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A Study on Response Control Efficacy by Using Rotary Inertia Mass Damper Filled with Magneto-Rheological Fluid

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Abstract

This paper relates to response control of a base-isolated structure with a hybrid vibration device ("MR rotary inertia damper") aiming at two purposes: 1) mass effects with rotary inertia and 2) variable damping effects with magneto-rheological fluid, developed by authors in order to control vibration response to earthquakes. Our goal is to propose a method to reduce response displacement of seismic floor by controlling floor response acceleration with semi-active control toward various earthquakes that generally used for aseismic design in Japan. Based on these results, a vibration analysis model is proposed in this paper with performance tests of the MR rotary inertia damper as a semi-active vibration control device, to review frequency characteristics and propose a semi-active control with a skyhook method. Response control effects of the MR rotary inertia damper to earthquakes are discussed with time-history response analysis in regards to the control method proposed. Findings obtained in this paper are the following.

In performance tests of the MR rotary inertia damper, a prototype with the maximum output of 100kN was prepared and the basic characteristics were summarized by using a vibration test with displacement input of an actuator, to verify adequacy of theoretical formulas. Energy absorption effects with resistance to shear flow of MR fluid as well as with yield stress upon magnetic field action were confirmed in the sin-wave input tests, to indicate the effectiveness as a semi-active control device that uses variable damping force.

Based on the performance tests of the MR rotary inertia damper, we review the seismic isolation model, from the viewpoint of transfer function in the frequency range as well as of time-history response to earthquake motions. The range that can reduce both acceleration transmission and displacement transmission by adopting a proper mass ratio is suggested from the transfer function in the frequency range. However, there are advantages and disadvantages in the mass ratio and damping ratio, and we suggest that their tradeoff relationship cannot be resolved only with passive control. By adopting the skyhook method toward this problem, we suggest the possibility of reducing the transmission adjacent to the resonance frequency without deteriorating the transmission in the high frequency range. In addition, it is clarified from the review on time-history response that the floor response acceleration can be effectively reduced in the case of pulse earthquakes particularly with major vibration with 1-2 seconds period by adopting a proper mass ratio and damping ratio. At the time of passive control, semi-active control effects on each input earthquake motion were identified in the case of combination of mass ratio and damping ratio that minimizes the maximum floor response acceleration, confirming that the maximum floor response acceleration and the maximum response displacement can be reduced by approximately 1% and 30% on average, respectively. It was concluded in accordance with these results that the semi-active control method that incorporates inertia mass effects proposed in this paper is effective to control the floor response acceleration while reducing the response displacement of seismic floor at the same time.

Keywords: Seismic isolation, Damper, Magnetorheological fluid, Inertia mass, Semi-active control

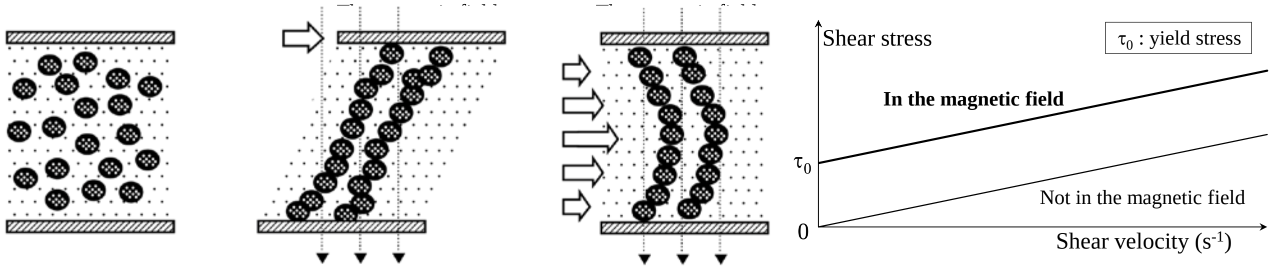
1. Introduction

In regards to a rotary inertia mass damper using magnetorheological fluid ("MR fluid"), the vibration control device developed by authors, basic characteristics as a vibration control device are summarized in this paper with the purpose to control vibration response of building structures to earthquakes. The rotary inertia mass damper that uses MR fluid developed by the authors ("MR rotary inertia damper") is a hybrid vibration control device aiming at (1) mass effects with rotary inertia and (2) variable damping effects with MR fluid, by adding improvements applicable to building structures toward a vibration control device utilizing rotary inertia mass which is used as a vibration measure for piping equipment at nuclear facilities and plants, and by further using MR fluid with which semi-active control is possible.

The concept to utilize a mass effect for vibration control has been incorporated in the field of mechanical vibration control from early on, and the fixed points theory[1] by Den Hartog is widely known as the optimum design method for tuned mass dampers (TMD). TMD is often used for wind swinging control of towering structures and high-rise structures in the field of construction, while the structural mass as the control target is large in comparison with the added mass, requiring a very large added mass to obtain major vibration control effects, which will lead to unnecessary increase of load bearing on the structure subject to control as the main vibration system. In addition, only one mode of vibration can be controlled in principle, and there are disadvantages, including that effects are less likely from strong and unsteady vibration; therefore practical application to seismic movements was difficult. With this background, a mechanism to amplify and convert axial motions to high-speed rotary motions with ball screws have been proposed in recent years in order to achieve major vibration control effects at the time of great earthquakes, as attempts to amplify a small virtual mass. In particular, the ball-screw mechanism is realized with the viscous damping device called a "rotary damping tube (Gensui-koma in Japanese)" to acquire resistance force from shear resistance of viscous materials filled in the space inside of the external cylinder, which has been put to practical application as a vibration control device for building structures in the past. Tangential displacement of the internal cylinder in the rotational direction is amplified to 5 to 40 times as much as the axial displacement, and the mass of the internal cylinder rotates at a high speed to generate the rotary inertia mass, which is amplified to the value of virtual mass multiplied by the square of the displacement amplification ratio; therefore becomes more than as 1,000 times as the virtual mass of the internal cylinder. As a result of such technology development, vigorous studies are progressing in regards to adjustment methods to mutually link the mass term, damping term and stiffness term in the vibration equation.

