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Development of Advanced Energy Absorption Device Consisting of Oil Damper and Coned-disc Spring Unit

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Abstract

Japan is one of the earthquake countries in the world. In Japan, the large earthquakes have occurred in the recent years. In particular, the 2011 off the Pacific coast of Tohoku earthquake was the most magnitude and duration time in the seismic observation records. Thereat, the seismic loads of the structure have become more severe than former seismic loads. The seismic technologies such as the isolation technology and the vibration control technology, which reduces the seismic loads for a component and a structure, are very important. In the vibration control technology, to cope with severe earthquakes, the damping force of the damper installed in the structure is increased. The displacement in structure is decreased by increasing the damping force of the damper. On the other hand, the vibration of a high frequency is transmitted to the building and the structure for the high damping force of the damper. Consequently, the effect of reducing the response acceleration in the high frequency is reduced.

In this study, authors develop Advanced damping device, which decrease the response acceleration in the high frequency area of the equipment and the facilities and maintain the response displacement suppression due to the high damping force. This damping device consists of the conventional oil damper and the spring device which can adequately set stiffness. The spring device is attached in series to the cylinder head of the oil damper. The responses of the structure are controlled by setting stiffness of the spring device.

The test specimen was made from the conventional oil damper and the spring device, which was made with the coned disc spring units. The mechanical characteristic test of this damping device was performed, further the influence of the mechanical characteristic by the stiffness of the spring device was confirmed. In addition, the reproducibility by the mechanical characteristic model was also confirmed. Furthermore, the seismic response analysis of the structure with this damping device was carried out. The effect on the response displacement and the response acceleration of the structure by the stiffness of the spring device was investigated. As a result, the response acceleration of the arbitrary position was controlled suppressing the increase in the response displacement by appropriately setting the stiffness of the spring device. From these results, the effectiveness of the damper device with the spring device was confirmed.

Keywords: vibration control technology, seismic response analysis, oil damper, coned disc spring unit, vibration test

1. Introduction

In Japan, the large earthquakes have occurred in the recent years [1]. The seismic loads of the structure have become more severe than former seismic loads. Thereat, the seismic technologies such as the isolation technology and the vibration control technology, which reduces the seismic loads for a component and a structure, are very important. In the vibration control technology, the damping force of the damping device has been increased to cope with severe earthquakes. The displacement in structure decreases with increasing the damping force of the damper. On the other hand, the vibration of a high frequency is transmitted to the building and the structure for the high damping force of the damper. Accordingly, the effect of this response increase acceleration in the high frequency. In order to solve this problem, we develop the advanced damping device, which decreases the response acceleration in the high frequency area of the equipment and the facilities. Moreover, the damping device maintains the response displacement suppression. In this study, this damping device consists of the conventional oil damper and the spring device. This spring device can set stiffness of the damping device. The responses of the structure are controlled by setting stiffness of the spring device.

2. Outline of Oil Damper with Spring Device

The structural concept of the damping device in this study is shown in Fig. 1. The damping device consists of the spring device and the oil damper. The spring device is attached in series to the cylinder head of the oil damper. This structure enables the spring device to set the stiffness of damping device.

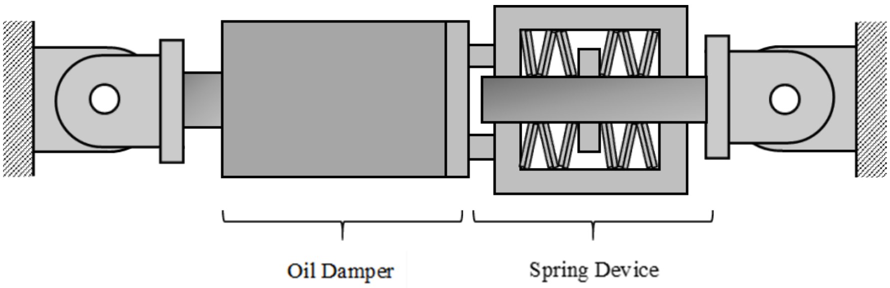


Fig. 1 - Conceptual diagram of damping device

The damping device and the spring device are shown in Fig. 2. In this study, the spring device is composed the coned-disc springs. The stiffness of the spring device is decided by the combination and shape of the coned-disc spring. The structure of the spring device combines the coned-disc spring in series and parallel.

