RESEARCH ON NEW SEISMIC ISOLATION SYSTEM USING CENTER-OF-GRAVITY POSITION VARIATION

Osamu Furuya[1] and Shota Saito[2]

[1] Professor, Tokyo Denki University, Saitama, Japan (osamu.furuya@mail.dendai.ac.jp)
[2] Graduate School Student, Tokyo Denki University, Saitama, Japan

ABSTRACT

In Japan, large earthquakes have been occurring frequently in recent years, and a large earthquake is expected to occur within a few decades. Facilities of high social importance and industrial facilities requiring expensive equipment are at economic risk due to damage to equipment caused by large earthquakes. In addition, there are performance requirements to avoid system shutdown at the level of small to medium earthquakes and to have vibration countermeasures at all times. However, vibration countermeasure technology that covers the range from large earthquakes to microvibrations is not yet available. In this study, the authors investigate a method that covers both the vibration isolation and seismic regions. Specifically, a new type of seismic isolation mechanism in which the position of the center of gravity changes three-dimensionally by moving the supporting points vertically and horizontally will be studied from both analytical and experimental perspectives.

INTRODUCTION

In Japan, the probability of earthquakes occurring in the Tokai, Tonankai, Nankai, and directly under the Tokyo metropolitan area is increasing, Japan Society for Disaster Information (2018). Therefore, the economic risk of critical equipment installed in facilities that maintain social functions, such as power generation facilities, in the event of a severe earthquake is also considered important. On the other hand, there are also performance requirements to avoid functional destruction of equipment at the level of small and medium earthquakes. To maintain the functionality of such facilities, the introduction of seismic isolation and vibration control technologies is considered a good countermeasure against vibration in a wide range of frequency ranges and acceleration regions, Fukazawa et. al. (2023), Nakamura et. al. (2021), Ishioka et al. (2021) . In addition, facilities with critical equipment, such as nuclear power plants, must maintain their functions in a region that exceeds the design base earthquake motion, and seismic isolation and vibration control technologies can be fully expected to be one way to ensure the required margin.

This study examines a new seismic isolation system that focuses on reducing the response displacement required in maintaining the seismic function of equipment. The objective of this study is to reduce the response displacement of the main vibration system by adding a sub-vibration system to the main vibration system, thereby improving the performance of maintaining system functions during earthquakes. As the first step of the research, a new type of seismic isolation mechanism was studied analytically and experimentally using a structure in which the position of the center of gravity can be changed three-dimensionally by moving the support points of the suspension structure vertically and laterally. This paper summarizes the effect of response reduction by moving the support point of a pendulum structure with horizontal periodicity.

BASIC RESPONSE REDUCTION EFFECTIVENESS BY TIME HISTORY RESPONSE ANALYSIS

To investigate the basic effectiveness of the proposed mechanism, a time history response analysis is conducted in the horizontal direction using an analytical model that simulates equipment installed in a building. The differences between a fixed fulcrum and a horizontally movable fulcrum are investigated through time history response analysis using one-degree-of-freedom and two-degree-of-freedom vibration system analysis models.

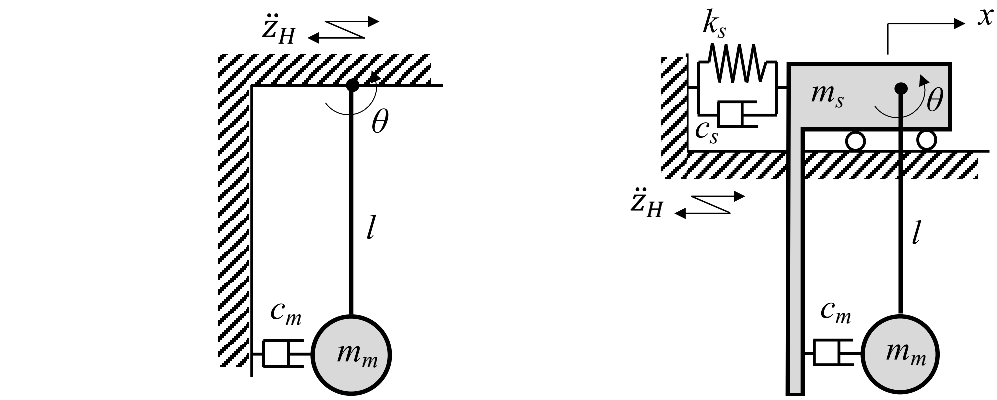
Analytical Model and Equations of Motion