The MR rotary inertia damper by the authors uses MR fluid as viscous materials filled in the space inside of the external cylinder in the above "rotary damping tube (Gensui-koma in Japanese)" and its apparent viscosity increases with the action of the magnetic field. Magnetic particles are dispersed in MR fluid, and were first applied to clutches by Rabinow[2]. As shown in Fig.1(a) to (c), magnetic particles are polarized upon being subjected to the magnetic field and chainlike particles are organized in the fluid (clusters are created); therefore viscosity increases as resistance is created to shear flow or pressure flow. The level of resistance varies depending on the size of the magnetic field, and apparent viscosity increases to generate a stronger magnetic field to a certain extent. On the other hand, clusters collapse when the magnetic field is withheld, magnetic particles return to the dispersed condition, and resistance returns to the original state. Thus, as indicated in Fig.1(d), shear speed and shear stress are generally in a proportional relationship, i.e., characteristics of Newtonian fluid are indicated when the magnetic field is not in effect, while characteristic of Bingham fluid with the yield stress τ_0 are presented when the magnetic field is in effect. An MR damper is a vibration control device in which MR fluid is filled in the working fluid of the damper consisting of cylinder and piston by utilizing these characteristics of MR fluid. The MR damper is a semi-active vibration control device that can control the damper output by installing electromagnets within the device and changing the current applied to electromagnets to fluctuate the magnetic field received by MR fluid. It has the characteristic of discretionary control, and various control methods have been proposed[3], [4] mainly targeting seismic buildings. It is applied to not only seismic buildings but also control proposed as a seismic control system for general buildings (clipped-optimal control[5]) and wind control at cable-stayed bridges as well as of traffic vibration[6].

In this paper, the appropriateness of the theory is verified with vibration tests, etc. using actuator displacement input in regards to MR rotary inertia damper with the maximum output of 100kN.



(a) Not in the magnetic field (b) In the magnetic field (shear flow) (c) In the magnetic field (pressure flow) (d) The relation between shear velocity and stress

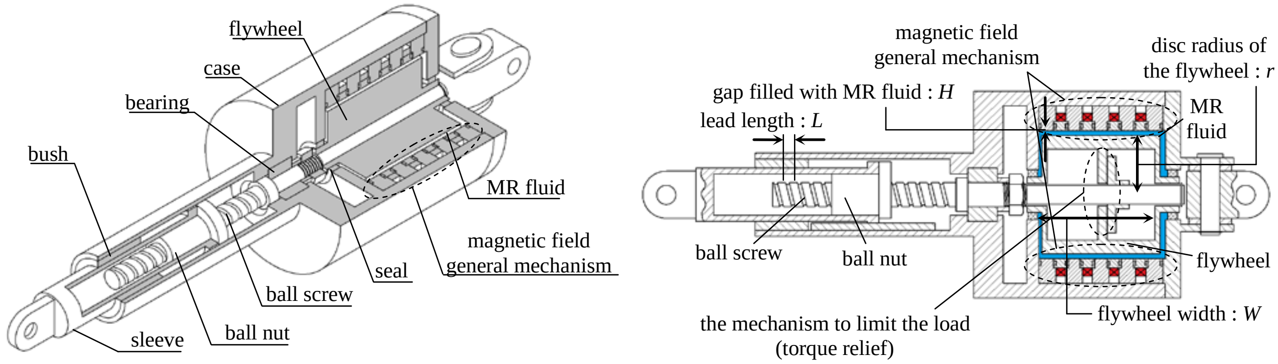
Fig. 1 — Resistance mechanism of MR fluid

2. STRUCTURAL OVERVIEW OF ROTARY INERTIA MASS DAMPER USING MAGNETORHEOLOGICAL FLUID

Fig.2 is showing the schematic diagram of the structure of MR rotary inertia damper. The output generation part of MR rotary inertia damper mainly consists of a ball screw, ball nut, flywheel (added mass), and MR fluid as well as of the magnetic field general mechanism (electromagnet). Linear motions are converted into rotary motions with the ball screw and ball nut, rotary inertia force is generated with rotation of the flywheel attached at the tip of the ball screw, and inertia force in proportion to axial acceleration is output due to mass effects to multiply rotary inertia force through the ball screw.

The equivalent mass with the amplification mechanism is 27.4ton in comparison with the virtual mass of the flywheel (=20kg), achieving 1,370-fold inertia force. On the other hand, shear speed is generated from the relative displacement between the flywheel and case, as a result of flywheel rotation. Thus, damping force can be obtained with resistance to the shear flow of MR fluid filled around the flywheel at the same time as inertia force. As indicated in Fig.3, the case where MR fluid is filled is equipped with the magnetic field generation mechanism, and has the structure to be able to adjust the damping force by changing the strength of the magnetic field working on MR fluid so that the resistance force of MR fluid can be voluntarily established to adjust the damping force. Magnetic particles of MR fluid used are iron particles with the diameter of approximately 10μm or less, and chemosynthetic oil is used for fluid. MR fluid is generally at a high cost, and magnetic particles are deposited due to the difference of specific gravity between magnetic particles and oil; therefore there may be challenges in practical application. In regards to sedimentation, dispersing agents or surface activation agents may be added or special processing may be applied onto the surface of magnetic particles in some cases, in order to maintain the condition where magnetic particles are dispersed in the oil as long as possible. Authors are attempting to solve these problems for practical application with 1) agitation action to MR fluid with high-speed rotation motions with the ball screw mechanism and 2) reduction of MR fluid usage with effective viscous resistance utilizing high-speed shear flow. In comparison with a common piston-type MR damper with the same level of maximum output, the usage of MR fluid can be significantly reduced to approximately 10 to 20% even though the usage of MR fluid depends on pressure setting within the piston and cylinder as well as on the design of the magnetic field generation mechanism part.

The output with MR rotary inertia damper is expressed as the sum of inertia force F_I with rotary inertia mass and damping force F_V with shear resistance force of MR fluid. The relationship between inertia force and acceleration as well as the relationship between damping force and speed is indicated in Fig.4, respectively. Main specification characteristics of MR rotary inertia damper are indicated in Table 1. A mechanism to limit the load (torque relief) is equipped with the rotation part to prevent overloading to a damper in the case of input exceeding expectation to MR rotary inertia damper. Friction materials are used for the contact part between the axial part and rotation part, with the structure that the axis slides when the friction force exceeds a certain value and the output reaches the peak.