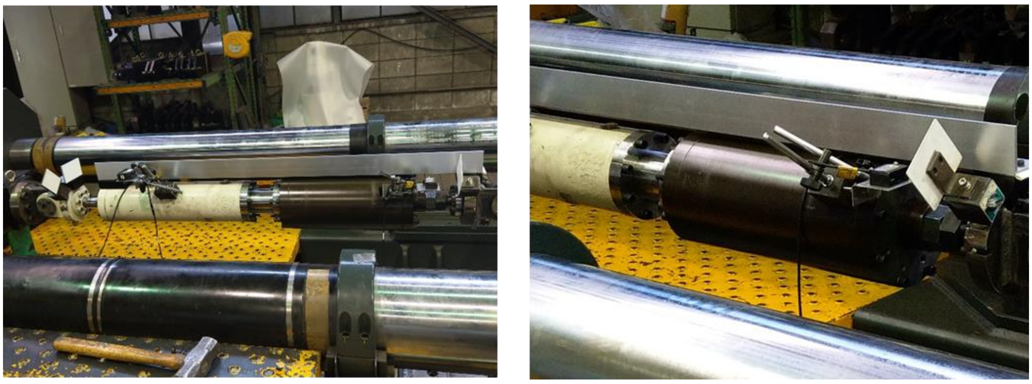


Fig. 2 - Damping device and spring device

3. Mechanical Characteristic Test of Damping Device

The mechanical characteristic test of the damping device was conducted. The damping device consits of the spring device and the oil damper in the mechanical characteristic test. The characteristic of the oil damper is shown in Table 1 [2]. The damping force characteristics of the oil damper is shown in Fig. 3. The damping coefficient of the oil damper is bilinear. In addition, the relief force, which changes the damping coefficient, is 150kN. Parameters of the spring device is shown in Table 2. In the mechanical characteristic test, the stiffness of spring device is 80 kN and 40 kN. The spring device of 80kN is composed of 3 stacks in series and 2 stacks in parallel with the coned-disc springs. This damping device which connected to the spring device was 1/2 of the stiffness of the oil damper. The spring device of 40kN is composed of 6 stacks in series and 2 stacks in parallel with the coned-disc springs. This damping device which connected to the spring device was 1/3 of the stiffness of the oil damper.

Table. 1 - Characteristic of oil damper

Max damping force [kN/mm]	Stiffness [kN/mm]	1st damping coefficient [kNs/mm]	2nd damping coefficient [kNs/mm]	Relief velocity [mm/s]	Max velocity [mm/s]	Relie force [kN]
200	80	2.0	0.154	75	400	150

Table. 2 - Parameters of spring device

Model	Stiffness [kN/mm]	Stroke [mm]	Disc springs (One Side)		
			Number of sheets	Series	Parallel
1	80	± 2.5	6	3	2
2	40	± 5.0	12	6	2

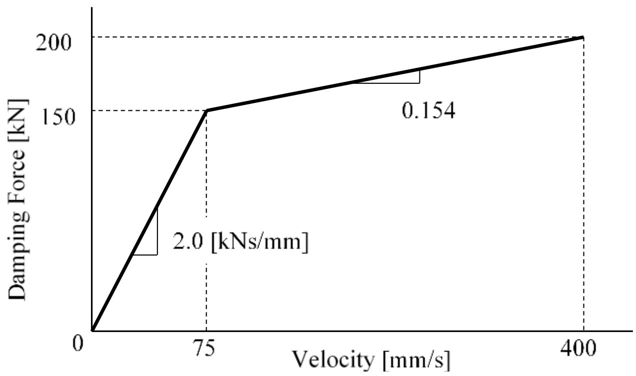


Fig. 3 - Relationship between force and velocity of oil damper

The input displacement in the mechanical characteristic test is a sine wave. The Input sine wave conditions is shown in Table 3. Table 3 shows the maximum velocity of the input sine wave. In the examination, the force of the damping device, the displacement of the oil damper, the displacement of the spring device, and the total displacement of the damping device was measured. The mechanical characteristic test was performed in following three cases.

Case1 ; Oil damper only

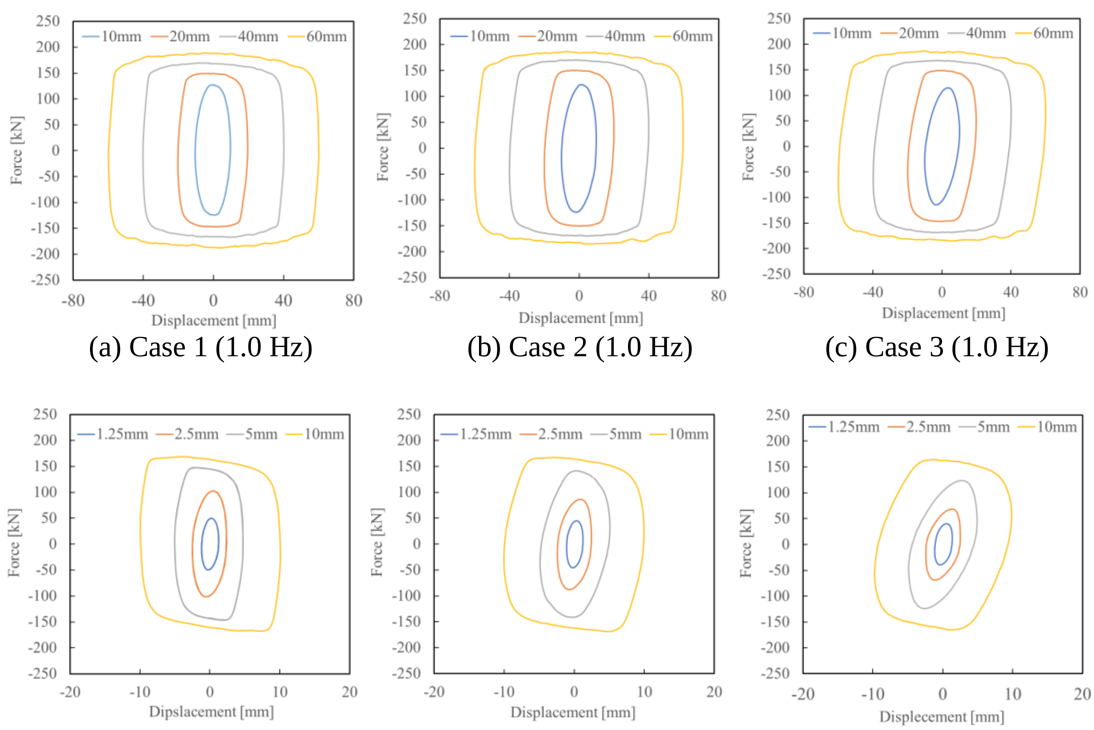
Case2 ; The stiffness of the damper device is 1/2 stiffness of the oil damper

