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SHAKING TABLE TEST ON INDOOR SEISMIC SAFETY OF HIGHRISE BUILDINGS
(Part 1. Performance test on BRI Large stroke shaking table)

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ABSTRACT

A new shaking table called "BRI Large Stroke Shaking Table" was developed in 2006 in the Building Research Institute. The shaking table is driven by wire connected with dynamic actuator and its displacement is increased by 6 sets of pulleys and is 13 times of actuator's deformation, theoretically. Dynamic range of the table is 2.5 m and is enough to estimate the deformation of 50th floor of high-rise buildings. Performance test of the shaking table was performed on March 2006 by loading 6 periods of sine waves. By these loadings, unexpected vibration around 1.8 Hz were observed. Therefore, analytical model study was performed and it was estimated that unexpected vibration might be caused by telescopic motion of wire. Then, parametric case study was performed and designed oil damper was installed in the shaking table in July 2007. Performance test for damper installed shaking table was performed in July 2007. The unexpected vibration around 1.8 Hz was eliminated by the damper and the shaking table has been ready to perform long period shaking test.

KEYWORDS : shaking table, long period vibration, high-rise buildings, indoor human safety

1. INTRODUCTION

In Japan, Tokai, Tonankai, and Nankai Earthquakes are expected to occur in the near future and those may cause long period earthquake ground motions in Tokyo, Nagoya, and Osaka area. It has become large subject of public attention in Japan. Long period components of earthquake ground motions may amplify the response of large-scale structures with long natural periods such as high-rise buildings, long-span bridges, and oil storage tanks. To examine the safety of living space in high-rise buildings, a new shaking table called "BRI Large Stroke Shaking Table" was developed in 2006 in the Building Research Institute as a part of research cooperation project among following four organizations; the Building Research Institute, Chiba University, the National Institute for Land and Infrastructure Management (NILIM), and the National Research Institute for Earth Science and Disaster Prevention (NIED).

The mechanism of the shaking table is shown in Figure 1. The mechanism is patented as Minowa's invention (2003-130755). In this case, there are 6 pairs of fixed and movable pulleys, and the displacement of dynamic actuator shown in Figure 2 is amplified 13 times and transferred into the shaking table by wire.

The outline of the shaking table is shown in Figure 2. At the both side of dynamic actuator, there are 6 pairs of pulleys. The maximum stroke of the shaking table is 2.5 m.