Figure 1 shows the analytical model used in the time history response analysis to investigate the effectiveness of the proposed mechanism. Figure (a) shows an analytical model in which a damping element is added to a single pendulum, and horizontal forced vibration is applied to the rotating support of the single pendulum. Figure (b) shows an analytical model in which a vibration system is installed at the fulcrum of the same single pendulum. Equations of motion for the analytical model of the vibration system in Figure 1(a) are shown in Equation (1), and Equation (2) for the analytical model of the vibration system in Figure 1(b).

$$m_m l^2 \ddot{\theta} + c_m l^2 \dot{\theta} + m_m g l \, sin\theta = -m_m l \ddot{z}_H \tag{1}$$

$$\left.\begin{aligned} (m_s + m_m)\ddot{x} + ml\ddot{\theta} + c_s \dot{x} + k_s x &= -(m_s + m_m)\ddot{z}_H \\ m_m l \ddot{x} + m_m l^2 \ddot{\theta} + c_m l^2 \dot{\theta} + m_m g l \, sin\theta &= -m_m l \ddot{z}_H \end{aligned}\right\} \tag{2}$$

In here,
m_m: Mass of the vibration system of the suspension structure
m_s: Mass of the vibration system at the rotating support of the suspended structure
c_m: Damping coefficient of the vibration system of the suspended structure
c_s: Damping coefficient of the vibration system at the rotating support point of the suspension structure
k_s: Spring constant of the vibration system installed at the rotating support point of the suspension structure
l: Suspension length of the vibration system of the suspended structure
z_H: Input displacement of the suspension structure and the vibration system at the rotating support
x: Horizontal displacement of the vibration system installed at the rotating support point of the suspended structure
θ: Angular displacement around the rotating support of the vibration system of the suspended structure



(a) Forced vibration model of a single pendulum
(b) Vibration model with vibration system at the support of a single pendulum

Figure 1. Analytical model used for time history response analysis.

Time Response Analysis

A time history response analysis is performed using the previously derived equations of motion. Table 1 shows the analytical parameters. The response of the suspended structure is compared with and without the vibration system at the single pendulum support, assuming the same specifications for the vibration system (natural frequency of 1.0 Hz, damping ratio of 0.05). The mass ratio between the mass of the single pendulum and the mass of the vibration system at the single pendulum support point is 0.1 to 1.0, and the natural frequency of the vibration system at the rotating support point of the suspension structure is 0.1 to 5.0 Hz. The input seismic waves are the El Centro NS and Hachinohe EW waves of the building center, which are commonly used in seismic design, and both input waves are standardized to have a maximum velocity of 50 kine.

Figures 2 and 3 show the results for the El Centro NS and Hachinohe EW wave inputs, respectively. Both results are summarized by the ratio of the maximum response of the single pendulum to the maximum response when the vibration system is installed at the single pendulum support. The red, blue, and black lines in the figure indicate a mass ratio of 0.1, 0.5, and 1.0, respectively. As a result, it was confirmed that the maximum response acceleration and maximum response displacement (deformation angle) can be reduced by setting the natural frequency of the vibration system to within 1.5 Hz at the single pendulum support with a mass ratio of 0.1.

Figure 4 compares the maximum response of the vibration system at the single pendulum support when four types of input earthquake motion are applied when the mass ratio is set to 0.1, the natural frequency to 1.0 Hz, and the damping ratio to 0.05. Figure 4(a) shows the maximum input acceleration, the maximum response acceleration of the suspension structure without the single pendulum fulcrum vibration system, and the maximum response acceleration of the suspension structure with the single pendulum support vibration system. Figure 4(b) shows the maximum response displacement of the suspended structure without the single pendulum support vibration system and with the single pendulum support vibration system. The maximum response acceleration was confirmed to have a response reduction effect of 1/2 or more of the input, and the maximum response displacement was confirmed to have a response reduction effect of 1/10 or more of the input. Analysis is still ongoing to determine the appropriate specification conditions for the single pendulum support vibration system.

Table 1:Analytical parameters used in time history response analysis.