Case3 ; The stiffness of the damper device is 1/3 stiffness of the oil damper

Table. 3 - Input sine wave conditions (Maximum velocity [mm/s])

Frequency [Hz]	Amplitude [mm]						
	1.25	2.5	5	10	20	40	60
0.5	-	3.9	7.9	15.7	31.4	62.8	94.2
1.0	7.9	15.7	31.4	62.8	125.7	251.3	377
2.0	15.7	31.4	62.8	125.7	251.3	-	-
4.0	31.4	62.8	125.7	251.3	-	-	-

The representative load-displacement curve in the characteristic test is shown in Fig. 4. The input sine waves of the representative load-displacement curve are 1.0 Hz and 4.0 Hz. Regardless of the input conditions, the slope of the load-displacement curve of Case 2 is gentler than that of Case 1. Moreover, the slope of the load-displacement curve of Case 3 is gentler than that of Case 2. Therefore, the slope of the load-displacement curve became gentle when the stiffness of the damping device decreases. The stiffness of damping device is controlled by adjustment of the spring device. Accordingly, the slope of the load-displacement curve is controlled by adjustment of the spring device.



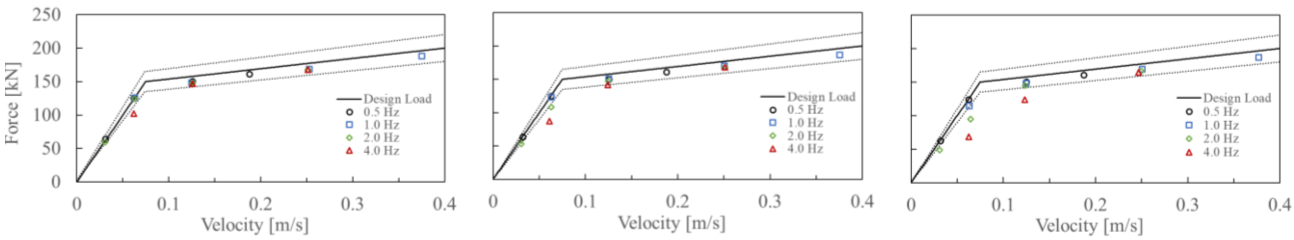
(a) Case 1 (1.0 Hz) (b) Case 2 (1.0 Hz) (c) Case 3 (1.0 Hz)

(d) Case 1 (4.0 Hz) (e) Case 2 (4.0 Hz) (f) Case 3 (4.0 Hz)

Fig. 4 - Load-displacement curve of damping device

The damping force-velocity characteristics are shown in Fig. 5. In Case 1, the damping force was approximately within ± 10% of the design value at most frequencies. On the other hand, the damping force of the damping device decreased at 4.0 Hz than the designe value. The decrease occurred before the relief load of the oil damper. This effect is due to the frequency dependence of the oil damper. In addition, the effect of frequency dependence was decreased after the relief force. For the reason, the damping coefficient of the oil damper becomes lower. In Case 2, the damping force of the damping device decreased at 4.0 Hz than the Case 1. Moreover, the damping force decreased in Case 2 not only 4.0 Hz but also 2.0 Hz. In the Case 3, the damping force of the damping device decreased at 2.0 Hz and 4.0 Hz than the Case2. Moreover, The damping force decreased from ± 10% of the designe value at 2.0 Hz and 4.0 Hz. This decrease of the damping force gradually decreased after the relief force. In addition, the damping force was within the design value in high velocity input.

The damping force of damping device decreases, when the damping force of the oil damper is lower than the relief force. The damping force of damping device is same as that of the oil damper, when damping force of the oil damper is greater than the relief force. That is, the decrease of the damping force is negligible in the high velocity input. Accordingly, the influence of the spring device is confirmed at the high frequency.