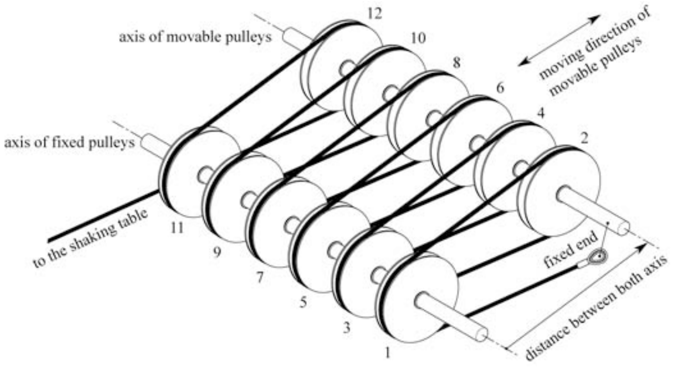


Figure 1 Mechanism of displacement amplification

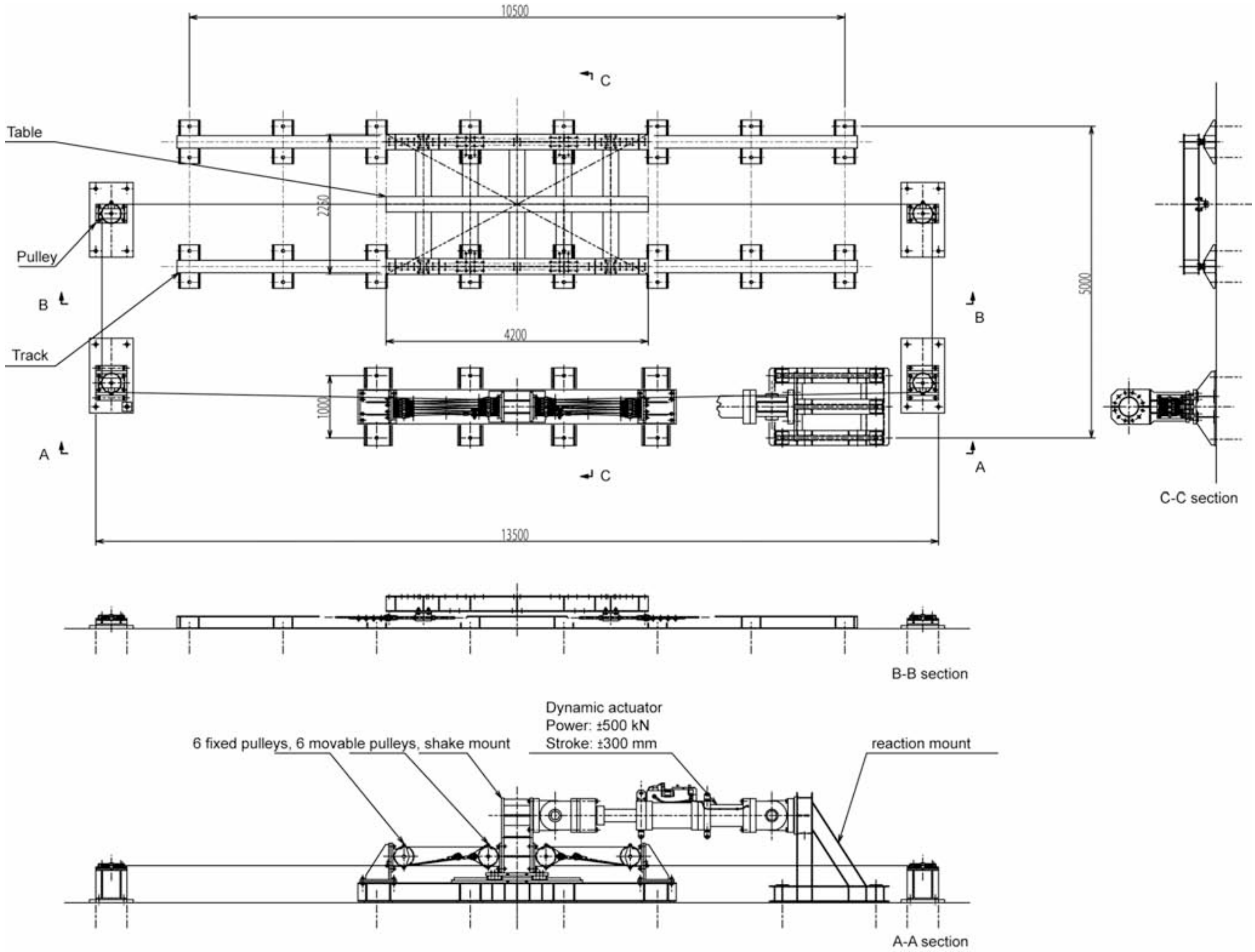


Figure 2 Outline of the shaking table

2. PERFORMANCE TEST

Performance test for the original system was performed on March 31, 2006. Acceleration of the table, displacement of the actuator and the table were observed. The results are shown in Figures 3. Although the displacement of the table looks smooth, accelerations on the table were jagged especially between 0.1 Hz to 0.5 Hz. Fourier amplitude spectra of the accelerations are shown in Figure 4. Noisy peak around 1.8 Hz can be seen especially for 0.1 Hz, 0.16 Hz, 0.25 Hz and 0.5 Hz. The peak was not observed for 0.75 Hz nor 1.0 Hz.

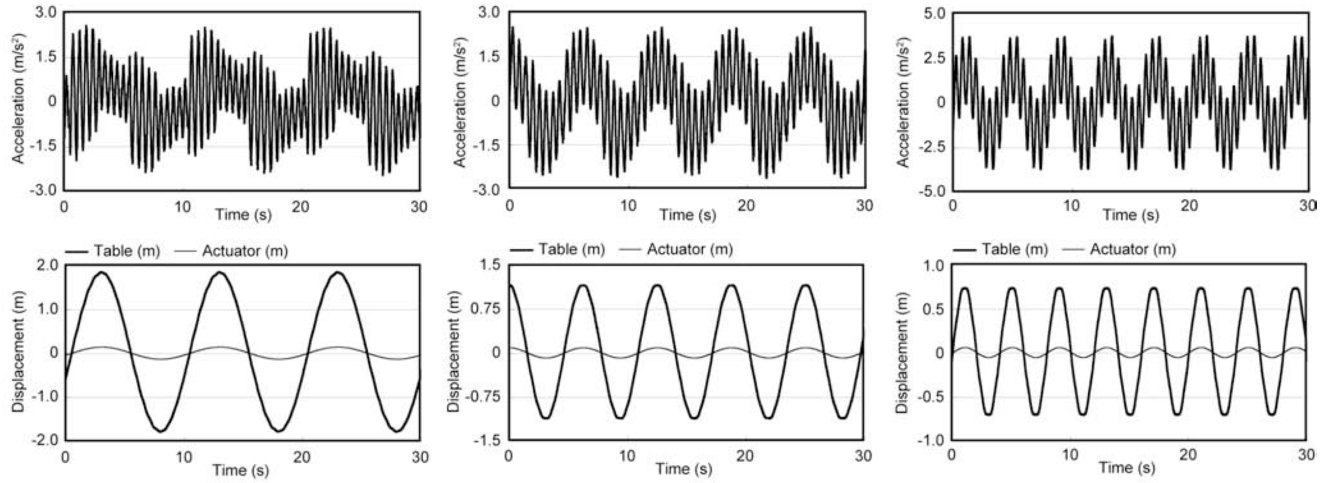
The authors built a model for this vibration system as shown in figure 5, and considered friction between the track and the shaking table, wire elongation and so on. The authors finally judged this noisy vibration was caused by the first natural period of the wire elongation vibration.

