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Dynamic Characteristics of Seismically Isolated Structure in Micro-Vibration

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Abstract

Due to damages during earthquakes in recent years, applications of seismic isolation to production facilities and development facilities have been increasingly considered aiming to keep the performances after earthquakes. However, seismically isolated buildings are seemed to have several disadvantages: 1) the effect of soil-structure interaction is quite small and thus dissipation damping to the ground cannot be expected, and 2) the conventional damping devices adopted in the seismic isolation layer can't perform the enough damping effects in micro-vibration. Thus, micro-vibration during normal times is concerned for adversely affecting the equipments that are sensitive to vibration.

In general, the responses of the isolated buildings subjected to the earthquake and micro-vibration are significantly depended on the characteristic of isolation story. The authors newly developed a special viscous damper to reduce the micro-vibration response of the isolated building which stores the production facilities and the sensitive equipments such as electronic microscope. This damper has the multi-layer resistance plates in the viscus fluid in order to perform the high damping in small displacement amplitude during micro-vibration. The maximum displacement is set to 50 mm and release pin is installed in order to prevent the fracture during earthquakes. The features are shown as follows: 1) It operates in a horizontal (X, Y) plane, 2) There is no allowance in the operation part and the damping force is demonstrated in minute displacement amplitude, and 3) The release pin is splitted at the earthquake to protect the damper from an excessive horizontal force. It is possible to replace the release pin after the earthquake.

The effect of the newly developed viscous damper against the micro-vibration has been examined and the dynamic characteristic of this damper is described with Maxwell model based on the experiments. The first seismic isolated facility with this damper constructed in Miyagi prefecture is 2 story (10.08 m) above the ground and the total weight is about 50MN. It is designed as isolated building made with steel framed-structure supported by 18 rubber bearings and 6 sliding bearings with rubber bearings. Four oil dampers are installed in each two (X and Y) directions against the earthquake, and two viscous dampers are specially installed to suppress the micro-vibration.

In this study the micro-vibration responses of this facility were monitored aiming to verify the properties and to establish prediction technologies and countermeasures. Forced vibration tests and microtremor measurements were conducted concerning a newly developed viscous damper to reduce the micro-vibration response, and comparisons were made of response-reducing effects under different conditions as with or without the dampers. As a result, the damping constant of the isolated building in the micro-vibration region can be doubled to about 0.16 owing to the dampers.

Keywords: seismically isolated building, micro-vibration, viscous damper, forced vibration test, development facility

1. Introduction

Due to the damages caused by recent earthquakes, the application of seismically isolation systems to production facilities and development facilities has been increasingly studied in order to maintain the performance and functions of buildings and organizations after the earthquake.

However, seismic isolated buildings have several disadvantages: 1) Since the effect of the interaction between the soil and the structure is very small, it is not expected that the vibration energies will dissipate to the ground.2) The conventional damping device adopted in the seismic isolation layer does not exhibit sufficient damping effect for micro vibration such as traffic vibration. Therefore, there is a concern that the micro-vibration during normal operation may adversely affect equipments which are sensitive to vibration.

In general, the response of a base-isolated building subjected to an earthquake or micro-vibration largely depends on the characteristics of the base-isolated layer. The authors have newly developed a special viscous damper to reduce the microvibration response of seismically isolated buildings, including vibration-adversion equipments such as production facilities and electron microscopes.

In this study, we measured the micro-vibration response of a facility equipped with this viscous damper in order to verify the micro-vibration characteristics of a base-isolated building and establish its prediction technology and countermeasures. In the actual measurement, a microtremor measurement and a forced vibration test were performed, and the responses were compared under different conditions depending on the presence or absence of dampers. As a result, the newly developed viscous damper in a base-isolated building significantly reduced the micro vibrations.

2. Outline of the developed viscous damper

The viscous damper, which has been developed as a measure against micro-vibration of a base-isolated building (hereinafter referred to as VD, immediately attenuates the shaking of the building above the base-isolated layer with high damping performance against daily micro-vibration. Fig. 1 shows the outline of the VD.

In this damper, a plurality of resistance plates are set up with the proper clearance in a viscous body. Since there is no gap that causes the connection mechanism to be loosen, the damper exhibits high damping performance even with extremely minute vibration. Also, by changing the number of resistance plates, the damping resistance can be adjusted according to the scale of the building and the required performance.