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 5 - Damping force-velocity characteristics of damping device

4. Reproduction Analysis of Load Displacement Curve

The reproduction analysis of the load-displacement curve of the damping device was performed. The analysis model of the damping device with the spring device, which controls stiffness of damping device, is investigated. In the analysis, the Maxwell model is used. The Maxwell model is shown in Fig. 6. The analysis model of the damping device is shown in Fig. 7. The stiffness of the damping device is calculated, because the spring device is attached to the oil damper in series. The equation of the equivalent stiffness is shown in Eq. (1).

$$k = \frac{k_s \cdot k_d}{k_s + k_d} \tag{1}$$

where, k: Stiffness of damping device, k_s: Stiffness of spring device and k_d: Stiffness of oil damper.

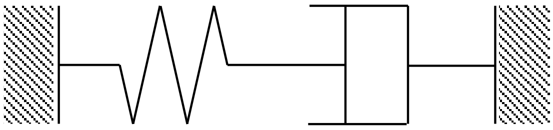


Fig. 6 - Maxwell-model

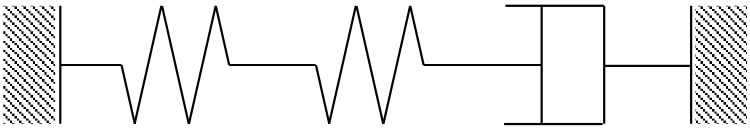


Fig. 7 - Equivalent stiffness of damping device

The damping force of the oil damper in the Maxwell model are shown Eq. (2) and Eq. (3). The damping force lower than the relief force, is shown in Eq. (2). Further, the damping force more than relief force is shown in Eq. (3).

$$\dot{F}(t) = k \cdot \left(\dot{x} - \frac{F}{c_{B1V}}\right) \quad (F < c_{B1V}\, v_{RV}) \tag{2}$$

$$\dot{F} = k \cdot \left[\dot{x} - \frac{F + sgn(F) \cdot (c_{B2V} - c_{B1V}) \cdot v_{RV}}{c_{B2V}}\right] \quad (F \geq c_{B1V}\, v_{RV}) \tag{3}$$

where, t: Time [s], $\dot{x}$: Velocity [m/s^2], k: Stiffness of damping device [N/mm], c_{B1V}: 1st damping coefficient [Ns/mm], c_{B2V}: 2nd damping coefficient [Ns/mm], v_{RV}: Relief velocity [mm/s] and F: Damping force[N].

Input sine wave conditions is shown in Table 4. Tabel 4 shows the maximum velocity of the input sine wave. The reproduction analysis of the load-displacement curve was performed in following three cases.

Case 1 ; Oil damper only

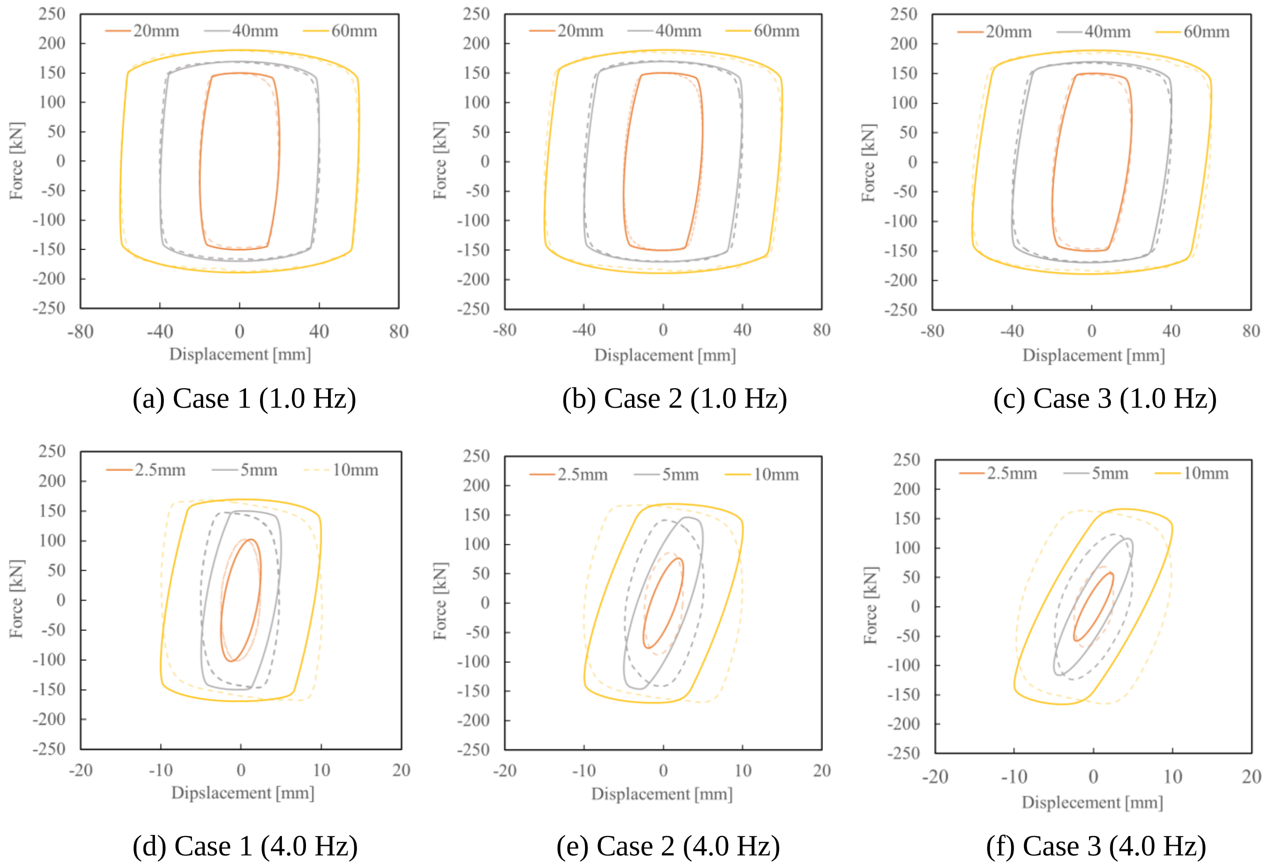
Case 2 ; The stiffness of the damper device is 1/2 stiffness of the oil damper