3. INSTALLATION OF DAMPER

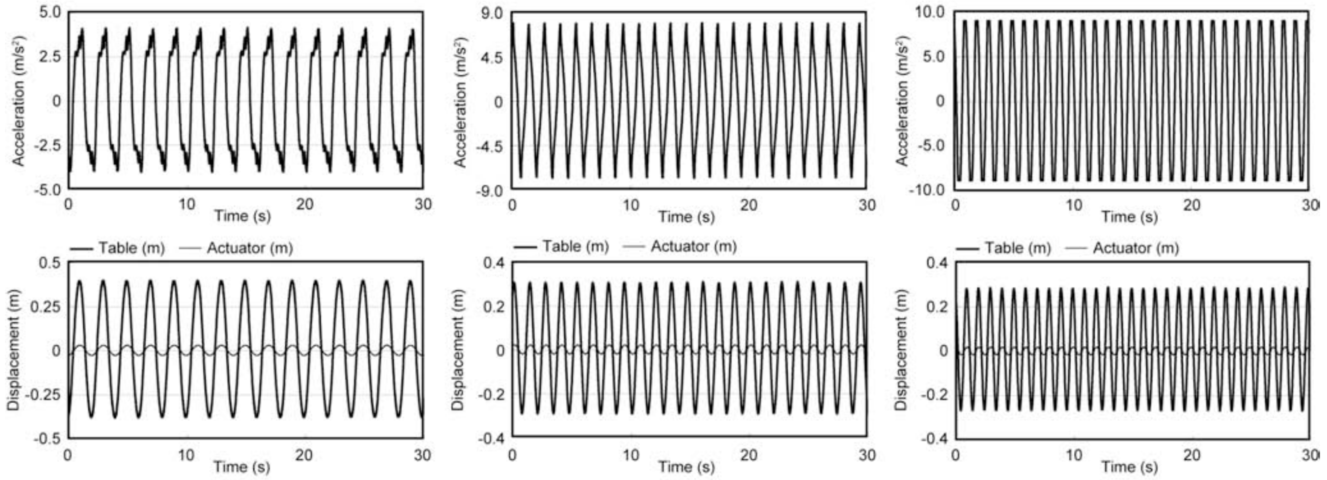
The authors decided to install noise reduction damper for the system. To define the suitable parameters for the damper, the authors performed parameter studies using the model shown in Figure 6. This system has one mass with two degree of freedom. The equation of vibration at the point *q* in Figure 6 is defined as follows:

$$-c_1\dot{x}_1 - k_1x_1 + c_2\left(\dot{x}_2 - \dot{x}_1\right) + k_2\left(x_2 - x_1\right) = 0 \tag{3.1}$$

The equation of vibration at the point *r* in Figure 6 is defined as follows:



(a) 0.1 Hz (b) 0.16 Hz (c) 0.25 Hz



(d) 0.5 Hz (e) 0.75 Hz (f) 1.0 Hz

Figure 3 Results of performance test (March 31, 2006)

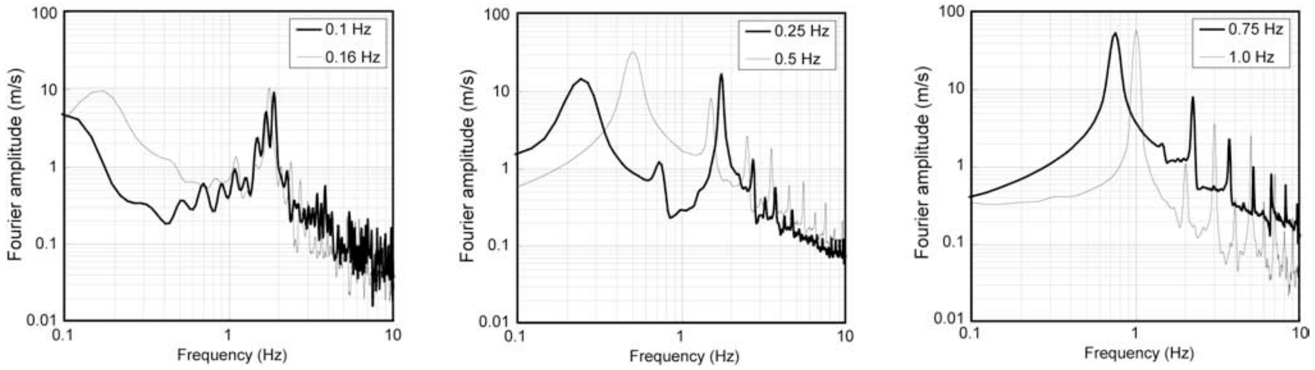


Figure 4 Fourier Spectra of the performance test (March 31, 2006)

