMD dampers, it was necessary to prolong the natural period of the seismic-isolation as well as adding mass in the order of 0.1W (where W is the weight of the structure).

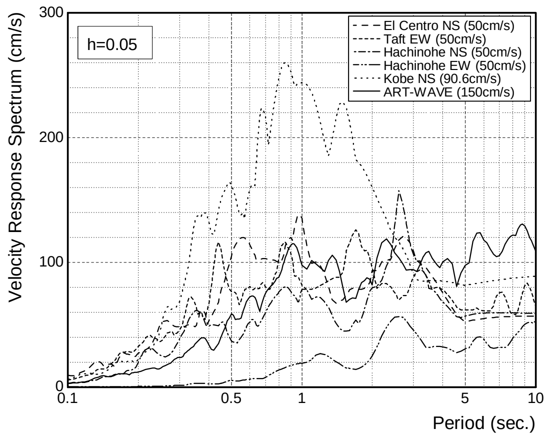


Figure 8. Response spectra

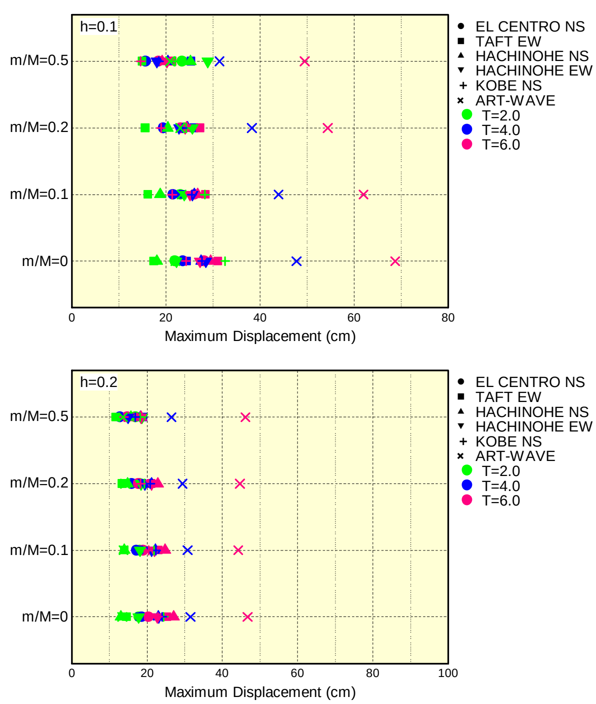


Figure 9. Maximum response displacement

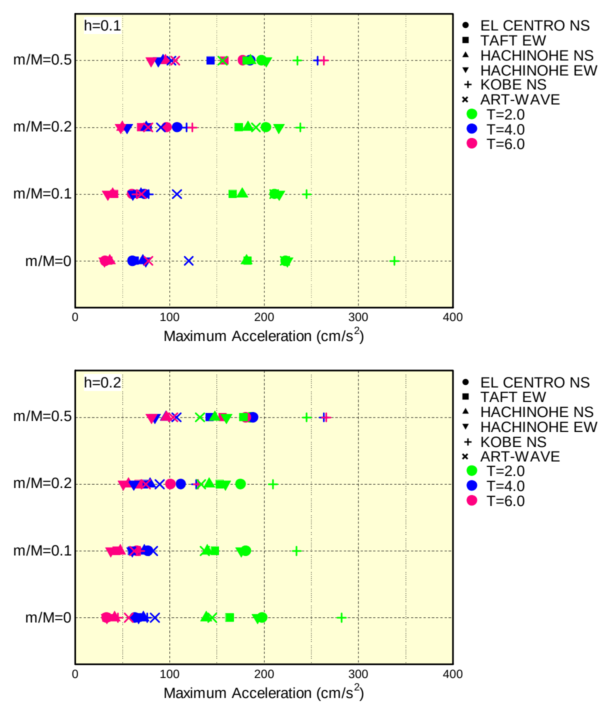


Figure 10. Maximum response absolute acceleration

Response characteristics for multi-mass system

The analysis model is a seven-story office building with a typical steel-frame as shown in figure 11.
The analysis model is a lumped mass-shear spring system. Table 3 shows the weight on each story and the spring constant on each layer. The internal damping of the building is set as 2%.
A simulated earthquake motion used for the analysis of the single-mass model was adopted as the input earthquake motion.