Case 3 ; The stiffness of the damper device is 1/3 stiffness of the oil damper

Table. 4 - Input sine wave conditions on reproduction analysis (Maximum velocity [mm/s])

Frequency [Hz]	Amplitude [mm]					
	2.5	5	10	20	40	60
1.0	-	-	-	62.8	125.7	251.3
4.0	62.8	125.7	251.3	-	-	-

The load-displacement curve of the reproduction analysis is shown in Fig. 8. The solid line is the load-displacement curve in the analysis. The dotted line is the load-displacement curve in the mechanical characteristic test. In all case, the load-displacement curves of the analysis at 1.0 Hz almost match that of mechanical characteristic test. On the other hand, there was a difference at 4.0 Hz. In Case 1, the slopes of the load-displacement curve of the analysis at 4.0 Hz almost coincided with that of the mechanical characteristic test. In Case 2 and Case 3, the slopes of the load-displacement curves in the analysis were gentler than that of the mechanical characteristic test. Moreover, the slope of the load-displacement curve in Case 3 was gentler than in Case 2. That is, the stiffness of the damping device in the mechanical chracteristic test is increased more than the analysis. The increase of the stiffness in the characteristic test is probably due to the friction of the coned-disc spring of the spring device. Accordingly, the stiffness of the spring device at high frequency and low amplitude is more than the design stiffness



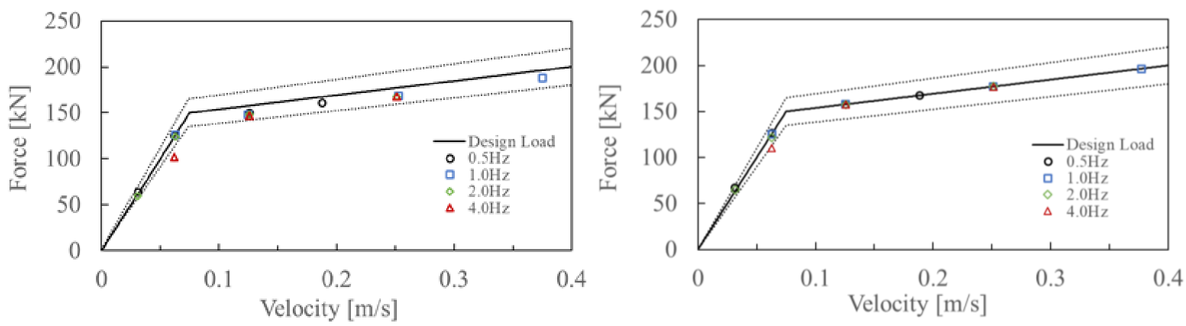
(a) Case 1 (1.0 Hz) (b) Case 2 (1.0 Hz) (c) Case 3 (1.0 Hz)

(d) Case 1 (4.0 Hz) (e) Case 2 (4.0 Hz) (f) Case 3 (4.0 Hz)

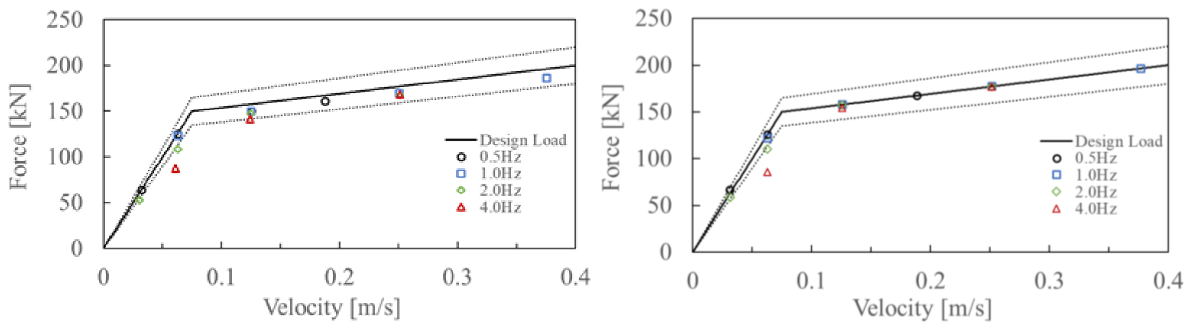
Fig. 8 - Load displacement curve on reproduction analysis