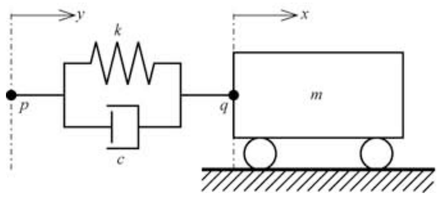


Figure 5 Model of this vibration system

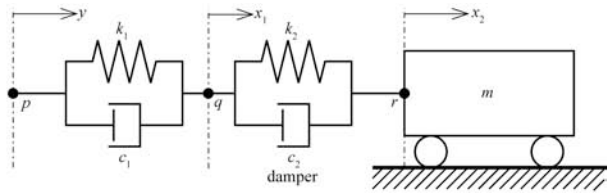


Figure 6 Model with noise reduction damper

$$m\ddot{x}_2 + c_2\left(\dot{x}_2 - \dot{x}_1\right) + k_2\left(x_2 - x_1\right) = -m\ddot{y} \tag{3.2}$$

where, assume $\dot{x}_2 = z$ and substitute it into Eqns (3.1) and (3.2), we got following differential equation.

$$\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{z} \end{Bmatrix} = \begin{bmatrix} -\dfrac{k_1+k_2}{c_1+c_2} & \dfrac{k_2}{c_1+c_2} & \dfrac{c_2}{c_1+c_2} \\ 0 & 0 & 1 \\ \dfrac{k_2c_1-k_1c_2}{m\left(c_1+c_2\right)} & \dfrac{-k_2c_1}{m\left(c_1+c_2\right)} & \dfrac{-c_2c_1}{m\left(c_1+c_2\right)} \end{bmatrix} \begin{Bmatrix} x_1 \\ x_2 \\ z \end{Bmatrix} + \begin{Bmatrix} 0 \\ 0 \\ -\ddot{y} \end{Bmatrix} \tag{3.3}$$

Then, we made Laplace transform of Eqn (3.3) and got transfer function of this system. Assume $X_1(s)$, $X_2(s)$, $Y(s)$ and $Z(s)$ as the Laplace transform of $x_1(t)$, $x_2(t)$, $y(t)$ and $z(t)$, we got following Eqn.

$$s\begin{Bmatrix} X_1 \\ X_2 \\ Z \end{Bmatrix} = \begin{bmatrix} -\dfrac{k_1+k_2}{c_1+c_2} & \dfrac{k_2}{c_1+c_2} & \dfrac{c_2}{c_1+c_2} \\ 0 & 0 & 1 \\ \dfrac{k_2c_1-k_1c_2}{m\left(c_1+c_2\right)} & \dfrac{-k_2c_1}{m\left(c_1+c_2\right)} & \dfrac{-c_2c_1}{m\left(c_1+c_2\right)} \end{bmatrix} \begin{Bmatrix} X_1 \\ X_2 \\ Z \end{Bmatrix} + \begin{Bmatrix} 0 \\ 0 \\ -s^2Y \end{Bmatrix} \tag{3.4}$$

Eqn (3.4) leads the relation between X_1 and Y, and X_2 and Y. Where, assume $H_1(s)$ as a transfer function of displacement of shaking table, we got following Eqns.

$$H_1(s) = \frac{X_1(s)}{Y(s)} = \frac{P_1(s)}{Q(s)} \tag{3.5a}$$

$$P_1(s) = -\frac{c_2}{c_1+c_2}s^3 - \frac{k_2}{c_1+c_2}s^2 \tag{3.5b}$$

where, $Q(s)$ in Eqn (3.5a) was defined as follows,

$$Q(s) = s^3 + \frac{c_1c_2 + m(k_1+k_2)}{m(c_1+c_2)}s^2 + \frac{c_1c_2(k_1+k_2) + k_1c_2^{\,2} + k_2c_1^{\,2}}{m(c_1+c_2)^2}s + \frac{k_1k_2}{m(c_1+c_2)} \tag{3.6}$$