Analytical Item	Parameters
Natural frequencies of suspended structures	1.0 Hz
Damping ratio of the suspension structure	0.05
Mass ratio of the mass of the suspension structure to the mass of the vibration system at the rotating support	0.1 - 1.0
Natural frequency of the vibration system at the rotating support of the suspended structure	0.1 - 5 Hz
Damping ratio of the vibration system installed at the rotating fulcrum of the suspended structure	0.05

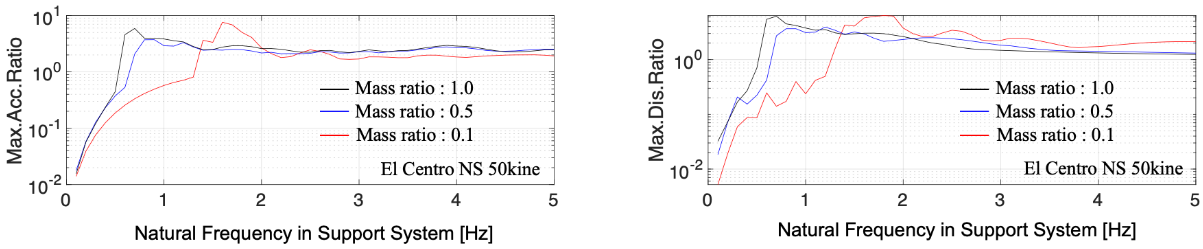


Figure 2. Relationship between natural frequency, mass ratio and response of the vibration system installed at the rotating support of the suspension structure.
(El Centro NS 50kine equivalent wave)

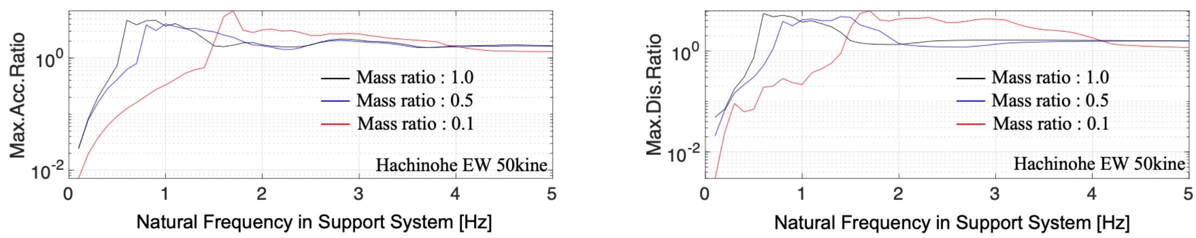
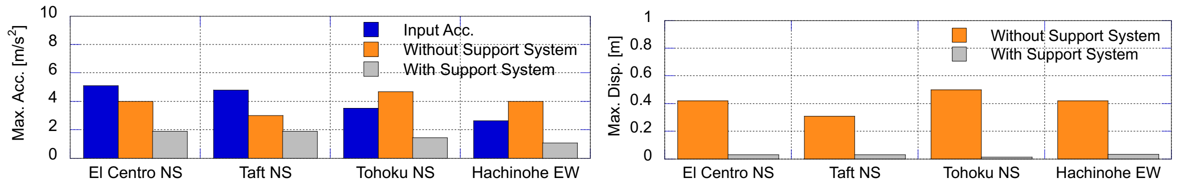


Figure 3. Relationship between natural frequency, mass ratio and response of the vibration system installed at the rotating support of the suspension structure.
(Hachinohe EW 50kine equivalent wave)



(a)Comparison of maximum response acceleration (b) Comparison of maximum response displacement
Figure 4. Comparison of maximum response of suspended structures.

INVESTIGATION OF BASIC RESPONSE REDUCTION EFFECT BY SHAKING TABLE TEST

In order to confirm the basic seismic isolation performance, shaking table tests are conducted to check the difference between the method of fixing the support with bolts and nuts and the method of horizontal movement with a slider.

Test Apparatus

Figure 5 shows a full view of the vibration test apparatus. The vibration system of the suspension structure is realized by connecting four solid round bar supports, which are assumed to be rigid, to the suspension mass, and connecting a plate spring element to the upper end of the support. A support plate is placed above each plate spring element, and the support plate is connected to the top surface of the beam to which the slider is attached. The natural frequency of the support plate can be adjusted by pre-tensioning a coil spring from the edge of the beam. Figure 6 shows the configuration of the support plate (mass section). Table 2 shows the specifications of the test apparatus.

Seismic Wave Testing

To confirm the basic seismic isolation effect, the seismic waves used in the analysis were input to investigate the response reduction effect. Figure 7 summarizes the results of the comparison between the case without (a) and with (b) the vibration system of the suspension structure support point when the Tohoku NS waves are input. The graphs show, from the top of the left column, the input wave, the acceleration at the suspension support point, and the acceleration of the suspension structure, and from the top of the right column, the displacement at the suspension support point and the displacement of the suspension structure. It was confirmed that moving the support point was effective in reducing the maximum response acceleration of the suspension structure by 40 to 70% and the maximum response displacement by 46 to 80%.