The damping force-velocity characteristics of the reproduction analysis and that of the mechanical characteristic test are shown in Fig. 9. In Case 1, the damping force of the damping device in the analysis was approximately within ± 10% of the design value at most frequencies. This decrease of the damping force in the analysis at 4.0 Hz is due to the frequency dependence of the oil damper. Moreover, the damping force in the analysis at 4.0 Hz was 110 kN. The damping force in the mechanical characteristic test at 4.0 Hz was 102 kN. The damping force in the analysis is 8 kN greater than that in the mechanical characteristic test. For the reason, the oil damper in the mechanical characteristic test was a slightly lower than the damping force of the design value. In Case 2, the damping force of the damping device at 4.0 Hz decreased than the Case 1. The damping force decreased from ± 10% of the designe value at 4.0 Hz. Moreover, the damping force decreased in Case 2 not only 4.0 Hz but also 2.0 Hz. The damping force in the analysis at 4.0 Hz was 86 kN. The damping force in mechanical characteristic test at 4.0 Hz was 87 kN. The damping force in the analysis was 1 kN lower than that of the mechanical characteristic test. In Case 3, the damping force of the damping device at 2.0 Hz and 4.0 Hz decreased than the Case 2. The damping force decreased from ±10% of the designe value at 2.0 Hz and 4.0 Hz. The damping force in the analysis at 4.0 Hz was 69 kN. The damping force in the mechanical characteristic test at 4.0 Hz was 67 kN. The damping force of the analysis was 2 kN lower than that of the mechanical characteristic test. For the reason, the stiffness of the spring device in the mechanical characteristic test is due to increased. That is, the damping force of the danping device in the mechanical characteristic test is greater than that in the analysis. In this study, the analysis model of the damping device didn't consider the increase of the stiffness of the spring device at high freqency. Accordingly, the damping force of the damping device was slightly reduced in the analysis.

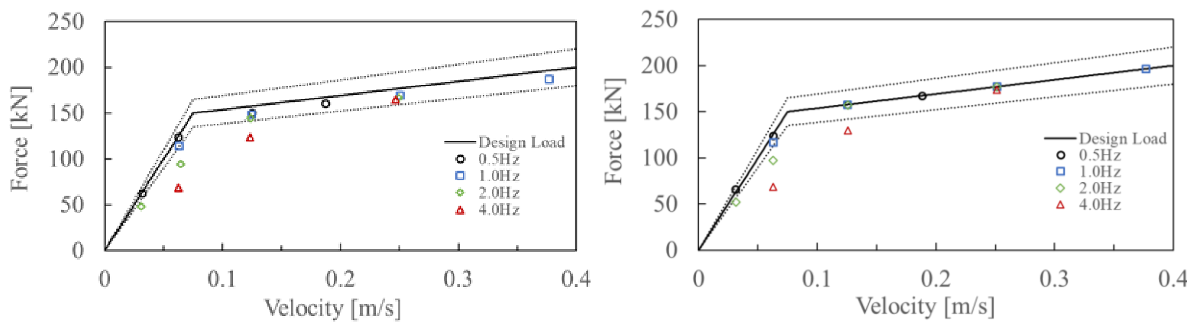
The decrease of the damping force occurred in 2.0 Hz and 4.0 Hz. The stiffness of the spring device at high frequency isn't increased in the analysis. Accordingly, the damping force of the damping device in the analysis is slightly than decrased, that of the mechanical characteristic test. The damping force-velocity characteristics of the analysis almost match that of mechanical characteristic test in most cases.



(a) Case 1



(b) Case 2



(c) Case 3

(d) Mechanical characteristic test (e) Reproduction analysis

Fig. 9 - Comparison of damping force characteristics

5. Simulation Analysis for Tower Structures

Recent earthquakes have become very severe. Hence the various structures have been damaged. For the example is the chimney of a thermal power plant. In this chapter, we investigated the seismic response of the tower structure with the damping device, which consists of the oil damper and the spring device.

The analysis model of the chimney model is shown Fig. 10[4]. The chimney model is an equivalent shear model of two mass points. This analysis model has a reinforcement structure around the chimney model, which is supported by reinforcement sturucture and the damping device. The total mass of the chimney model is 2000 t. Moreover, we set the total mass of the chimney model to be equal for each mass point. The stiffness of the analysis model was set so that the natural period is 3.0 s. This chimney model the damping ratio was set 1.0%. The equation of motion of the chimney model are shown Eq. (4) and Eq. (5). In addition, Equations of motion of the damping device are shown Eq. (2) and Eq. (3).

$$m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) + F_2 = -m_2\ddot{z}_h \quad (4)$$

$$m_1\ddot{x}_2 + c_2(\dot{x}_1 - \dot{x}_2) + c_1\dot{x}_1 + k_2(x_1 - x_2) + k_1x_1 + F_1 = -m_1\ddot{z}_h \quad (5)$$

where, m_1: Lower mass [kg], m_2: Upper mass [kg], k_1: Lower stiffness [N/m], k_2: Upper stiffness [N/m], c_1: Lower damping [Ns/m], c_2: Upper damping [Ns/m], F_1: Damping force of lower damping [N] and F_2: Damping force of upper damping [N] and $\ddot{z}_h$: Input seismic wave acceleration.