Displacement of the damper $d(t) = x_1(t) - x_2(t)$ can be gotten as follows

$$\mathcal{L}\left[x_1(t) - x_2(t)\right] \equiv \left[X_1(s) - X_2(s)\right] \tag{3.7}$$

therefore, assume transfer function from input motion to the displacement of damper can be defined as follows,

$$H_D(s) = \frac{X_1(s) - X_2(s)}{Y(s)} = \frac{P_2(s)}{Q(s)} \tag{3.8a}$$

$$P_2(s) = -\frac{c_1}{c_1+c_2}s^3 - \frac{k_1}{c_1+c_2}s^2 \tag{3.8b}$$

The authors assumed the mass of the shaking table m = 2,235 kg, and stiffness of the wire k_1 = 300 kN/m, and got the suitable parameters for the damper as follows,

$$c_2 = 24 \text{ kNs/m} \tag{3.9a}$$

$$k_2 = 30 \text{ kN/m} \tag{3.9b}$$

The result of parameter study is shown in Figures 7 and 8. These parameters divided into two dampers because of keeping symmetry of the system, and installed on July, 2007. Photo 1 shows the shape of the damper.

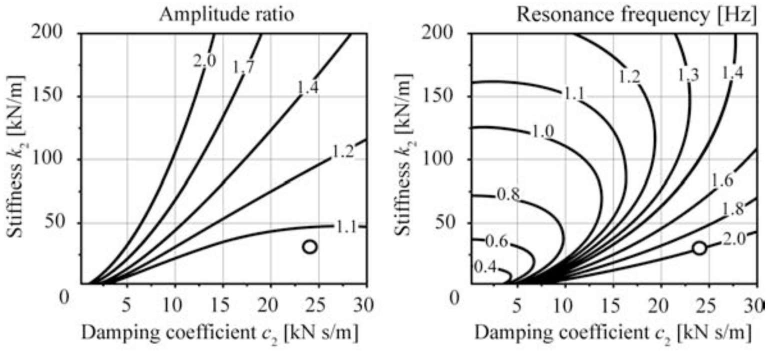


Figure 7 Result of parameter study for noise reduction damper (relative displacement of table)
(The circle pointed in the figure was the parameter used in actual damper)

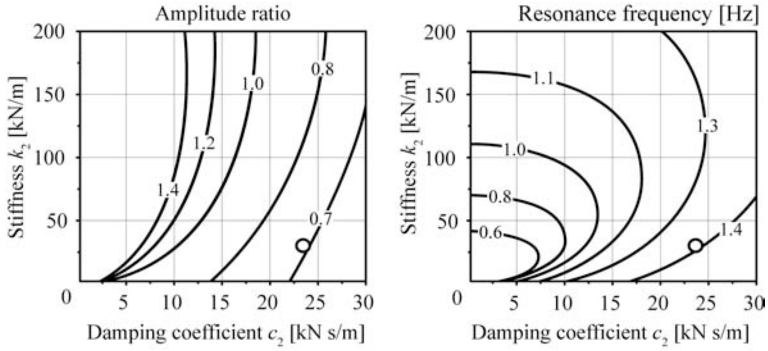


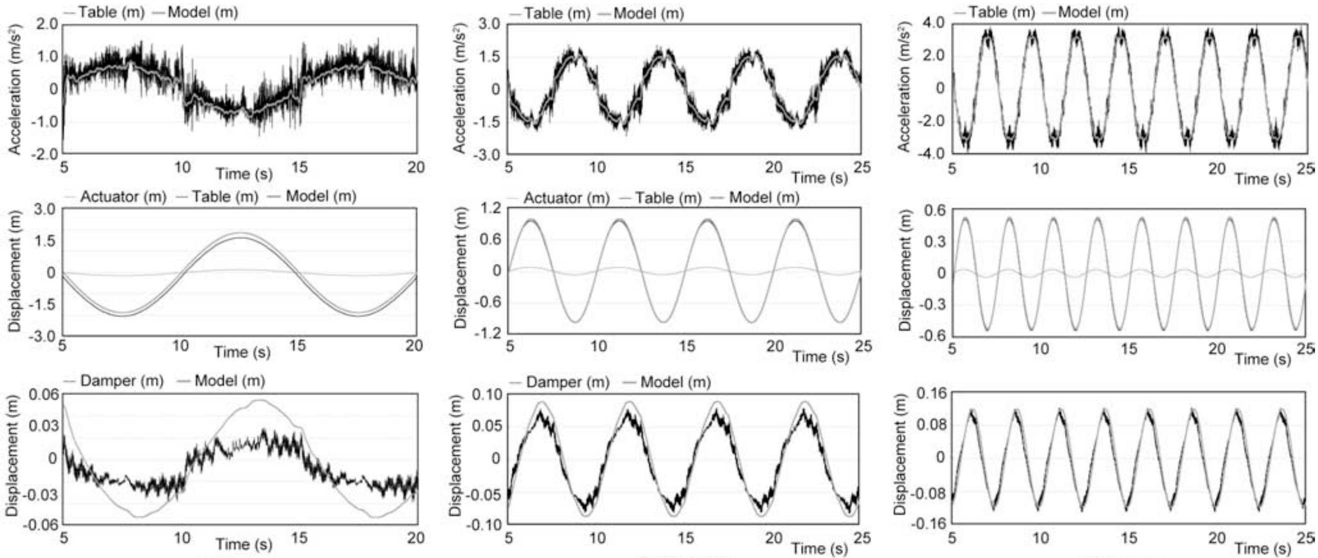
Figure 8 Result of parameter study for noise reduction damper (relative displacement of damper)
(The circle pointed in the figure was the parameter used in actual damper)

