Development and Verification of Vertical Excitation System by Using Horizontal Shaking Table

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Abstract. Shaking table is used to test the seismic resistance or assess the seismic behavior of structures. Considering that the seismic excitation is generally accepted as the horizontal motion of the ground, the most common shaking tables operate by moving unidirectionally and horizontally a lightweight platform on which a scaled model of the structure is attached. However, some structures like the Tuned Mass Damper (TMD) are intended to vibrate or operate vertically. Accordingly, this paper proposes a method using the shaking table to excite the structure vertically rather than using actuators. In order to validate the proposed system, the vertical motion induced by the shaking table is predicted numerically and compared to data obtained from test on a TMD.

Introduction

Most of experimental studies dedicated to the seismic behavior or control of structures focus on the horizontal vibration of the structure. However, in addition to the horizontal vibration, the vertical vibration of the structure is also a matter of interest for vibration control like in bridges subjected to vertical traffic loads or in large structures subjected to wind or earthquake loading. These horizontal vibrations are mainly controlled by means of the Tuned Mass Damper (TMD), and numerous applications have been implemented in pedestrian bridges to limit the vertical vibrations [1,2]. Considering that the natural frequency of pedestrian bridges runs around 2 Hz, it is important to examine experimentally the frequency response for the verification of the dynamic response of the TMD. The problem here is that the testing devices operating vertically are generally more expensive that those operating horizontally, which makes them rare.

A popular testing device operating horizontally is the shaking table. The most common shaking tables operate by moving unidirectionally and horizontally a lightweight platform on which a scaled model of the structure is attached. Therefore, this paper proposes a method using the shaking table to excite the structure vertically rather than using actuators. In order to validate the proposed system, the vertical motion induced by the shaking table is predicted numerically and compared to data obtained from test on a TMD.

Proposed System

The proposed system relies on the concept of the friction pendulum system (FPS) shown in Figure 1. FPS is an isolator or bearing that combines the frictional sliding of steel surfaces, which are separated by a specific coating layer, and the pendular motion of the slider on a perfectly spherical surface [3]. Since these mechanisms endow the FPS with recentering ability, the FPS presents very simple composition. Moreover, it is possible to set the oscillation period (T) of a structure regardless of its weight because the FPS depend only on the radius of curvature of the spherical surface as expressed in Eq. 1.
\[ T = 2\pi \sqrt{\frac{W}{gk}} = 2\pi \sqrt{\frac{R}{g}} \tag{1} \]

where \( T \) = oscillation period of pendulum; \( W \) = weight of superstructure; \( g \) = gravitational acceleration; \( k \) = stiffness of structure; and, \( R \) = radius of curvature of spherical surface.

Based upon the concept of FPS, the proposed system intends to convert the horizontal motion of the unidirectional shaking table into a vertical motion. To that goal, a curved interfacial plate is affixed to the platform of the table. The structure is then installed over the curved plate by means of a ball bearing so as to move only vertically along vertical linear guides, as shown in Figure 2. Various motions can thus be simulated by changing the radius of the curved plate.

**Prediction and Verification of Proposed System**

The vertical displacement, velocity and acceleration resulting from the proposed system are formulated to predict them with respect to the radius of curvature of the curved interfacial plate.
Assuming that the spherical plate has constant radius $r$, the spherical surface can be expressed simply as a circle in the vertical plane $(x, y)$ along the horizontal motion of the platform.

$$(x - a)^2 + (y - b)^2 = r^2$$

where the variables and constants are shown in Figure 4.

$$x = c \sin(dt)$$

where $c$ = amplitude of vibration; and, $d$ = frequency of vibration.