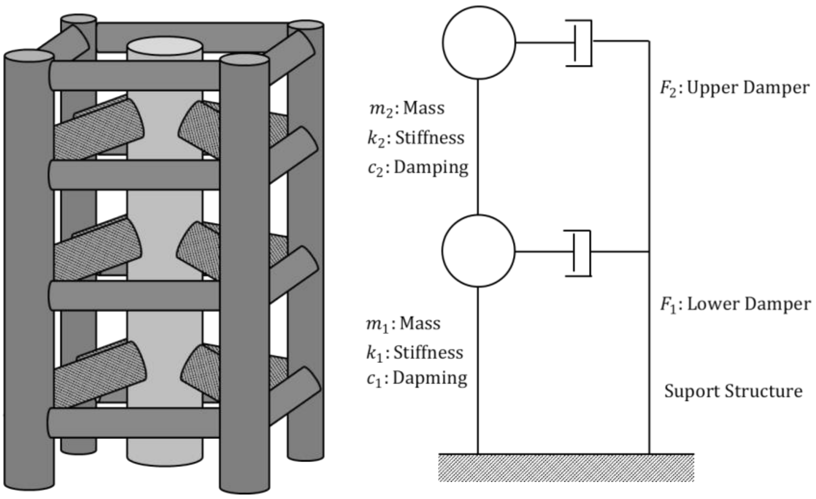


Fig. 10 - Structure analysis model

The input seismic wave was El Centro wave. The maximum acceleration of this seismic wave was normalized at 2.5 m/s^2. The 2nd damping coefficient of the oil damper is 0.068 times the 1st damping coefficient [1].The seismic response analysis was performed in following two cases.

Pattern 1 ; Oil dampers are installed on the upper and lower, and the damping ratio in the primary mode is set to 20%.

Pattern 2 ; Oil dampers are installed on the upper and lower, and the stiffness of the upper oil damper is setting to half. In addition, the damping ratio in the primary mode is set to 20%.

Plot of the maximum response acceleration and maximum response displacement for each layer are shown in Fig. 11. In addition, The maximum response values of Fig. 11 is shown in Table 5. Moreover, the maximum response focusing on upper and lower layers are shown Fig. 12. The maximum response acceleration of Pattern 1 and Pattern 2 is lower than the input acceleration. The reason is the natural period of the model is 3.0 s.

The maximum response acceleration in the upper layer of Pattern 1 is 0.65 m/s^2. The maximum response acceleration in the upper layer of Pattern 2 is 0.71 m/s^2. At the upper layer, the maximum response acceleration of Pattern 2 increased than that of Pattern 1. The maximum response acceleration in the lower layer of Pattern 1 is 0.90 m/s^2. The maximum response acceleration in the lower layer of Pattern 2 is 0.85 m/s^2. At the upper layer, the muximum response acceleration of Pattern 2 incresed than of Pattern 1. On the other hand, the lower layer the maximum response accelaration decrased than that of Pattern 1. The maximum response acceleration of the lower layer can be decreased by setting the stiffness. However, the upper layer response acceleration increased. The displacement of the upper layer of Pattern 1 and Pattern 2 is approximately 0.12 m. The displacement of the lower layer of Pattern 1 and Pattern 2 is approximately 0.09 m. Accordingly, the effect of displacement is negligible. The maximum response acceleration is controlled by the damping device.

