**Proposal of Damping Systems for Chandeliers**

**DOI 10.37153/2686-7974-2019-16-449-459**

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**ABSTRACT**

Chandeliers hanging from floor slabs or beams swing during earthquakes. When the swing is strong, it could cause uneasiness to the people in the building. In the worst case, the chandelier may fall.

The authors propose two types of damping systems that can reduce the response of chandeliers. The first system (system 1) is effective when the distance between the floor slab and the ceiling, which defined as suspended ceiling depth, is large. The second system (system 2) is a simplified version of system 1. This system can be applied even if the suspended ceiling depth is narrow; however, its effect is smaller than that of system 1. The common feature of the two systems is that the energy dissipation system is placed only between the floor slab and the ceiling. Since the energy dissipation system is placed in the ceiling space, it does not distract from the appearance of the chandelier.

The authors investigated the effect of the proposed supplemental damping systems using a time history response analysis. It was confirmed that the maximum response of a chandelier with the energy dissipation system was reduced to less than half of that without the system.

*Keywords: Damping System, chandelier, energy dissipation*

**1. INTRODUCTION**

One of the damages caused by an earthquake to a building is the damage to the nonstructural members (Rajesh P. Dhakal et al. 2011, Eduardo Miranda et al. 2012). In the East Japan Earthquake, a 9.0-magnitude earthquake that occurred on March 11, 2011, significant damage to suspended ceilings and equipment was observed (Y. Hisada et al. 2012). Thus, the necessity of securing seismic resistance for nonstructural members has been recognized. Earthquake resistance method of suspended ceilings is gradually becoming systematized; however, it is not enough for other nonstructural members.

In this paper, we propose a vibration control method for chandeliers. A chandelier is often installed in a large space with a colonnade, and its hanging length is longer than that of other equipment. If the natural period of a chandelier is close to that of a building, the chandelier may resonate with the shaking of the building, thus causing the former to swing strongly during an earthquake. Moreover, since a chandelier has a low damping capacity, it swings easily during an earthquake and this takes a long time to stop. This could cause uneasiness to the people in the building. In the worst case, the chandelier may fall.

As a countermeasure for the earthquake resistance of the chandelier, arranging a hooking material can be done to suppress the shaking of the chandelier (The Japan Building Equipment and Elevator Center Foundation. 1996). However, in this method, it is necessary to install a reinforcement on the chandelier itself, which distracts from its appearance. As the chandelier is supposed to have an aesthetic appearance, this type of countermeasure poses an issue. Another issue is that the strength of the reinforced chandelier is not guaranteed.

Given the above background, the authors propose two types of damping systems that can reduce the response of a chandelier by using measures limited to the suspended ceiling depth without affecting the appearance of the chandelier. In the following, we first explain the outline of the suggested systems and then derive their equations of motion. Next, we organize the conditions that minimize the amplitude ratio of the fixed point of the transfer function based on a fixed point theory and show the characteristics of the systems by using a transfer function evaluated by the study model. Finally, we validate the effect of the two systems by performing an earthquake response analysis.

**2. the proposed DAMPING systemS**

***2.1 Outline of the Damping Systems***

Figure 1(a) shows the installation view of a conventional system. It is common for the conventional system to be suspended with chains from a frame fixed to a ceiling slab with anchor bolts. Since the damping capacity of the chain itself is small, it takes a long time for the swing of the chandelier to decrease. On the other hand, the feature of the suggested system is to absorb the vibration with a damper placed between the ceiling slab and the ceiling (Figure 1(b) and (c)). Figure 1(b) shows an outline of system 1, consists of three elements: a rigid bar, a rigid body, and some dampers. The chandelier and the rigid bar, and the rigid bar and the ceiling slab are respectively pin-jointed. The rigid body with mass *m*2 and moment of inertia *I*2 is attached to the rigid bar. Dampers are placed between the rigid body and the ceiling slab. During an earthquake, energy is absorbed by deformation of the damper due to the vertical displacement of the rigid body edge. Figure 1(c) shows an outline of system 2, which consists of two elements: a rigid bar and some dampers. System 2 corresponds to system 1, but without a rigid body. System 2 can add damping to a chandelier even when the suspended ceiling depth is small. In both systems, the installation position of the dampers is not limited to that shown in Figure 1. The position of the dampers can be anywhere as long as the required damping coefficient can be secured.