(a) Perspective (b) Section

Fig. 2 — Schematic diagram - structure of MR rotary inertia damper

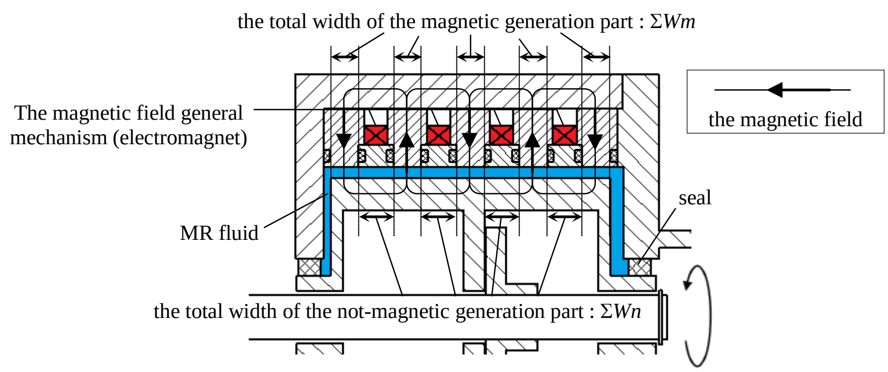
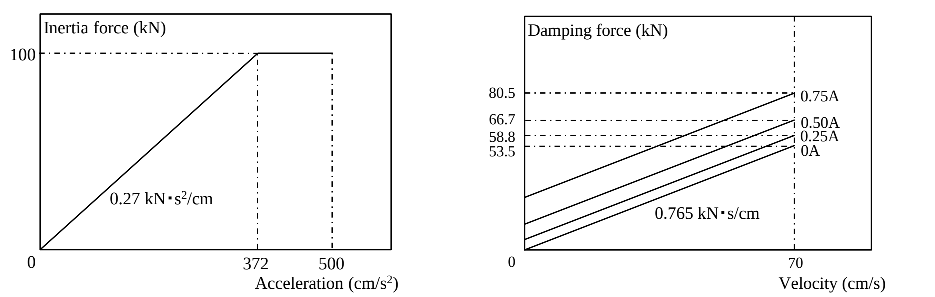


Fig. 3 — Schematic diagram – part of magnetic field generation mechanism



(a) The relationship between acceleration and inertia force (b) The relationship between velocity and damping force

Fig. 4 — Characteristics of MR rotary inertia damper

Table 1 — Main specification characteristics of MR rotary inertia damper

Item	Unit	Value
Allowable Max. load	kN	100
Allowable Max. acceleration	cm/s^2	500
Allowable Max. velocity	cm/s	70
Allowable stroke	mm	250（±125）
Inertia mass	ton	27.4
Damping factor	kN・s/cm	0.765
Variable damping force of MR fluid	kN	5.3（0.25A）
	kN	13.2（0.50A）
	kN	27.0（0.75A）

Table 2 － Conditions of sin-wave excitation test

Period (sec.)		0.2	0.3	0.5	1.0	1.5	3.0	4.0	5.0
Frequency (Hz)		5.00	3.00	2.00	1.00	0.67	0.33	0.25	0.20
Radian frequency (rad./s)		31.42	18.87	12.57	6.28	4.19	2.09	1.57	1.26
Amplitude (±mm)	1	3.1	1.9	1.3	0.6	0.4	0.2	0.2	0.1
		98.7	35.6	15.8	3.9	1.8	0.4	0.2	0.2
	5	15.7	9.4	6.3	3.1	2.1	1.0	0.8	0.6
		493.5	178.0	79.0	19.7	8.8	2.2	1.2	0.8
	10	－	18.9	12.6	6.3	4.2	2.1	1.6	1.3
		－	356.0	157.9	39.5	17.5	4.4	2.5	1.6
	20	－	－	25.1	12.6	8.4	4.2	3.1	2.5
		－	－	315.8	79.0	35.1	8.8	4.9	3.2
	50	－	－	－	31.4	20.9	10.5	7.9	6.3
		－	－	－	197.4	87.7	21.9	12.3	7.9
	80	－	－	－	50.3	33.5	16.8	12.6	10.1
		－	－	－	315.8	140.4	35.1	19.7	12.6
	100	－	－	－	62.8	41.9	20.9	15.7	12.6
		－	－	－	394.8	175.5	43.9	24.7	15.8
	120	－	－	－	－	50.3	25.1	18.8	15.1
		－	－	－	－	210.6	52.6	29.6	18.9

* Shown in the above table, in each case vibration pressure, the upper white cell show the value of maximum speed (cm/s), the lower gray cell show the value of maximum acceleration (cm/s^2)

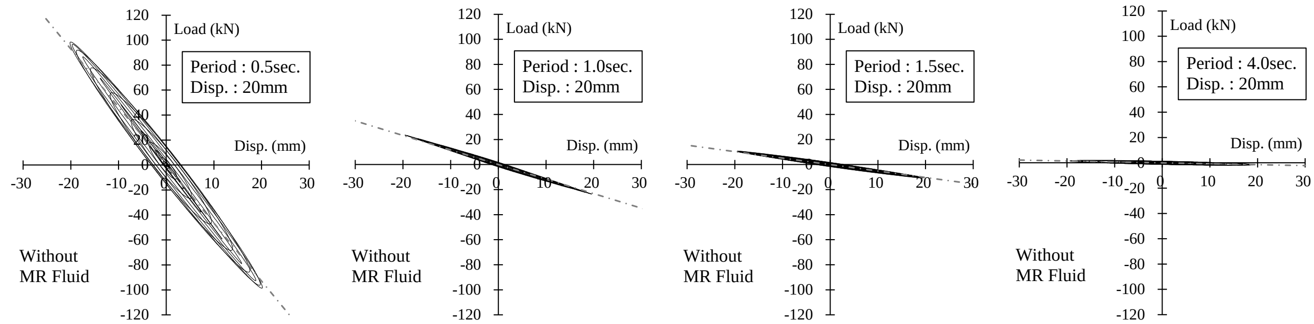


Fig. 5 － Load-displacement relationship in sin-wave excitation test (before filling of MR fluid)