In the event of a large earthquake, before the horizontal deformation of the seismic isolation layer exceeds the specified range (± 5cm), the shear pin provided in the damper is splitted and the damping mechanism of VD is cut off from the building. Then the structure performs as a normal seismic isolation building. After rhe large earthquake, the splitted shear pin can be easily replaced with a new shear pin.

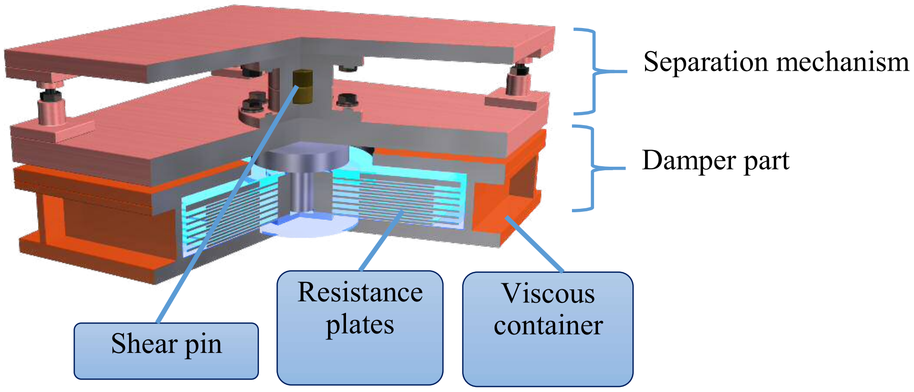


Fig.1- Outline of viscous damper for micro vibration (Cross Section)

3. Outline of the Building

In order to verify the performance of the damper for micro-vibration countermeasures, we performed micro-vibration measurements and forced vibration tests on an actual building. The target building is a newly constructed steel-framed two-story seismically isolated structure in Miyagi Prefecture ordered by NS TOOL CO., LTD. This is a research and development base for carbide small-diameter end mills with precision and micro-machining. By applying the optimal seismic isolation devices and the dampers for micro-vibration, the safety during large earthquakes and the suppression of micro-vibration at all times are achieved.

Figure 2 shows the layout of the seismic isolation devices. The adopted isolation devices are three types of rubber bearings (RB) and two types of dampers (D). RB consists of eight natural rubber bearings (NRB), ten high-damping rubber bearings (HRB) and six elastic sliding bearings (ESB). D has two oil dampers (OD) in the X and Y directions respectively. Two viscous dampers for micro vibration (VD) are installed.

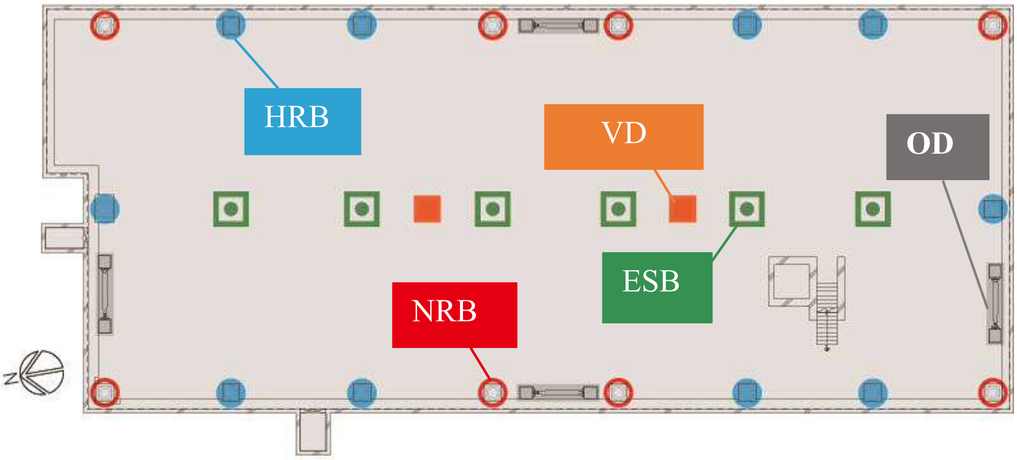


Fig.2- The layout of the seismic isolation device

Table 1 shows the total equivalent stiffness and equivalent damping coefficients in design values for each seismic isolation devices. The shear modulus, Geq, of the rubber used for the laminated rubber is 0.392 N / mm, and the total thickness of the rubber layers of NRB and HRB is about 200 mm. The table shows the values when the seismic isolation layer is deformed in 200 mm (at the time of the earthquake). The design natural frequency of the building is 0.246 Hz, the damping constant is 0.502. During micro-vibration, the stiffness becomes higher and the damping coefficient tends to be smaller than those during earthquakes. The OD is designed to be effective only during earthquakes and the VD is effective only during normal times. The damping characteristic of the VD is represented by a Maxwell model in which a dashpot element that generates a damping force proportional to the velocity and a spring element are connected in series.