Photo 1 Shape of noise reduction damper

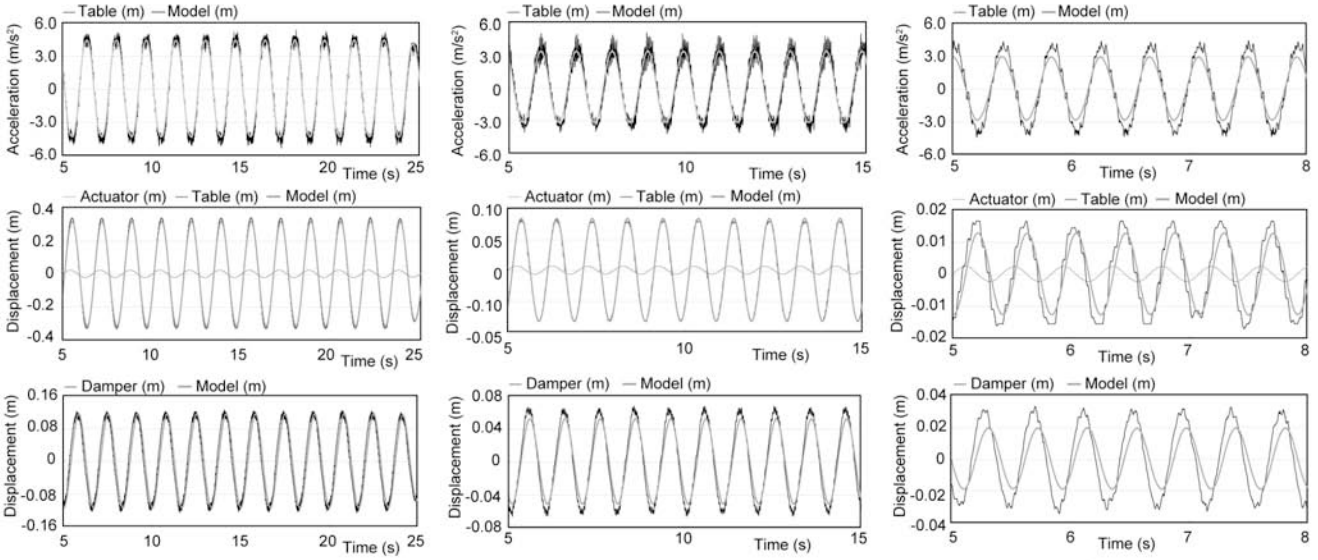
4. ANOTHER PERFORMANCE TEST FOR THE SYSTEM WITH DAMPER

4.1. Stationary Input

Performance test for damper-installed system was performed on November 29, 2007. Some examples of the test are shown in Figure 9. In Figure 8, calculation result of the model shown in Figure 6 is also illustrated. For the model, 13 times amplified displacement of dynamic actuator was used for the calculation.



(a) 0.1 Hz (b) 0.2 Hz (c) 0.4 Hz



(d) 0.6 Hz (e) 1.0 Hz (f) 2.4 Hz

Figure 9 Result of performance test on damper-installed system (November 29, 2007)