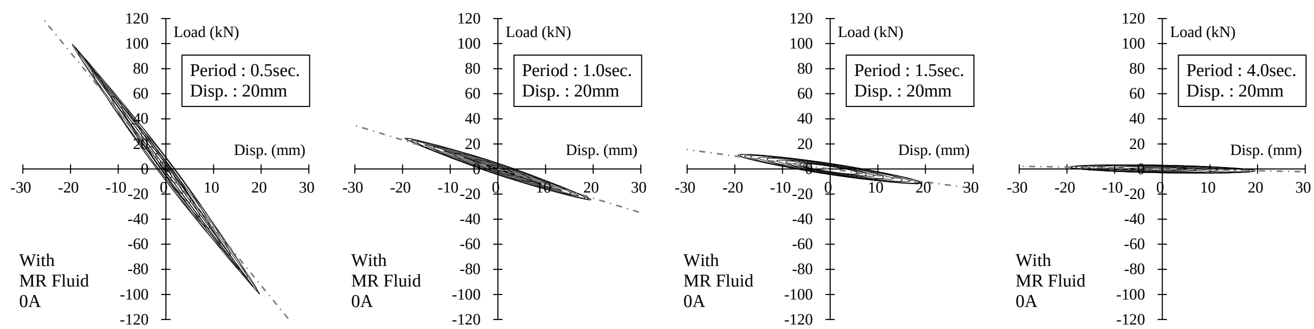


Fig. 6 － Load-displacement relationship in sin-wave excitation test (after filling of MR fluid without applying the current)

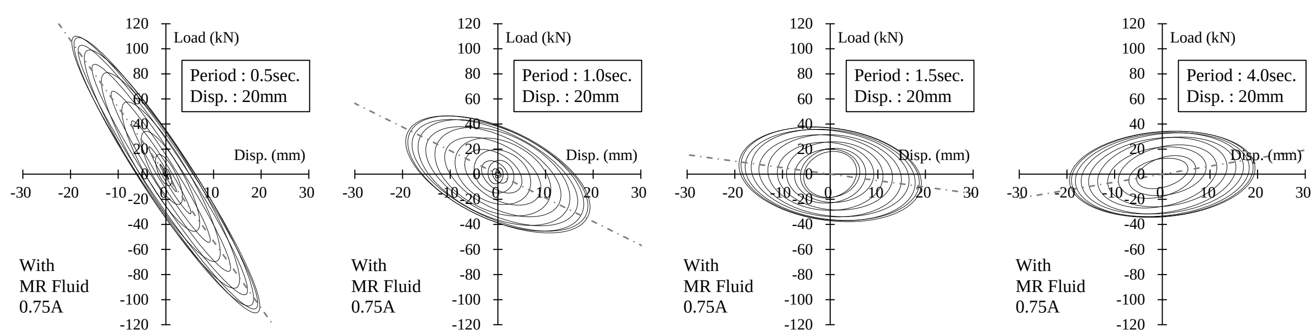


Fig. 7 － Load-displacement relationship in sin-wave excitation test (after filling of MR fluid upon applying 0.75A)

3. PERFORMANCE TESTS

A prototype model with the maximum output of 100kN was prepared and performance tests were conducted, in order to confirm the basic characteristics of MR rotary inertia damper. The performance tests were conducted including sin-wave excitation tests. Similar tests were conducted before and after filling of MR fluid in order to confirm the influence of MR fluid.

Test conditions of sin-wave excitation tests are indicated in Table 2. A total of 48 cases of sin-wave excitation tests were conducted within the cycle of 0.2 to 5.0 seconds and the amplitude level of 1 to 120mm as indicated in the figure. Representative load-displacement relationship is indicated in Fig.5 to 7. Fig.5 is the case prior to filling of MR fluid, Fig.6 is the case after filling of MR fluid without applying the current, and Fig.7 is the case after filling of MR fluid upon applying the constant current of 0.75A. Excitation cycles are 0.5, 1.0, 1.5 and 4.0 seconds and excitation amplitude is ±20mm for results of all cases. Comparison is conducted in regards to the cases enclosed with bold lines in Table 2. As a general trend, apparent negative spring characteristics are confirmed. When the excitation cycle is longer, its gradient becomes moderate.

Comparison before and after filling of MR fluid in Fig.5 and 6 shows increase in the hysteresis area, confirming energy absorption with shear resistance of MR fluid. Furthermore, energy is absorbed with significant increase in the hysteresis area when the current is applied in Fig.7; therefore effective vibration control can be expected with semi-active control that uses this variable damping force by utilizing MR rotary inertia damper. In addition to each of the respective effects of rotary inertia mass and variable damping, realization of response control to reduce the increase in floor response acceleration can be expected by adding major damping in order to limit excessive response displacement of a building, as a synergy effect of conducting semi-active control of variable damping while applying negative spring characteristics with rotary inertia mass.

4. REVIEW ON THE FREQUENCY DOMAIN

In this chapter, vibration characteristics in the case of adding an MR rotary inertia damper to the undamped vibration model of one mass system as indicated in Fig.8 are organized in the form of a transfer function to review the response control efficacy. A base-isolated building is envisioned as a target model, and natural frequency of the structure is set at 0.25Hz (4-second natural period). With absolute displacement of the structure as x_1 and absolute displacement of the supporting member as x_0, the vibration equation in the case that the supporting member is excited in the target model in Fig.8 can be expressed as (1). The vibration equation is expressed with the absolute coordinate system, and the transfer function of the output (response) to the input (excitation) is nondimensionalized with mass ratio μ and damping ratio ζ to the structure as well as with a natural circular frequency ratio λ for the purpose of give generality. Variable damping force with MR fluid is 5% of the sum of structural mass M and inertia mass m_d.

$$M\ddot{x}_1 + K(x_1 - x_0) + m_d(\ddot{x}_1 - \ddot{x}_0) + c_d(\dot{x}_1 - \dot{x}_0) + f_{MR} \cdot sign(\dot{x}_1 - \dot{x}_0) = 0 \quad (1)$$

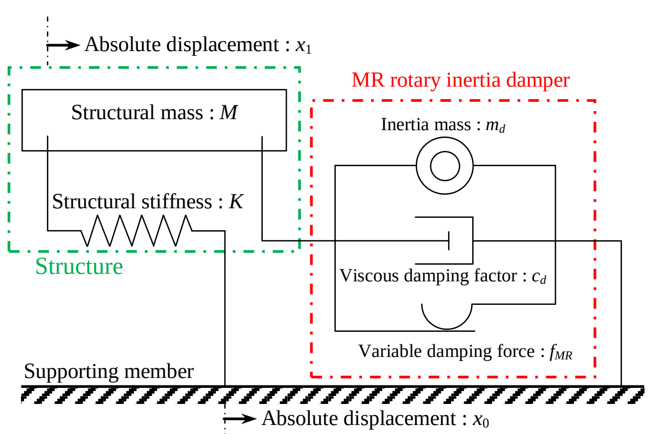


Fig. 8 — Target model

Natural radian frequency of the structure : $\omega_n = \sqrt{\frac{K}{M}}$, Natural radian frequency ratio : $\lambda = \frac{\omega}{\omega_n}$