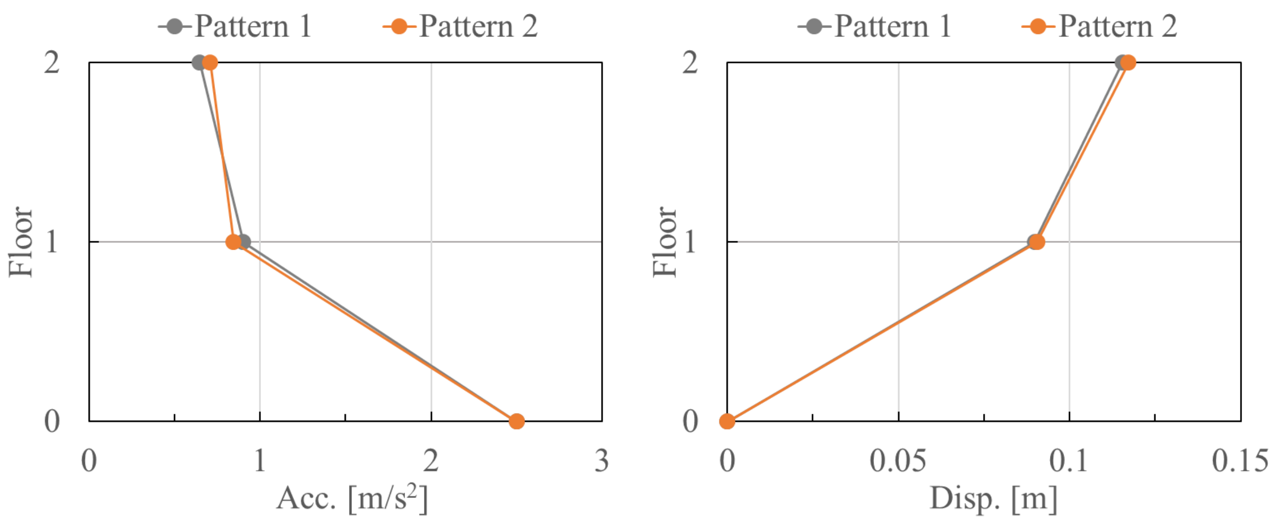


Fig. 11 - Maximum response in analyzed of seismic response

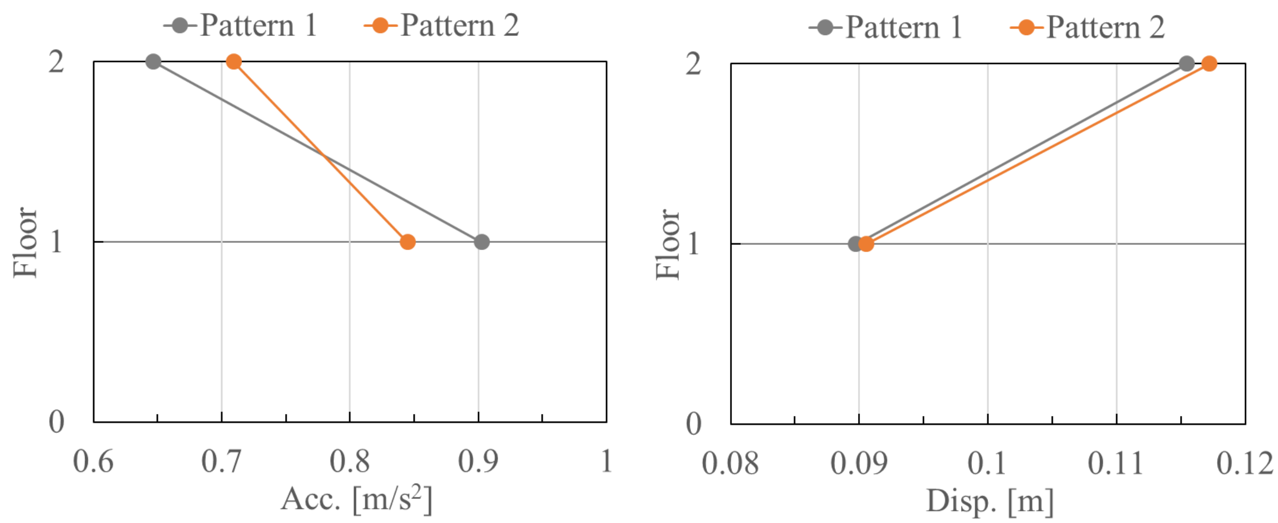


Fig. 12 - Maximum response focusing on upper and lower layers

Table. 5 - Maximum response value in analyzed of seimic response

Pattern	Layer	Input wave [m/s^2]	Acceleration [m/s^2]	Displacement [m]
1	2	2.5	0.647	0.115
	1		0.902	0.090
2	2		0.709	0.117
	1		0.845	0.091

6. Conclusions

We examined the effect of the damping device, which coordinates the stiffness. The effect was investigated in the mechanical characteristic test, the reproduction analysis and seismic response analysis. As the result, the slope of the load-displacement curve became gentle when the stiffness of the damping device decreases. The stiffness of damping device is controlled by adjustment of the spring device. The damping force of damping device decreases when damping force of the oil damper is less than the relief force. That is, the influence of the spring device is confirmed at the high frequency. In addition, the decrease is negligible in the high velocity input.

The load-displacement curves of the reproduction analysis almost match that of mechanical characteristic test. On the other hand, there was a difference in the load-displacement curve at high freqency. For the reason, the stiffness of the spring device increased in the mechanical characteristic test. The damping force-velocity characteristics of the reproduction analysis almost match that of mechanical characteristic test. However, the damping force of the analysis was slightly less than the damping force of the mechanical characteristic test. In this study, the analysis model of the damping device didn't increase the stiffness of the spring device. Accordingly, the damping force of the damping device was slightly reduced in the analysis. From the above reason, the characteristics of the damping device in the mechanical test could be probably reproduced with the Maxwell model.

In the result of the seismic response analysis, the response changed by adjusting the stiffness of the damping device. The maximum acceleration of the lower layer was reduced by adjusting the stiffness. However, the maximum acceleration of the upper layer increased. The maximum response acceleration changes with the damping device. Accordingly the maximum response acceleration is controlled by the damping device.

We consider the following in the future. The analysis model of the damping device didn't consider the stiffness of the spring device at high frequency. Therefore, the analysis model needs to be improved. The effect of the damping device was considered with El Centro waves. The effect be considered for other seismic waves. Moreover, the effectiveness of the damping device at other-than the chimney structure be should examined.

7. Acknowledgement

The mechanical characteristics tests for this study has been performed at Sanwa tekki Corporation Reserach and Development Division.

8. Rererrences

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