Assuming the upper structure is a rigid body, the seismically isolated floor is given a spring stiffness whose natural period is 6.0 seconds. As for viscous damping and added mass, six cases were set out: 3 cases of h=15%, h=20% viscous damping provided by an RDT and 4 cases of h=10% viscous damping provided by an GMD and added mass ratios of 0.0, 0.1, 0.2, and 0.5 to the total mass respectively.

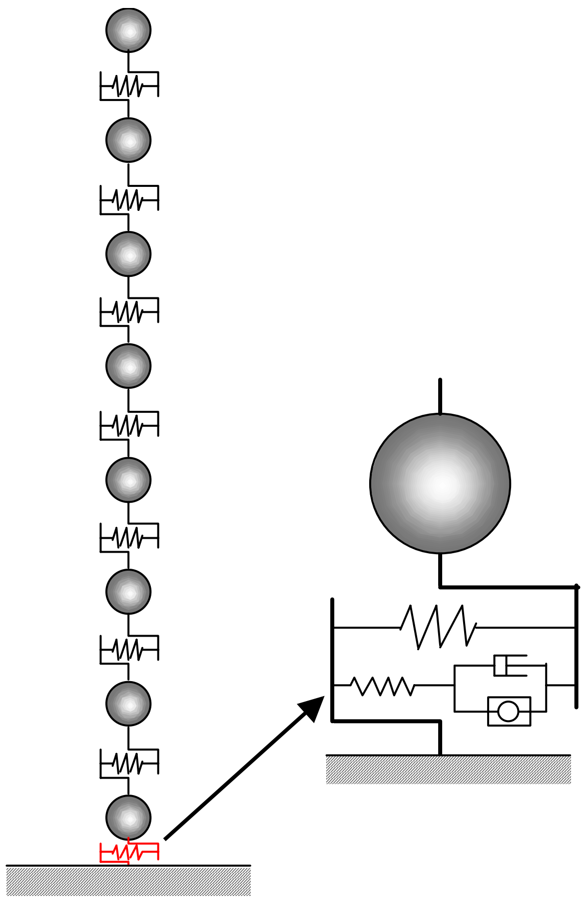


Figure 11. Analysis model

Table 3. Model weight and spring constantsl

LEVEL	M(ton)	K(kN/ m)
8	141.5	
		54830
7	124.8	
		60760
6	146.2	
		98740
5	146.2	
		106120
4	147.9	
		121660
3	149.7	
		140190
2	151.2	
		126290
1	166.3	

Figure 12 shows the maximum model responses. With an increase in the ratio of the added mass, the response displacement is reduced; yet the response acceleration increases. The maximum response displacements, in the case of 10% viscous damping and 0.5 ratio of added mass, is equal to the case of only 20% viscous damping by an RDT. However, the maximum response acceleration and the maximum response shear forces, in the cases of more than 0.2 ratio of added mass, increase significantly. To control the displacement and the acceleration simultaneously, the appropriate added mass ratio is around 0.1.