1. Conventional System (b) System 1 (c) System 2

Figure 1. Outline of the Systems

***2.2 Equation of Motion of System 1***

Figure 2 shows a diagram of system 1. We assume that the chandelier is a pendulum with 1 degree of freedom (DOF). Considering the equilibrium of the moment at point and setting , we can obtain equation (1) as follows:

, (1)

where and . The damping factor of the chandelier is neglected.

Next, considering the equilibrium of the moment at point and setting and , we can obtain equation (2) as follows:

, (2)

where , , , , , , and .

By expressing the equation of state using equations (1) and (2), we can obtain equation (3) as follows:

, (3)

where

,,.



Figure 2. Diagram of System 1

***2.3 Equation of Motion of System 2***

Figure 3 shows a diagram of system 2. Considering the equilibrium of the moment at point and setting , we can obtain equation (4) as follows:

, (4)

where and *K*. The damping ratio of the chandelier is neglected.

Next, considering the equilibrium of the moment around point and setting and , we can obtain equation (5) as follows:

, (5)

where .

By expressing the equation of state using equations (4) and (5), we can obtain equation (6) as follows:

, (6)

where .



Figure 3. Diagram of System 2

**3. Study of the optimal parameter based on a fixed-point theory**

In equations (3) and (6), for a certain frequency, there are two fixed points where the amplitude ratio of the harmonic vibration becomes a constant value regardless of the value of the damping coefficient. The existence of such fixed point is known as the “fixed-point theory.” The optimum state is defined as the state wherein the amplitude ratio of two fixed points are same values and the values are the maximum value in the entire frequency range. In this section, we derive the optimum parameters in each system and validate the damping effect by using the transfer function of the study model.

***3.1 Optimal Parameter of System 1***

In equation (3), the steady-state response by the harmonic vibration is expressed as and . Considering the amplitude ratio , we find that the value of for a certain circular frequency is constant regardless of the value of the damping coefficient . At this time, the values of *ω* and can be obtained by equations (7) and (8).

When ,

. (7)

When ,

, (8)

where , , , , and .

Two fixed points obtained from equation (7) are referred to as point P and point Q, whereas a fixed point obtained from equation (8) is referred to as point R. Next, considering the condition wherein the amplitude ratios of points P and Q are the same value, using equation (7), we can express the condition as “.” When simplified, the condition is expressed by equation (9) as follows:

. (9)

When this condition is satisfied, the value of the fixed point is expressed by equation (10):

. (10)

When the condition of “” is established, the amplitude ratio expressed by equation (10) is larger than that of point R expressed by equation (8). When the values of are determined, the moment of inertia required to satisfy equation (9) is obtained by equation (11):

(11)

When dampers with an appropriate damping coefficient satisfying the above condition are installed, the amplitude ratios of points P and Q become the maximum values in the entire frequency range. Since the derivation of the damping constant *h* at that time is complicated, it is omitted in this paper.

***3.2 Optimal Parameter of System 2***

In equation (6), the steady-state response by the harmonic vibration is expressed as and . Considering the amplitude ratio , we find that the value of for a certain circular frequency is constant regardless of the damping coefficient *C*. At this time, the values of *ω* and can be obtained by equation (12):

(12a)

, (12b)

where .