Substituting Eq. 3 in Eq. 2 and solving for $y$ gives,

$$y = \frac{2b - \sqrt{(4r^2 - (c \sin(dt) - a)^2)}}{2}$$

Eq. 4 expresses the motion in the vertical direction. The derivation of Eq. 3, Eq. 4 provides the velocities in the horizontal and vertical direction in Eq. 5, Eq. 6, and further derivation gives the horizontal and vertical accelerations in Eq. 7, Eq. 8.

$$\dot{x} = cd \cos(dt)$$

$$\dot{y} = \frac{-cd \cos(dt)(a-c \sin(dt))}{\sqrt{r^2-(a-c \sin(dt))^2}}$$

$$\ddot{x} = -cd^2 \sin(dt)$$

$$\ddot{y} = \frac{c^2d^2 \cos^2(dt)}{\sqrt{r^2-(a-c \sin(dt))^2}} + \frac{cd^2 \sin(dt)(a-c \sin(dt))}{\sqrt{r^2-(a-c \sin(dt))^2}} + \frac{c^2d^2 \cos^2(dt)(a-c \sin(dt))}{\frac{1}{4}(r^2-(a-c \sin(dt))^2)}$$

Eq. 3, Eq. 5 and Eq. 7 represent the horizontal displacement, velocity and acceleration of the shaking table, and Eq. 4, Eq. 6 and Eq. 8 represent the corresponding vertical displacement, velocity and acceleration transferred to the structure by the proposed system.

The predictions given by these equations are verified by comparing them to the experimental data measured through test using the shaking table equipped by the proposed system. In the installed system, $r = 352$ mm, $a = -133$ mm, and $b = 326$ mm. The input motion of the shaking table is set as a sine wave with $c = 10$ mm and $d = 2$ Hz.

Figure 5 plots the measured horizontal displacement of the shaking table and the measured vertical displacement of the frame structure supported by the curved plate. In Figure 5, unlike our expectation, the graphs show that the shaking table shifted gradually in one direction with a lack of center-ward recovery, which reflected also on the vertical motion of the frame structure. This is due to some dysfunction of the shaking table that has no particular effect on the results. However, for further
comparison with the predictions, the shift of the experimental data was calibrated linear regression. The calibrated data are plotted in Figure 6.

![Figure 5. Measured displacements of shaking table (horizontal) and frame structure (vertical).](image)

Figure 5. Measured displacements of shaking table (horizontal) and frame structure (vertical).

![Figure 6. Calibrated displacements of shaking table (horizontal) and frame structure (vertical).](image)

Figure 6. Calibrated displacements of shaking table (horizontal) and frame structure (vertical).

Figure 7 compares the measured and simulated displacements and of the shaking table and frame structure. Figure 8 plots the same comparison for the acceleration. The simulated accelerations were emulated using Matlab [4]. Both figures show good agreement between the measured and simulated data. The slight difference between the graphs can be explained by the vibrations of the TMD in the frame.

These results prove the ability of the proposed system to transfer the horizontal excitation of the shaking table as a vertical excitation to the structure attached to it. The values given by Eq. 3 to Eq. 8 are seen to be valuable to predict the vertical acceleration or force applied to the structure with good accuracy for various arrangements regarding the radius of the curved plate and initial position of the ball bearing along the curved plate.

![Figure 7. Comparison of simulated and measured displacements of shaking table (horizontal) and frame structure (vertical).](image)
Conclusion

Shaking table is used to test the seismic resistance or assess the seismic behavior of structures. However, some structures like the Tuned Mass Damper (TMD) are intended to vibrate or operate vertically. This paper presented a system enabling to convert the horizontal motion of a unidirectional shaking table into a pure vertical motion relying on the concept of the friction pendulum system (FPS). The mechanical relations of the proposed system were formulated to predict the vertical motion by means of the characteristics of the input horizontal motion of the shaking table. The proposed system can adapt various vertical displacements of the structure by simply changing the radius of the curved plate attached to the platform of the shaking table. Moreover, owing to the reliance on the FPS concept, the proposed system can be applied regardless of the weight of the structure, and the unique limitation is the capacity of the shaking table. The validity of the proposed system and formulation was verified through comparison with test data. The shaking table test was conducted on a TMD using the proposed system. The proposed system can also be used for the assessment of the seismic behavior of structures considering that recent earthquakes exhibited increasing contribution of the vertical acceleration component.

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References