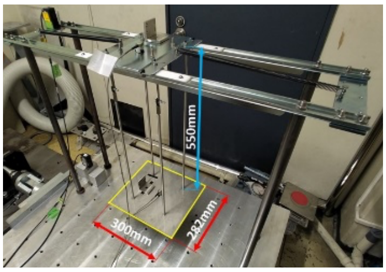


Figure 5. Overall view of vibration test apparatus.

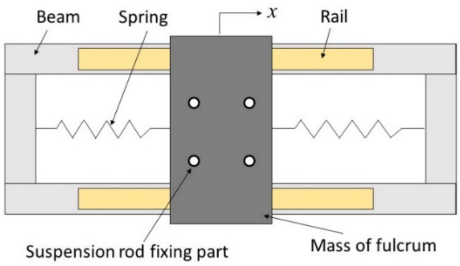
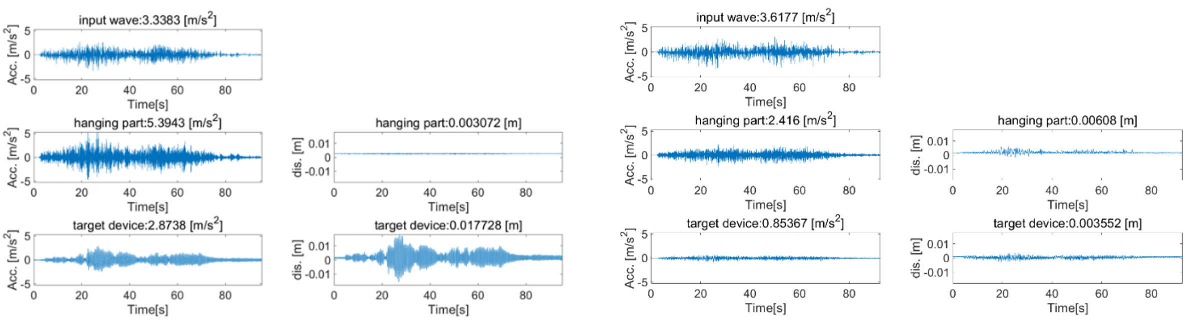


Figure 6. Vibration system configuration at the rotary support point.

Table 2: Specifications of test specimens used in shaking table tests.

Specification	Parameters
Mass of the suspended structure	2 - 8 kg
Mass of the vibration system installed at the rotating support point of the suspended structure	0.8 - 2.4 kg
Natural frequency of the vibration system at the rotating support point of the suspended structure	1.0 - 4.7Hz
Suspension length of the suspended structure	0.55 m

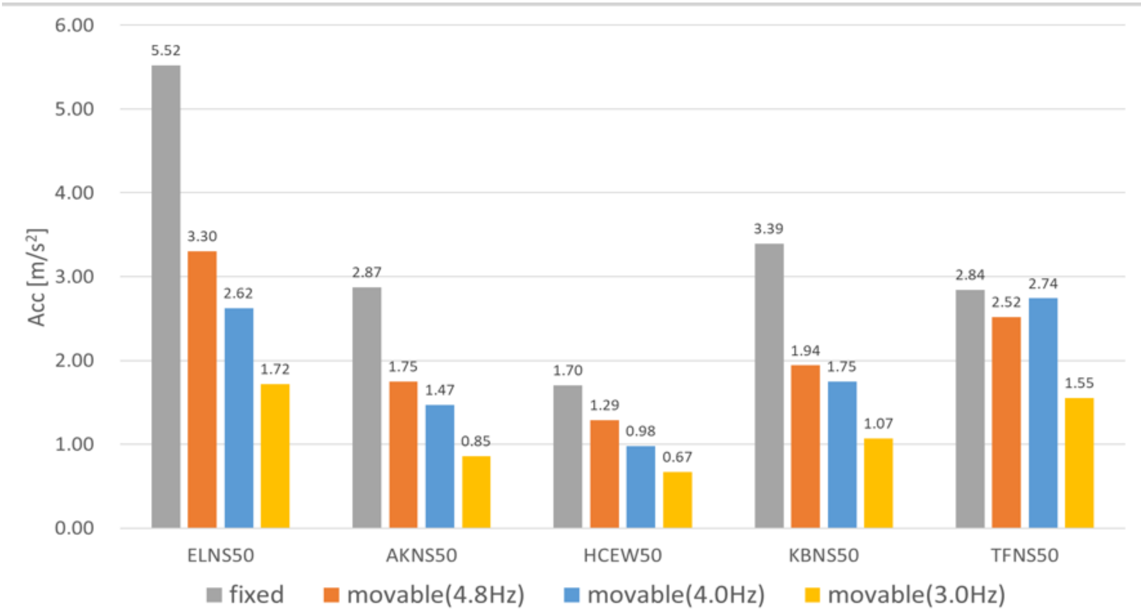
Figure 8(a) shows the maximum response acceleration of the suspended section when the support point is fixed and when the support point is movable during each seismic wave input. Figure 8(b) shows the maximum response displacement of the suspended section when the support point is fixed and when the support point is movable for each seismic wave input. When the support point is moved compared to when the support point is fixed, the response reduction effect is greatest when the natural frequency of the support point is 3.0 Hz, and the acceleration response is reduced by a maximum of 45-70%. The response reduction effect was greatest when the natural frequency of the support point was 3.0 Hz, and the response displacement was reduced by 43 to 80% at the maximum. The closer the frequency ratio of the suspension to the support point, the greater the response reduction effect. Since the response is reduced for each seismic wave input, the basic seismic isolation performance is considered to be effective for various types of seismic waves.