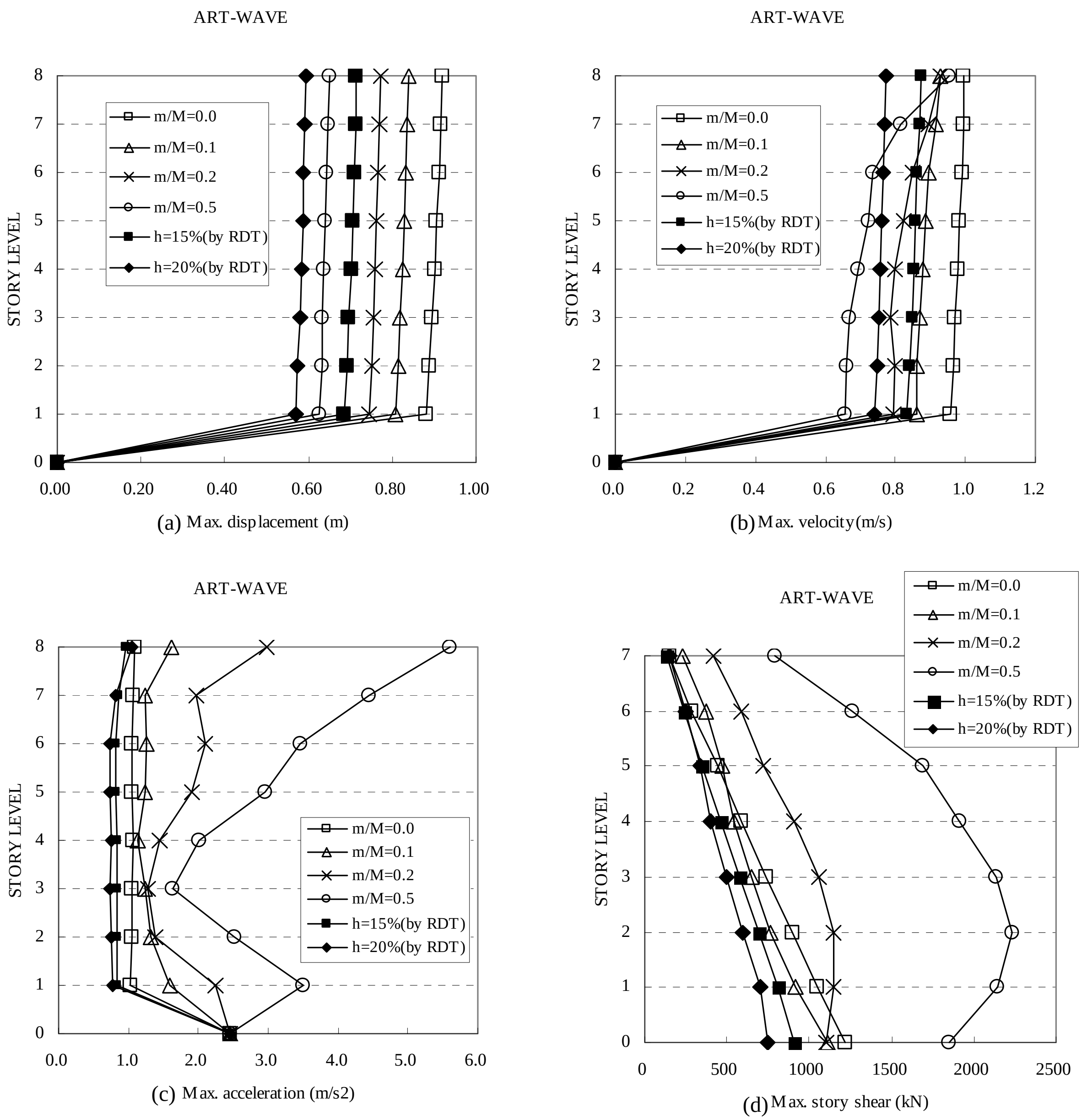


Figure 12. Model responses

CONCLUSIONS

Through some theoretical study and analyses, we have reached the following conclusions.

1. When added mass is applied to isolated structures, it is a practical approach to adopt values within the following ranges: added mass ratio; $\alpha \leq 0.2$、 damping ratio; $h \leq 0.20$.

2. When added mass is applied to a multi story structure to control the response, structures with more floors require more added mass. This is because the added mass in the each floor is the linear sum of the main mass above the floor.

3. Through the analytical study of a single-lumped mass system, it is concluded that in order to reduce both the displacement response and the acceleration response in isolated buildings with GMD dampers, it is necessary to prolong the natural period of the seismic-isolation as well as adding mass in the order of 0.1W (where W is the weight of the structure).

4. Through the analytical study of a multi-lumped mass system, we have reached the conclusion that an effective response control is possible with a damping constant of around 10% and a ratio of added mass around 0.1W in a considerably long natural period since the response is less sensitive to the effect of input earthquake motion.

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