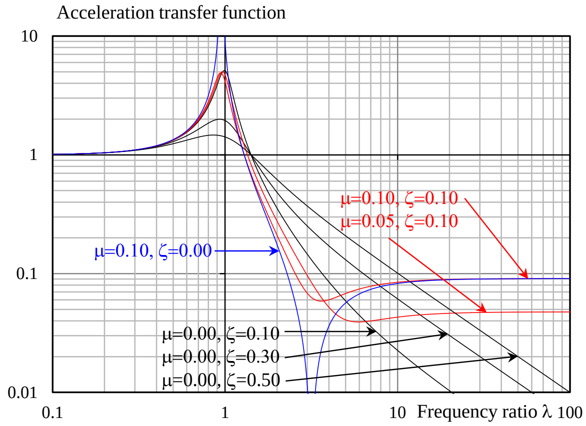
Mass ratio : $\mu = \frac{m_d}{M}$, Damping ratio : $\zeta = \frac{c_d}{2\sqrt{MK}}$

Acceleration of gravity : g, Radian frequency : ω

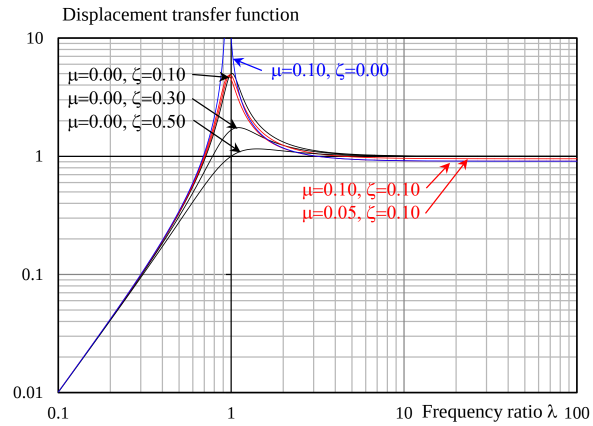
Variable damping force of MR fluid : $f_{MR} = (M + m_d) \cdot 0.05 \cdot g$

4.1 Case of passive control

In the case of passive control, the variable damping force f_{MR} with MR fluid in the fifth term of (1) is 0, and the transfer function of the output (response) to the input (excitation) X_1/X_0 is obtained as follows. $X1$ and $X0$ represent the displacement amplitude at the structure and supporting member.



(a) Acceleration transfer function



(b) Displacement transfer function

Fig. 9 — Transfer function in the case of passive control

Acceleration transfer function and displacement transfer function in the case of changing the mass ratio μ and damping ratio ζ are indicated in Fig.9. The black line in the figure is the case that the mass ratio is constant at μ=0 and the damping ratio ζ is changed to 0.10, 0.30 and 0.50, and the red lines are the case that the damping ratio is constant at ζ=0.10 and the mass ratio μ is changed to 0.05 and 0.10. When the mass ratio μ is constant, acceleration transfer function decreases when the damping ratio ζ is larger near resonance frequency (λ=1) according to Fig.9(a). This is similar in the case of displacement transfer function in Fig.9(b). In the high frequency region of $\lambda=\sqrt{2}$ or higher, however, acceleration transfer function increases when the damping ratio ζ is larger. On the other hand, displacement transfer function slightly decreases in the frequency region higher than resonance frequency, in the case that the damping ratio ζ is constant and the mass ratio μ is changed. A major change is observed in acceleration transfer function particularly in the high frequency region of $\lambda=\sqrt{2}$ or higher. When the case of μ=0.00 and ζ=0.50 is compared with the case of μ=0.05 and ζ=0.10 in acceleration transfer function in Fig.9(a) for example, it is possible to reduce acceleration transfer function in the case of μ=0.05 and ζ=0.10 rather than μ=0.00 and ζ=0.50 in the region of $\lambda=\sqrt{2}$ or higher, up to the range of around λ=20. On the contrary, acceleration transfer function increases in the case of μ=0.05 and ζ=0.10 when λ=20 is exceeded; however a frequency domain that can effectively reduce acceleration transfer function seems to exist by adding the mass ratio μ instead of increasing the damping ratio ζ. The periodic band of approximately 0.2 to 2.8 seconds ($\lambda=\sqrt{2}$ to 20) is equivalent to this range, since the natural period of the target model in this paper is 4 seconds. However, a major change in acceleration transfer function is not observed only with the change in the mass ratio μ near the resonance frequency (λ=1), and it is necessary to increase the damping ratio ζ in order to reduce acceleration transfer function. As described in the above, acceleration transfer function increases in the range $\lambda=\sqrt{2}$ or higher if the damping ratio ζ is larger. In the case that effects of the mass ratio μ with an equal damping ratio ζ are compared from the viewpoint of acceleration transfer function at the time of μ=0.00 and ζ=0.10 as well as μ=0.05 and ζ=0.10 for example, the frequency domain with relatively smaller acceleration transfer function decreases to the upper limit of λ=7 by giving the mass ratio μ when the damping ratio ζ is equal. In this way, the mass ratio μ and damping ratio ζ have their own merits and demerits in acceleration transfer function and displacement transfer function, and their tradeoff relationship needs to be property adjusted depending on the frequency characteristics of anticipated disturbance in the case of passive control.

4.2 Case of semi-active control

Based on the tradeoff relationship between the mass ratio μ and damping ratio ζ at the time of passive control in the above section, a solution method with semi-active control is proposed in this section. The tradeoff relationship described in the above in the case that the mass ratio μ and damping ratio ζ are respectively determined upon response control of ground motions mainly from the viewpoint of acceleration transfer function can be summarized as follows.