Table 1- Characteristic of seismic isolation device

	seismic isolation device	symbol	number	equivalent stiffness (kN/cm)	equivalent damping coefficient(kN/kine)
Rubber bearing (RB)	natural rubber bearing	NRB	8	49.17	—
	high-damping rubber bearing	HRB	10	73.13	30.87
	elastic sliding bearing	SRB	6	12.64	31.90
Damper (D)	oil damper	OD	2×2dir.	—	25.00
	viscous damper for micro vibration	VD	2	1393.6	366.6

4 Verification on actual building

4.1 Microtremor measurement

Microtremor measurement was performed on the building just before completion, and the vibration level of the building due to traffic vibration was confirmed.

Measurements were made for three different combinations of devices as (1) RB only (RB), (2) RB with oil damper (RB+OD), (3) RB with oil damper and viscous damper (RB+OD+VD). The measurement positions were on the base below the base isolation layer (input to the building) and on the 1st floor (the response of the building). Fig. 3 shows the measurement results. The natural frequencies of the base-isolated building are between 1 and 2 Hz, and the response levels are as large as about 1e-6 to 1e-5 cm. Fig. 4 shows the spectral ratios of the responses on the 1st floor to those on the base. The natural frequency of RB was 1.1 Hz, and the damping constant estimated from the response magnification was 0.008. As for RB+OD, the natural frequency was 1.46 Hz and the damping constant was 0.017, showing a slight damping effect. In addition, by providing two dampers for micro-vibration, the natural frequency is 1.8 Hz and the damping constant is about 0.056, and the response is reduced to about 1/3 that of the oil damper alone.

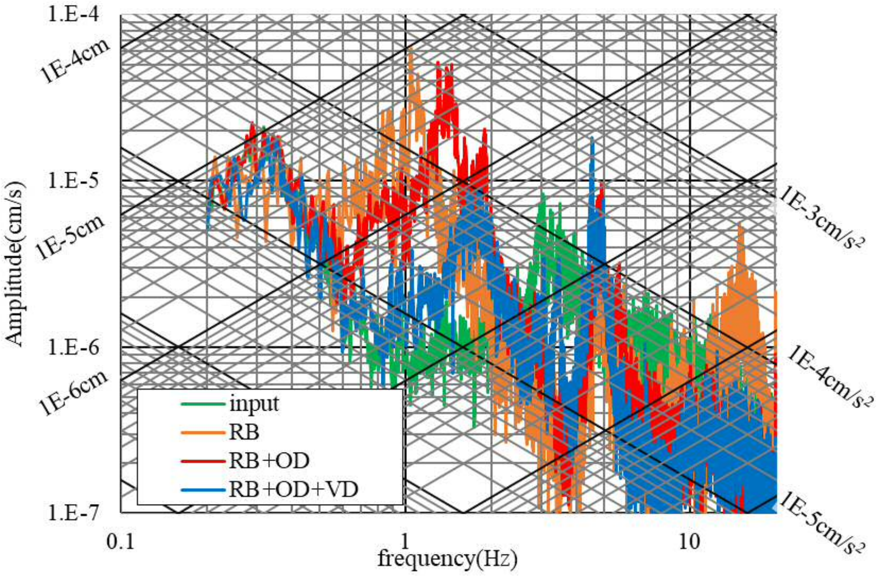
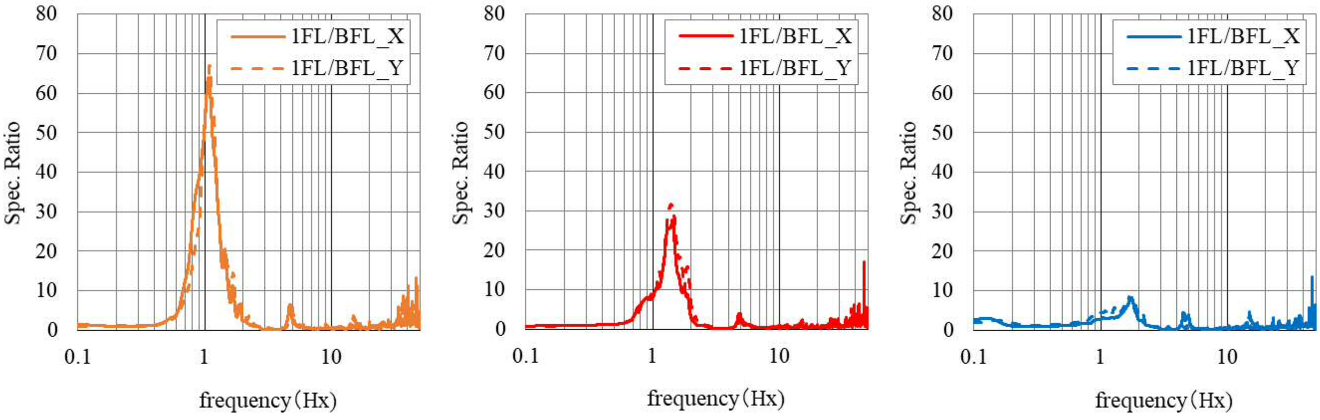