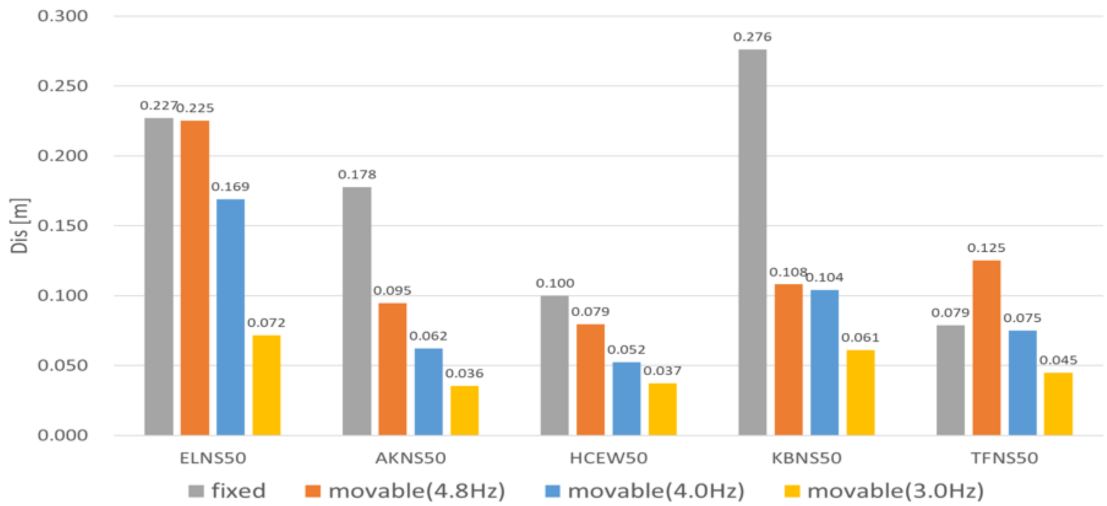
(a) Without vibration system installed at the rotary support point

(b) With vibration system installed at the rotating at the rotating support (natural frequency: 3.0 Hz)

Figure 7. Comparison of response in seismic wave excitation test (time history response).



(a) Comparison of maximum response acceleration for each seismic wave input



(b) Comparison of maximum response displacement for each seismic wave input

CONCLUSION

This study examined a new seismic isolation system focusing on the reduction of response displacement required for seismic countermeasures for equipment. As the first step of the research, the response reduction effect of a pendulum with horizontally periodic support points is summarized here. In the response analysis, the specification conditions necessary to obtain the response reduction effect were studied, and by using the obtained specification conditions, a response reduction effect of more than 1/2 in maximum response acceleration and less than 1/10 in maximum response displacement was confirmed for the input earthquake motion. In the shake table test, typical seismic waves used in the analysis were input to confirm the response reduction effect depending on the frequency ratio between the support point and the suspension. The response decreased as the frequency ratio became closer, and the maximum response reduction of 43~80% was confirmed.

It is difficult to apply this method directly to equipment in nuclear facilities. However, response reduction measures with high margins that can cope with various events, such as aircraft collisions and earthquakes, should continue to be studied in the future. In particular, it is important to actively adapt current seismic isolation and vibration control technologies to maintain the functionality of mechanical systems consisting of multiple components as well as individual components under inputs that exceed the design earthquake ground motions.

In the future, vibration analysis models in the horizontal and vertical directions will be considered, and the effectiveness of the proposed method will be verified from both analytical and experimental approaches.

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