The fixed point expressed by equation (12) is referred to as point P. From equation (12), the smaller the value of , the smaller the value of the circular frequency of point P and that of the amplitude ratio . When dampers with an appropriate damping coefficient satisfying the above condition are installed, the amplitude ratio of point P is the maximum value in the entire frequency range. Then, the appropriate damping constant is obtained by equation (13) as follows:

. (13)

***3.3 Transfer Function***

The characteristics of the proposed systems were determined. Table 1 shows the properties of the study model. The common settings to both systems are given below. Since the standard suspended ceiling depth of a real building is about 700 mm, *L*2 was taken as 600 mm. The mass of the chandelier was considered as 50 kg. The hanging length *L*1 was set to 1630 mm to make it closer to the natural period *T* = 2.55 s of the earthquake response analysis model described later.

Table 1. Properties of the Study Model

(a) System 1



(b) System 2



At first, the transfer characteristics of system 1 are determined as follows. The mass of the rigid plate is twice that of the chandelier. *L*3, which indicates the position of the rigid plate, was taken as 300 mm, which is half of *L*2. *I*2 was calculated by using these parameters and equation (11). The damping coefficient *C* was set to 0 and ∞ (equivalent to a single pendulum with a hanging length *L*1); in addition to these, the damping coefficient *C*opt, which minimizes the maximum value of the amplitude ratio in the entire frequency range, was also adopted. Figure 4 shows the amplitude ratios and . The three fixed points shown in Figure 4(a) coincide with the intersection points of the curves when the value of the damping coefficient *C* is set to 0 and ∞. The result of *C*opt represents the transfer characteristic when the amplitude ratios of points P and Q are the maximum value in the entire frequency range. In Figure 4(b), the value of the amplitude ratio (*C* = *C*opt) is smaller than that in the case of *C* = 0.



(a) ｜X1/Y0｜ (b) ｜X2/Y0｜

Figure 4. Illustration of the Transfer Function (System 1)

Next, the transfer characteristics of system 2 are determined as follows. The damping coefficient *C* was set to 0 (equivalent to a single pendulum with a hanging length *L*1+*L*2) and ∞; in addition to these, the damping coefficient *C*opt obtained from equation (13) was also adopted. Figure 5 shows the amplitude ratios and . Point P shown in Figure 5(a) coincides with the intersection point of the curves when the value of the damping coefficient *C* is set to 0 and ∞. The result of *C*opt represents the transfer characteristics when the amplitude ratio of point P is the maximum value in the entire frequency range. In Figure 5(b), the value of the amplitude ratio (*C* = *C*opt) is smaller than that in the case where *C* = 0. The result of system 2 is also shown in Figure 5. System 1 has two peak points: points P and Q, and the amplitude ratio in the frequency range around the two points gently changes. On the other hand, system 2 has a unimodal characteristic with the peak at point P.



System 1

System 1

(a) ｜X1/Y0｜ (b) ｜X2/Y0｜

Figure 5. Illustration of the Transfer Function (System 2)

**4. TIME HISTORY RESPONSE ANALYSIS**

In this section, we validate the damping effect of the two systems through an earthquake response analysis.

***4.1 Building Model and Input Wave***



The building model was equivalent to the shear model of a 24-story steel building shown in Figure 6. In the plan view, the longer side of the building has six spans, each measuring 6 m, whereas the shorter side consists of three spans measuring 9 m, 3 m, and 9 m, respectively. The weight of each floor was set to approximately 8.5 kN/m2. For level 2 earthquakes, as prescribed by the Building Standard Law of Japan, the member was set so that the maximum story drift angle was 1/100 or less and the plasticity ratio was 2 or less. In this paper, the shorter side direction is targeted, and the natural period of the building model is 2.55 s.

To validate the difference in damping effect for earthquake motions with different properties, we selected two types of waves. One was a pulse-like motion, and the other was a long-period ground motion. For the pulse-like motion, the 1995 Kobe Earthquake (JMA Kobe, NS direction) (Japan Meteorological Agency) was selected. For the long-period ground motion, the 2011 Tohoku Earthquake (TKY 007) (National Research Institute for Earth Science and Disaster Resilience) was selected. The input to the chandeliers was determined as the floor response wave obtained when the data from these earthquakes were inputted to the building model. In this paper, on the assumption that the three cases of chandeliers were respectively placed at the lower floor, the middle floor, and the higher floor, the response waves of 4F, 14F, and 24F, respectively, were inputted to the chandelier.