Fig.3-Spectral comparison of input vibration and building response



RB (h=0. 008) RB+OD (h=0. 017) RB+OD+VD (h=0. 056)

Fig. 4-Comparison of response amplitude ratio

4.2 Forced vibration test

Forced vibration tests were conducted on the building and the performance of the seismic isolation devices was confirmed. Photo 1 shows the vibration test device. In the experiment, the vibration test device was installed on the first floor, and the building was horizontally shaken by the reaction force of a moving 30kN weight excited with a hydraulic actuator.

In the experiments, the four types of the devices were arranged: (1) RB only (RB), (2) RB with oil damper (RB+OD), (3) RB with viscous damper for micro-vibration (RB+VD), (4) RB with both oil damper and viscous damper for micro-vibration (RB+OD+VD). The Excitation was performed at a 0.1 Hz pitch in the regions of ± 0.5 Hz with respect to the natural frequency in each state. The actuator was controlled so that the excitation force was a sin wave with a maximum of about 3 kN, and the steady-state response was measured for 82 seconds or more. The load of the actuator and the velocity of the first floor were measured at a sampling rate of 200 Hz.

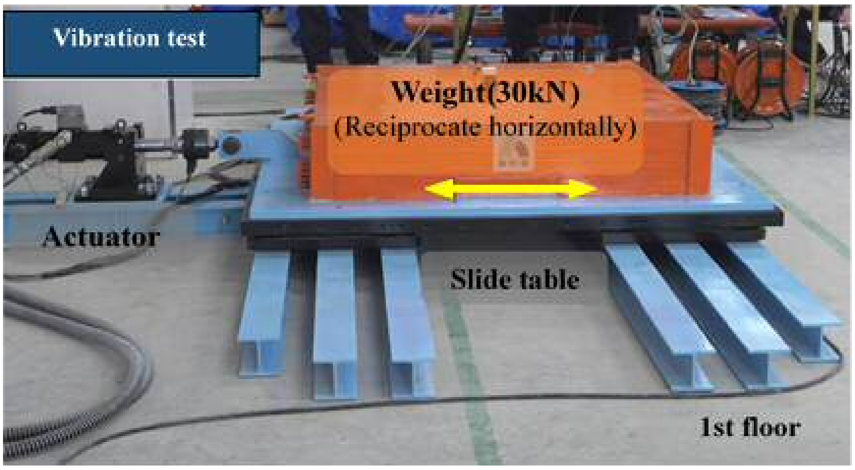


Photo.1- The vibration test device

Fig. 5 shows an example of the measured waveforms. These are the load of the actuator and the velocity of the 1FL floor when a vibration is applied at 1.07 Hz in the condition of RB+OD. Both waveforms were subjected to FFT analysis to extract the amplitudes at the excitation frequency. Subsequently, the velocity amplitude was divided by the circular natural frequency ω, converting it to the displacement amplitude A, and the response displacement amplitude per unit load (A / F) was obtained.