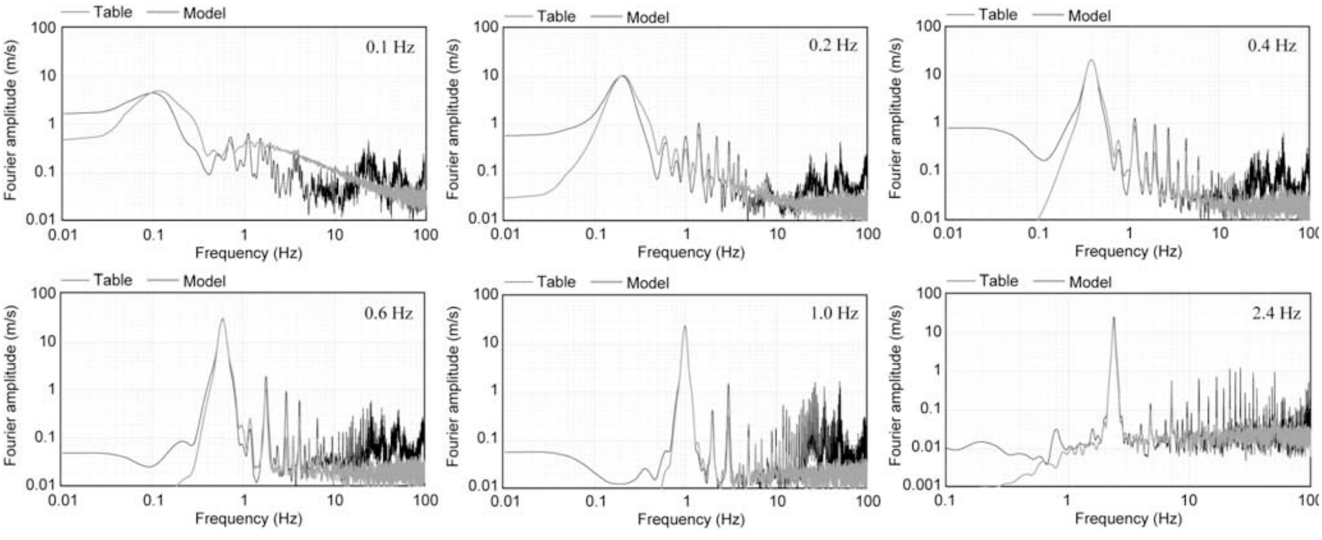


Figure 10 Fourier spectra of the performance test (Novenber 29, 2007)

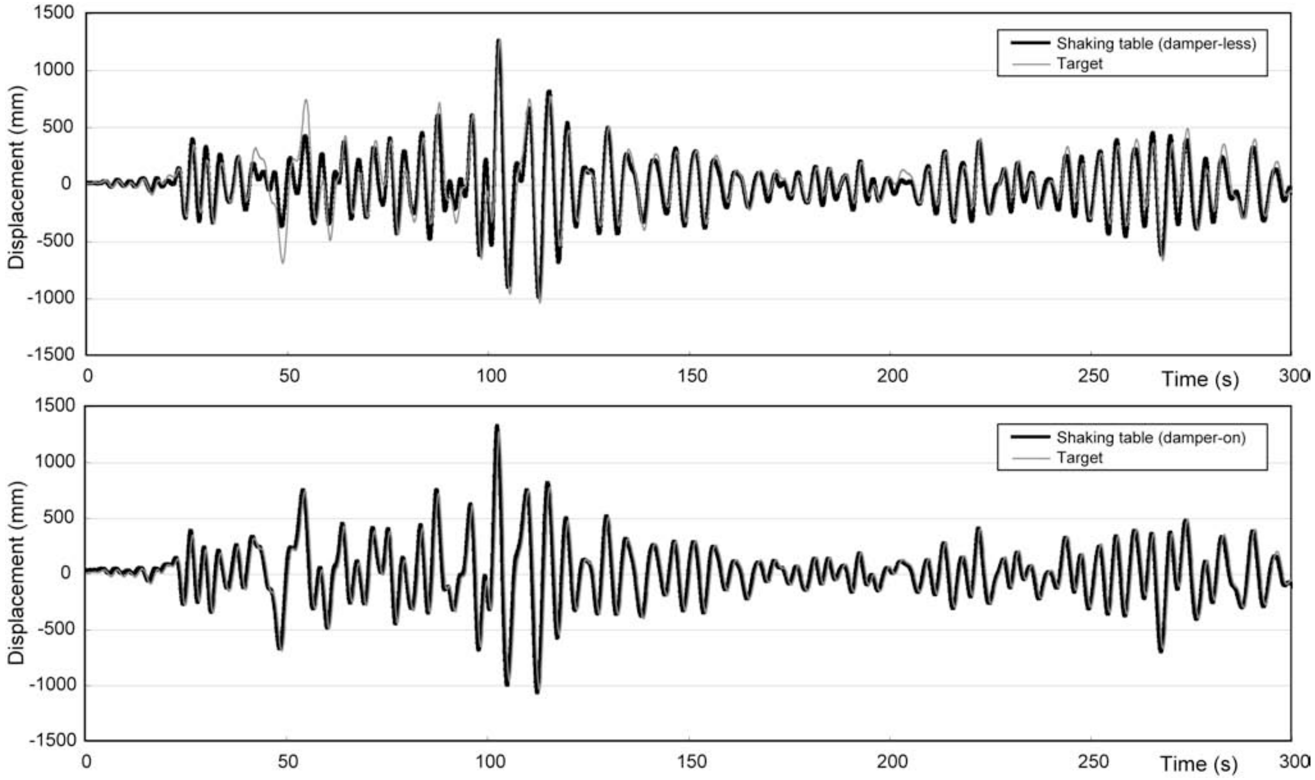


Figure 11 Comparison of before and after damper installation (Displacement of the shaking table)