1) When the mass ratio μ is determined first, a range of specific frequency exists where both acceleration transfer function and displacement transfer function decrease by using a proper mass ratio μ. This range is larger when the damping ratio ζ is smaller. However, it is necessary to increase the damping ratio ζ in order to reduce the transmissibility near the resonance frequency (λ=1).
2) When the damping ratio ζ is determined first, both acceleration transfer function and displacement transfer function decrease near the resonance frequency (λ=1) by increasing the damping ratio ζ. However, acceleration transfer function increases in the high frequency range of λ=$\sqrt{2}$ or higher.

The above solution method with semi-active control is considered. As a method to solve 1), transmissibility near the resonance frequency (λ=1) can be reduced with semi-active control by adopting proper combination of mass ratio μ and damping ratio ζ. As a method to solve 2), acceleration transfer function in the high frequency region of λ=$\sqrt{2}$ or higher can be reduced with semi-active control by adopting a proper damping ratio ζ. Regarding 2), the effect to reduce absolute acceleration has been reported in existing studies [7] by giving apparent negative rigidity with semi-active control. In this paper, semi-active control in regards to the method to solve 1) is discussed in the following on the premise to incorporate mass effects with inertia mass.

The basic idea of semi-active control method assumes a system to give full-active control force, with the output of only reproducible force out of necessary control force. Therefore, the control system in a frequency domain is discussed as an active method. The skyhook method is adopted as a method to reduce transmissibility near the resonance frequency (λ=1) in 1) above and not to deteriorate transmissibility in the high frequency range upon reviewing the control system. With the skyhook method, the structural mass M is linked to the absolute rest point with a dashpot or spring as indicated in Fig.10, and the damping coefficient of the dashpot or the spring constant is increased (to infinity in an extreme case), intending absolute rest of the structural mass M regardless of the size of disturbance at the supporting member. The former is called the skyhook damper and the latter is called the skyhook spring. In the case of skyhook method, the fifth term of (1) and the term of variable damping force with MR fluid are replaced with the term of control force in the following formula that uses the state feedback gain g_1 and g_2.

$$f_{skyhook} = g_1\dot{x}_1 + g_2 x_1 \tag{2}$$

The acceleration transfer function | X_1/X_0 | and displacement transfer function | $(X_1 - X_0)/X_0$ | are obtained in the same way as the above section, by substituting (2) in (1).

Acceleration transfer function and displacement transfer function are indicated in Fig.11. The red line in the figure is showing the case of passive method with the mass ratio μ=0.05 and the damping ratio ζ=0.10, and the blue lines are the case of the same mass ratio μ and damping ratio ζ, and adopting the skyhook method with active damping ratio ζa (=0.20) and active rigidity ratio Na (=0.20 or 0.00). The black line is indicating the case of μ=0 where only damping is added at ζ=0.30. According to Fig.11, transmissibility near the resonance frequency (λ=1) is at the same level or below the case of adding damping only at ζ=0.30 with the skyhook method, confirming that transmissibility in the high frequency region does not deteriorate if the mass ratio μ is the same. In the case that the skyhook spring is added to the skyhook damper, acceleration transmissibility transfer function becomes smaller in the low-frequency region mainly at the level or below the resonance frequency, and displacement transfer function also decreases up to the range of approximately λ=0.3 to 1.0 (4- to 13-second natural period in the target model of this paper). Based on these results, the skyhook method can be expected to be a method to solve 1).

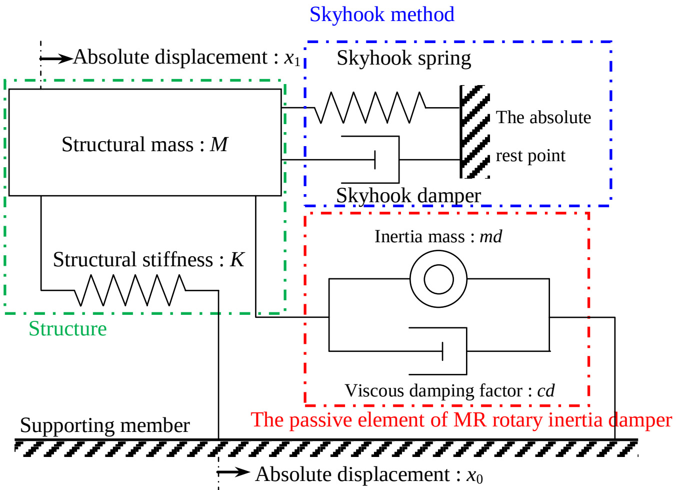
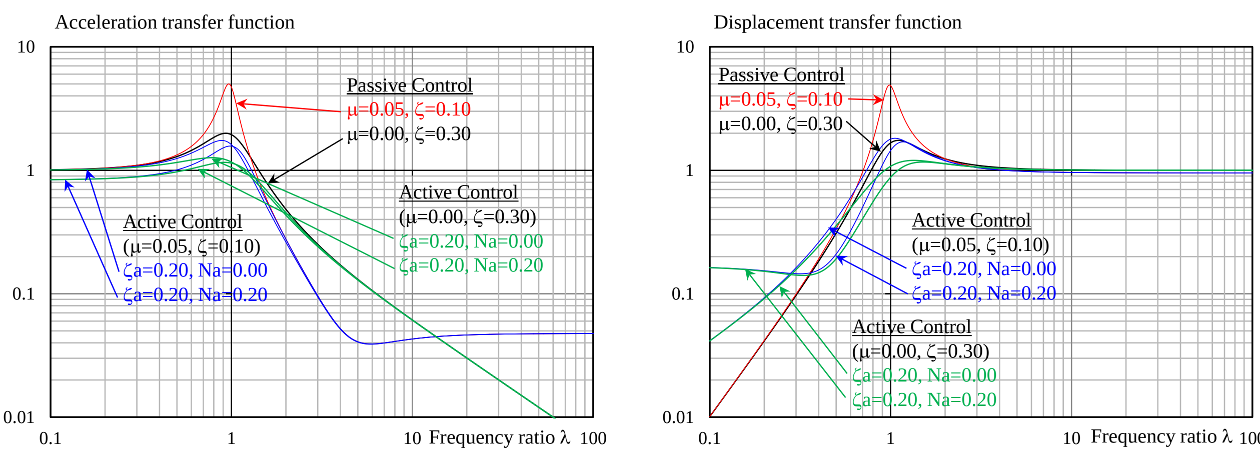