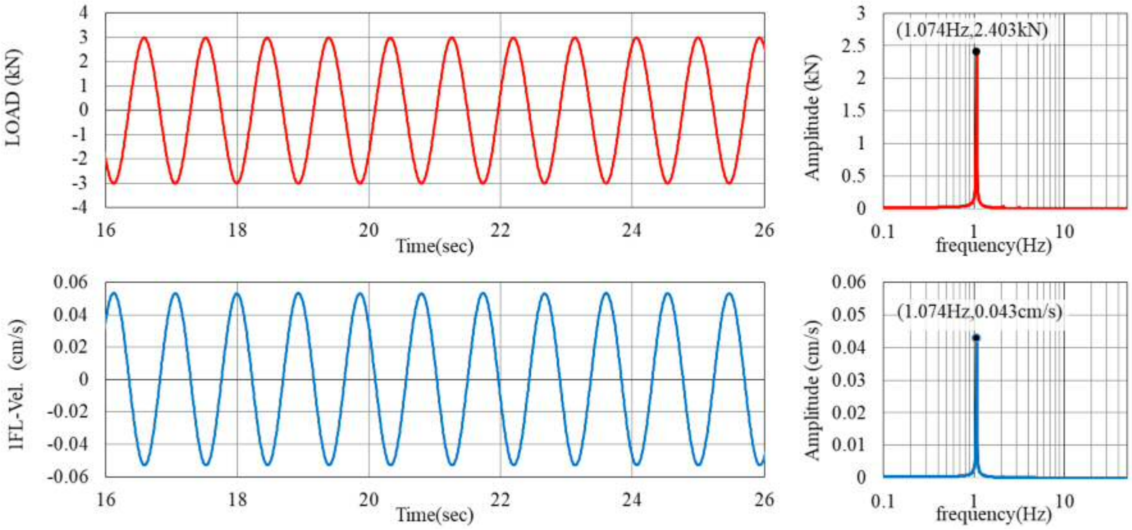


Fig.5-Example of measurement waveform

Fig. 6 shows the relationships between the vibration frequencies and the response displacement amplitudes per unit load, comparing the state of the four seismic isolation devices that were tested. Just adding OD to RB gives a response of about 2/3. When VD is added, the natural frequency increases slightly, and the response is further reduced to about 1/4 of that of the normal isolation as RB+OD.

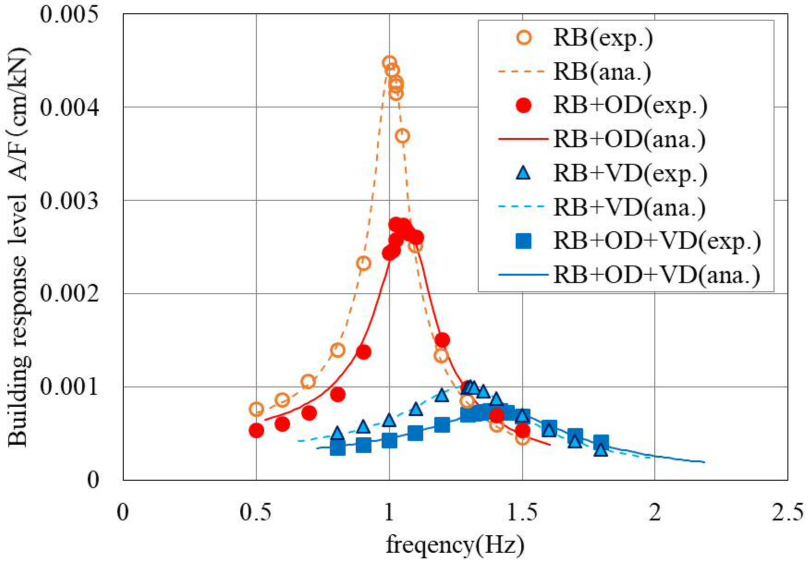


Fig. 6- Comparison of response displacement amplitude ratios by vibration test

The figure also shows the theoretical values in addition to the experimental values. The theoretical value is the amplitude when a harmonic external force is applied to a linear one-degree-of-freedom system, and is expressed by Eq. (1).

$$\frac{A}{F}=\frac{1}{\sqrt{\left((2\pi f)^2-(2\pi x)^2\right)^2+4h^2(2\pi f)^2(2\pi x)^2}}\cdot\frac{g}{\mathrm{W}} \tag{1}$$

where A: responce displacement (cm)

F: load (kN)

f: natural frequency of the building (Hz)

x: frequency of load (Hz)

h: damping factor

W: weit of the building (kN)

g: Gravitation $\left(=980.665\left(\mathrm{cm/s^2}\right)\right)$

Using Eq. (1), nonlinear curve fitting analysis was performed with the building weight *W*, the natural frequency *f*, and the damping constant *h* as parameters. At this time, the Levenberg-Marquardt Method was used for the iterative algorithm. The building weight *W* which was common, the natural frequency *f* and the damping constant *h* in the state of each seismic isolation device were obtained. Table 2 shows the analytical results and the maximum amplitude of the displacement corresponding to the applied load of 3.0 kN.