Figures 7 and 8 show the response analysis results and the floor response waves of 4F, 14F, and 24F. Figure 9 shows the velocity response spectrum (*h* = 5%) of each floor response wave. In the result of JMA Kobe, the acceleration response of the lower floor increased owing to the impact of higher modes. In the result of TKY 007, amplification was observed in the vicinity of the fundamental natural period.

Figure 6. Building Model



Figure 7. Response Analysis Result (JMA KOBE)



Figure 8. Response Analysis Result (TKY007)



1. JMA KOBE (b) TKY007

Figure 9. Velocity Response Spectrum (*h* = 5%)

***4.2 Response Analysis Result***

For the response analysis of system 1, the parameters of Table 1(a) were used. Similarly, for the response analysis of system 2, the parameters of Table 1(b) were used. For both systems, the *C*opt value, which is the optimum value for the damping coefficient, was adopted. For comparison, we also analyzed the 1 DOF model (*h* = 0.5%) by simulating a conventional system. Figures 10 and 11 show the displacement waves of 24F. Table 2 shows the maximum displacement and the standard deviations of 4F, 14F, and 24F. The parenthesized values in Table 2 represent the ratio of the maximum displacement to that of the conventional system.

In the result of JMA Kobe, the maximum displacement and the standard deviations of system 1 and system 2 were approximately the same, with no clear distinction between them. The maximum displacement was reduced by about 20% compared to that of the conventional system. The standard deviation was reduced by about 40% to 50%, indicating that the vibration was quickly reduced by using the suggested systems.

In the result of Shinjuku TKY 007, the effect was relatively larger than that of JMA Kobe, and the response displacement was reduced by about 70% to 80% compared to that of the conventional system. The result of the standard deviation also showed the same tendency.

In the case of an earthquake such as a pulse-like motion, wherein the acceleration increases instantaneously, the damper tended to be ineffective and the effect of the system was small. On the other hand, in the case of a long-period ground motion, which has a longer duration time and a longer period, the effect of the system looked great as the damper worked effectively.



1. JMA KOBE (b) TKY007

Figure 10. Analysis Result of System 1 (24F)



1. JMA KOBE (b) TKY007

Figure 11. Analysis Result of System 2 (24F)

Table 2. Maximum Displacement and Standard Deviation

1. JMA KOBE



1. TKY007



※parenthesized values：ratio of the maximum displacement to that of the conventional system.

**5. Conclusions**

The authors proposed two types of damping systems that can effectively reduce the swing of a chandelier. These damping systems are characterized by the incorporation of a vibration damping system between the ceiling slab and the ceiling to avoid distracting from the appearance of the chandelier.

We derived the equations of motion for the two types of damping systems, and the condition of the optimum state, which is defined as the state wherein the amplitude ratio of the fixed point is the maximum value in the entire frequency range, was arranged.

Next, a study model satisfying the optimum condition was set, and the frequency characteristics were determined using a transfer function. It was confirmed that the maximum amplitude ratio of system 1 was smaller than that of system 2. Therefore, the effect of system 1 was larger than that of system 2 in the transfer function.

Finally, we validated the effects of the suggested systems through a time history response analysis using the response wave of the building model as an input. Common to both systems, the maximum displacement when inputting a pulse-like motion, where the acceleration increases instantaneously, tended to be smaller than the result of the long-period ground motion. As a general trend, system 1 is superior, but a sufficient effect can be expected using system 2, which is a simplified version of system 1.

We are planning to validate the performance of the proposed systems through a shaking table test in the future.

**6. Acknowledgments**

The authors are grateful to the National Research Institute for Earth Science and Disaster Resilience for providing the records of strong-motion seismograph networks (K-NET and KiK-net).

We would like to thank Editage (www.editage.jp) for English language editing.

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