Fig. 10 — Principle of skyhook method



(a) Acceleration transfer function

(b) Displacement transfer function

Fig. 11 — Transfer function in the case of skyhook method

5. REVIEW ON TIME HISTORY RESPONSE

A series of review on the frequency domain in the above chapters is further reviewed from the viewpoint of time history response in this chapter. Control force feeds back absolute speed and absolute displacement of a structure in (2), while the direction of action by variable damping force of the actual MR rotary inertia damper depends on the direction of relative speed of the structure and supporting member. Thus, it is necessary to consider the absolute speed and absolute displacement as well as phase difference from relative speed in order to realize the skyhook method in the above. The switching rule with the skyhook method is indicated in Fig.12, by using the example of time-history waveforms in regards to the absolute speed of the structure as well as the relative speed between the structure and supporting member. As indicated in Fig.12, two conditions exist in regards to the absolute speed of the structure $\dot{x}_1$ and relative speed between the structure and supporting member $(\dot{x}_1 - \dot{x}_0)$: one is the case where the phase characteristics equalize in the region with time history, and the other is the case where they do not equalize. In order to achieve the skyhook method in semi-active control, therefore, the variable damping force of the MR rotary inertia damper is used to function as the control force only when $\dot{x}_1$ has the same sign as $(\dot{x}_1 - \dot{x}_0)$ as indicated in the following formula.

$$\begin{cases} f_{MR} = (M + m_d)\cdot \alpha_s \cdot g & (\dot{x}_1 \cdot (\dot{x}_1 - \dot{x}_0) \geq 0) \\ f_{MR} = 0 & (\dot{x}_1 \cdot (\dot{x}_1 - \dot{x}_0) < 0) \end{cases} \tag{3}$$

In the case that $\dot{x}_1$ has a different sign from ($\dot{x}_1$- $\dot{x}_0$), the control force functions to the direction opposite from the intended direction in the case of semi-active method; therefore the variable damping force of the MR rotary inertia damper is set at 0 as the next best solution. The response control efficacy to earthquakes at the time of passive and semi-active control is reviewed in the following with the analysis of time history response.

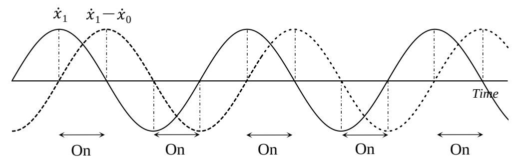


Fig. 12 ― Switching rule with the skyhook method

5.1 Target model

The target model in the analysis of time history response is similar to Fig.8, and a comparative review is conducted in regards to six cases of mass ratio μ including 0.00, 0.02, 0.05, 0.10, 0.30 and 0.50 and four cases of damping ratio ζ including 0.00, 0.10, 0.30 and 0.50. Address terms for the target model are established as follows.

Example: μ05 ζ10 (Case of mass ratio 0.05 and damping ratio 0.10)

ζ00, ζ10, ζ30, ζ50: damping ratio 0.00, 0.10, 0.30, 0.50

μ00, μ02, μ05, μ10, μ30, μ50: mass ratio 0.00, 0.02, 0.05, 0.10, 0.30, 0.50

Table 3 ― List of input earthquakes

Earthquakes	Duration time (sec.)	Max. value		
		Acceleration (gal)	Velocity (kine)	Displacement (cm)
ElCentro	53	510	50	17
Hachinohe	234	350	50	17
JMAKobe	160	818	91	20
JRTakatori	150	606	122	41

5.2 Input ground motions

El Centro 1940 NS, Hachinohe 1968 NS, JMA Kobe 1995 NS, and JR Takatori 1995 NS (hereafter abbreviated as "ElCentro," "Hachinohe," "JMAKobe," and "JRTakatori," respectively) are used for input earthquakes as representative observation records. The duration of each ground motion as well as maximum acceleration, maximum speed and maximum displacement are indicated in Table 3.

5.3 Case of passive control

Maximum floor response acceleration and maximum response displacement at the time of passive control are indicated in Fig.13 in regards to each input earthquake. Maximum floor response acceleration and maximum response displacement on the vertical axis are plotted by each damping ratio ζ with the mass ratio μ on the horizontal axis in Fig.13. A tendency is observed in the figure that maximum response displacement decreases and maximum floor response acceleration increases when the mass ratio increases as a whole in the range exceeding the mass ratio of approximately μ=0.10, except the cases that the damping ratio is ζ=0.00. This seems to be because acceleration transmissibility in the high frequency range increases when a large mass ratio μ is added as described in the above.

Next, maximum floor response acceleration tends to increase when the mass ratio μ increases, while downward-convex characteristics can be confirmed with extremely small values on the mass ratio μ=0.05 or μ=0.10. This is the effect of reducing acceleration in a specific frequency range by giving the mass ratio μ. Upon comparison between μ00ζ50 and μ05ζ10 for example, μ05ζ10 with a smaller damping ratio ζ has a larger effect to reduce acceleration in the periodic band of approximately 0.2- to 2.8-second natural period, as explained previously. It is confirmed in time history response that maximum floor response acceleration decreases by more than 50% in the case of μ05ζ10 compared with μ00ζ50, particularly in terms of JMAKobe and JRTakatori. With a proper mass ratio μ and damping ratio ζ in this way, floor response acceleration to pulse-like ground motion particularly with large amplitude of 1- to 2- second cycle seems to be effectively reduced. Looking at maximum response displacement in the case of JMAKobe and JRTakatori, however, maximum response displacement increases by 56% at maximum in the case of μ05ζ10 compared with μ00ζ50 which can be considered as enhanced isolation effects; however both maximum floor response acceleration and maximum response displacement cannot be refrained at the same time, suggesting the limitation of passive control only.