The building weight *W* was estimated as 44,546.16 kN. This is almost equivalent to the design weight of only the structure and the finish. The maximum amplitude during the experiment was as small as 0.013cm or less. The natural frequency of the rubber bearing only was 1.012 Hz, the damping factor was 0.062, and the maximum amplitude was 0.013cm. When the oil damper was combined with the rubber bearing, the natural frequency was 1.070 Hz, the damping constant was 0.088, the maximum amplitude was 0.008cm, and a slight damping effect was observed for the oil damper even in the minute amplitude region. When the micro-vibration damper was combined with the rubber bearing, the natural frequency was 1.323 Hz, the damping constant was 0.162, and the maximum amplitude was 0.003cm. The damping constant and the stiffness were larger than those of the oil damper. When both dampers are installed, the natural frequency is 1.456 Hz, the damping constant is 0.180, and the maximum amplitude is 0.002cm, which is almost the same as the case with only the micro-vibration damper.

Table 2 - The analysis results

Status of seismic isolation devices	Building weight W (kN)	Natural frequency f (Hz)	Damping constant h	Maximum amplitude A_{max}(cm)
RB	44546.16	1.0124	0.0618	0.013
RB+OD		1.0696	0.0883	0.008
RB+VD		1.3231	0.1616	0.003
RB+OD+VD		1.4562	0.1799	0.002

Based on this, the total stiffness K and total damping coefficients C in each state were converted by Eq. (2) and are shown in Table 3. Furthermore, the characteristics of each seismic isolation members were evaluated based on the difference in each state, and are shown in Table 4.

$$K = \omega^2 m$$
$$C = 2h\omega m \tag{2}$$

where m : mass of the building$(=W/g)$

Table 3- stiffness and damping coefficients of isolation layer in vibration test

Status of seismic isolation device	Stiffness K (kN/cm)	Damping coefficients C (kN/kine)
RB	Kr=1838.03	Cr=35.71
RB+OD	Kro=2051.60	Cro=53.91
RB+VD	Krn=3139.31	Crn=122.05
RB+OD+VD	Kall=3802.69	Call=149.54

Table 4 -Stiffness and damping coefficients of seismic isolation members in vibration test

Seismic isolation member	Stiffness K (kN/cm)		Damping coefficients C (kN/kine)	
Rubber Bearing (RB)	Kr=1838.03		Cr=35.71	
Oil damper (OD)	Ko1=Kro-Kr =213.57	Ko2=Kall-Krn =663.38	Co1=Cro-Cr =18.2	Co2=Call-Crn =27.49
	Ko=(Ko1+Ko2)/2=438.5		Co=(Co1+Co2)/2=22.8	
Viscous damper for micro vibration (VD)	Kv1=Krn-Kr =1301.28	Kv2=Kall-Kro =1751.09	Cv1=Crn-Cr =86.34	Cv2=Call-Cro =95.63
	Kv=(Kv1+Kv2)/2=1526.2		Cv=(Cv1+Cv2)/2=91.0	

The characteristics of these dampers have the dependencies on the displacement and velocity, however, the evaluation is based on the assumption of the linear system here. So the obtained results are not coherent with each other. Roughly estimated on average, the stiffness of the OD was 438.5 kN/cm, the damping coefficient was 22.8 kN/kine, the stiffness of the VD was 1526.2 kN/cm, and the damping coefficient was 91.0 kN/kine. Both the OD and the VD had the stiffness, and the stiffness of VD was about three times as large as that of OD. The damping effect of VD was about four times that of OD. The response amplitude in the vibration tests was reduced to about 1/4 by installing VD, compared to the case using only OD, showing the remarkable damping performance against the micro-vibration.

5. Conclusion

A viscous damper for micro vibration was developed and installed in seismically isolated building. In order to verify the effect, we measured the micro-vibration and performed the forced vibration test on the real building. From the micro-vibration observation, the damping constant was estimated to around 0.05 and the response was reduced to one third. As for the forced vibration test results, the damping constant was about 0.17 and the response of the building with the viscous damper remarkably reduce to one fourth of that of the conventional seismic isolation building.

From this studies, it is verified that the developed viscous damper for micro-vibration exhibited a large damping effect. The numerical modeling of the characteristics of the Maxwell model of the damper as the design technique is a future subject.

6. Acknowledgments

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