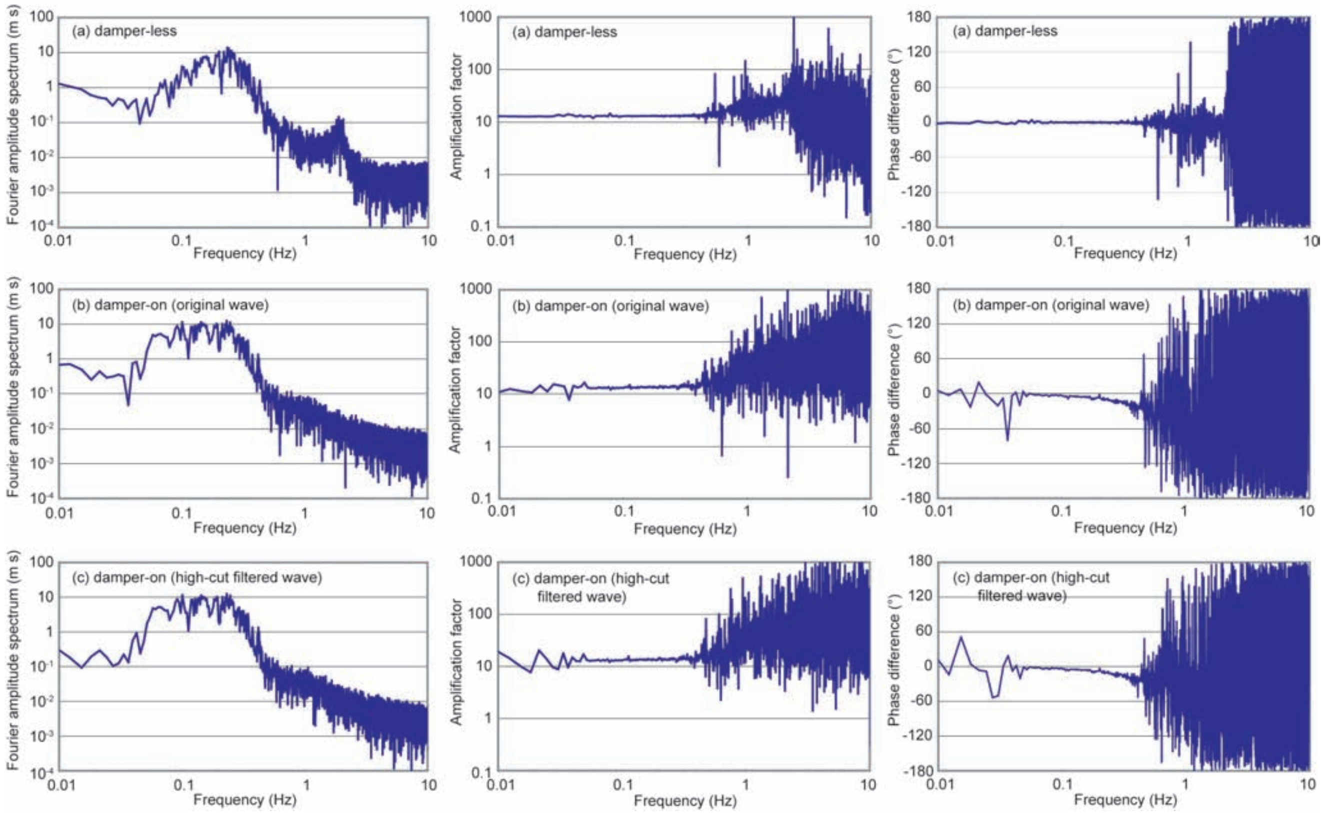


Figure 12 Fourier spectra, amplitude factor, and phase difference to the input motion

Comparing with Figure 3, jaggies in the accelerations were reduced well. When the input frequency is higher than 1.0 Hz, there seems phase-lag on the table displacement to that of dynamic actuator. Fitness with model is basically suitable except of over 10 Hz. There seems the other noise on this system.

4.2. Non-stationary input

Estimated floor response for Tokai-Tonankai-Nankai Earthquake (AIJ 2007) was used for the input. The ground motion was estimated by Furumura (AIJ 2007) for Tokyo area and the floor response was estimated by BRI as a response of top floor of 40-story RC condominium building. Comparison of before and after damper installation is shown in Figure 11. Before damper settlement, there are some differences between target and table motion. After installation, there seems no difference between target response and table motion.

Figure 12 shows Fourier spectra of above mentioned responses table amplification ratio (13 times, theoretically), and phase difference between actuator and table. Sub peak around 2 Hz on the Fourier spectrum of damper-less displacement was cleared away by setting the damper. Amplification factor is basically stable between 0.1 Hz to 0.5 Hz. Phase-lag appears over 0.5 Hz when the damper is installed.

5. CONCLUSION

Large stroke shaking table was developed and performance tests have been done. By introducing noise reduction damper, the table displacement becomes quite smooth and ready to perform floor response testing for top story of high-rise buildings.

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