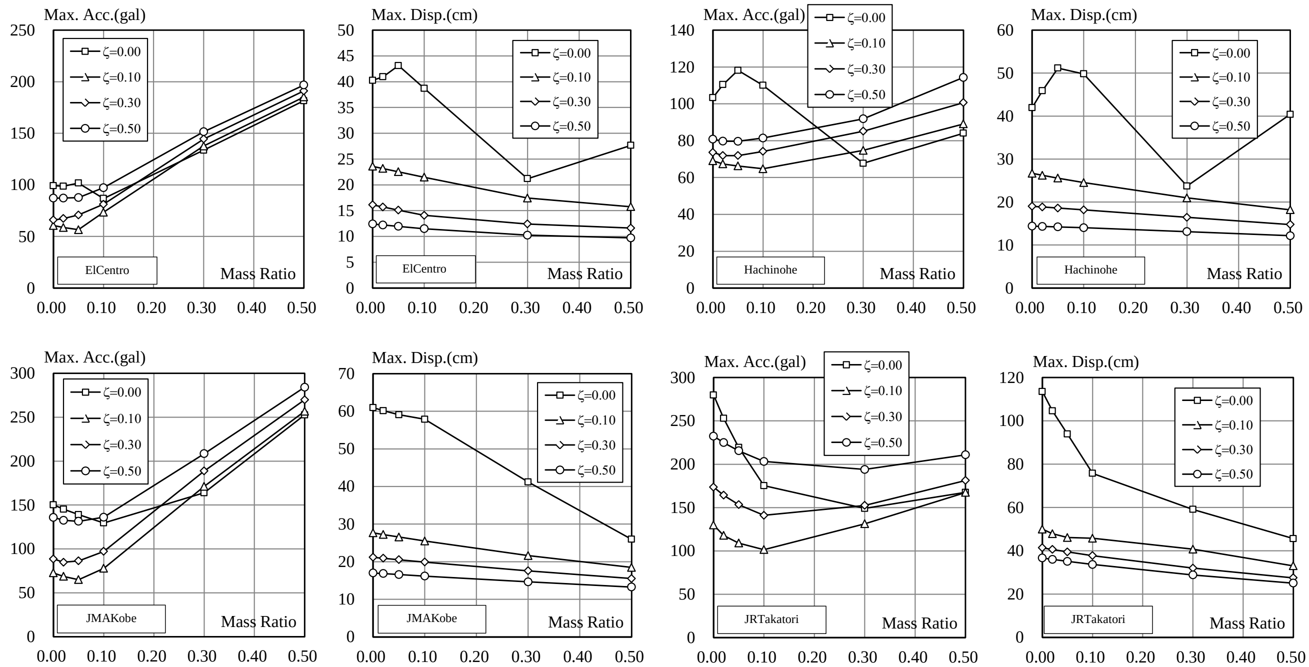
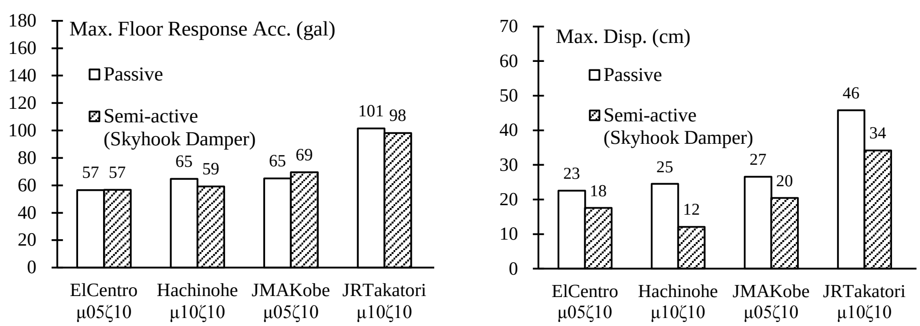


Fig. 13 ー Maximum floor response acceleration and maximum response displacement at the time of passive control in each input earthquake

5.4 Case of semi-active control

The case of semi-active control is reviewed next. Effects of semi-active control to each input earthquake are confirmed in the case of passive control indicated in Fig.13, in regards to the combination of mass ratio μ and damping ratio ζ that minimizes the maximum floor response acceleration. Fig.14 is indicating the maximum floor response acceleration and maximum response displacement in the case of μ05ζ10 for ElCentro, μ10ζ10 for Hachinohe, μ05ζ10 for JMAKobe, and μ10ζ10 for JRTakatori, respectively, at the time of passive control and semi-active control. The semi-active control rule in this section uses control only with a skyhook damper in the case that the active rigidity ratio Na is 0 in the skyhook method.



(a) Maximum floor response acceleration (b) Maximum response displacement

Fig. 14 ー Comparison of maximum values at the time of passive control and semi-active control

It is confirmed from Fig.14 that the response displacement can be reduced while refraining the maximum floor response acceleration at the same or smaller level at the time of semi-active control in comparison with passive control. The maximum floor response acceleration and maximum response displacement are reduced by approximately 1% and 30% on average, respectively, regarding the total of four types of ground motions used for review in Fig.14, suggesting that the semi-active control method with the skyhook method incorporating inertia mass effects proposed in this paper is an effective control method to reduce the response displacement in base-isolated layers while refraining the floor response acceleration.

6. CONCLUSION

A test model with the maximum output of 100kN was prepared in regards to MR rotary inertia damper, the vibration control device developed by the authors, and the basic characteristics were summarized with excitation tests by actuator displacement input. In addition, response control efficacy with an MR rotary inertia damper was reviewed by using the base-isolated building model with a 4-second natural period from the viewpoint of transfer function in a frequency domain as well as of time history response to earthquakes, to propose a semi-active control method with the skyhook method that incorporates inertia mass effects and discuss the effects. Knowledge obtained in this paper is the following.

1） Negative spring characteristics with inertia mass were confirmed according to sin-wave excitation tests. In addition, energy absorption effects with resistance force to the shear flow of MR fluid as well as with yield stress at the time of magnetic field action were confirmed, suggesting the usefulness as a semi-active control device using variable damping force.

2） It is clarified from the transfer function in a frequency domain that there is a domain that can reduce both acceleration transmissibility and displacement transmissibility by adopting a proper mass ratio μ.

3） If the premise is to design mass effects with inertia mass in the tradeoff relationship between the mass ratio μ and damping ratio ζ, transmissibility near the resonance frequency can be reduced without deteriorating transmissibility in the high frequency region by adopting the skyhook method.

4） Semi-active control efficacy to each input earthquake was confirmed in the case of combination of mass ratio μ and damping ratio ζ that minimizes maximum floor response acceleration at the time of passive control. Maximum floor response acceleration and maximum response displacement decreased by approximately 1% and 30% on average, respectively; therefore the semi-active control method with the skyhook method that incorporates inertia mass effects is an effective control method to reduce response displacement in base-isolated layers while refraining floor response acceleration at the same time.

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