**An inertial-type vertical isolation system with a smart friction damper for seismic protection of equipment**

**DOI 10.37153/2686-7974-2019-16-523-534**

Lyan-Ywan LU[[1]](#footnote-1), Ging-Long LIN[[2]](#footnote-2), Yi-Siang CHEN [[3]](#footnote-3), Ka Fung WONG[[4]](#footnote-4)

**ABSTRACT**

Vertical seismic excitation may have a detrimental effect on nonstructural component, such as equipment, within a building structure. Seismic isolation may be an effective solution for the protection of equipment. Nevertheless, most existing isolation systems are for mitigating horizontal excitations only. Development of a vertical isolation system (VIS) is difficult, due to a conflict between the demands of static and dynamic isolation stiffness. In other words, a VIS must have sufficient rigidity to sustain the static weight of the isolated object, while it must also have sufficient flexibility to mitigate the dynamic responses under an earthquake. To overcome this difficulty, a novel semi-active VIS that consists of an inertia-type vertical isolation system (IVIS) and an imbedded piezoelectric friction damper is proposed in this study. The primary difference between the IVIS and a traditional VIS is that the former has an additional leverage mechanism and a counterweight. Through the leverage mechanism, the counterweight will provide a static uplifting force and an extra dynamic inertia force, such that the effective vertical stiffness of the IVIS becomes higher in its static state and lower in the dynamic state. On the other hand, the piezoelectric damper will provide a controllable friction damping force for the IVIS, in order to further reduce the vertical isolator displacement without affecting isolation efficiency. To demonstrate the isolation efficiency, the seismic responses of the proposed system subjected to 14 different vertical ground motions, including the ones with long-period near-fault characteristics, were simulated numerically. The numerical results show that, as compared to the responses of a traditional system, the proposed system is able to reduce an average of 80% of the peak isolator displacement in the 14 selected earthquakes. As for the reduction of acceleration response, the new system is particularly effective for near-fault earthquakes or near-resonant excitations, but is less effective for far-field earthquakes of more high-frequency contents, as compared with the traditional system.

*Keywords: Vertical isolation; inertia type; equipment protection; leverage mechanism; near-fault earthquake*

**1. INTRODUCTION**

For critical facilities, such as medical institutions, power plants, and industrial facilities), the seismic performance of the equipment is as important as the structure itself, because to maintain the functionality of these facilities after the earthquake non-structural components such as equipment have to be undamaged. Some studies have shown that the vertical ground motions are more likely to cause damage to non-structural components and equipment (Memari et al. 2004; Furukawa 2013). Vertical components of earthquakes may cause a large amount of slippage or overturning of the unfixed equipment (Konstantinidis and Makris 2009). Anchoring the equipment on the floor may be an easy way to avoid slippage or overturning of the equipment under earthquakes; however, it also leads to large equipment acceleration and high-frequency responses, particularly, when dynamic amplification of the underlying structure is considered.

Alternatively, the technology of seismic isolation may be an effective means for seismic protection of equipment. Seismic isolation reduces seismic demands of the isolated object by introducing a soft isolation layer that elongates the vibration period of the object, so that the response of isolated object can be mitigated. Nevertheless, most existing seismic isolators or systems are for horizontal isolation, and studies on vertical isolation systems (VISs) are relatively few due to the practical difficulty, i.e., the conflict on the demands of vertical stiffness: a vertical isolation system must have sufficient vertical rigidity to sustain the weight of the isolated object, while it must also have sufficient flexibility in order to elongate the vibration period under seismic excitation. The following research works represent some of the efforts to achieve the purpose of vertical isolation.

Kitamura et al. (2005) proposed a vertical isolation system that made of large coned disk springs. The disc spring can provide high stiffness in small deformations and low stiffness in large deformations, therefore, sufficient stiffness in static and sufficient flexibility in dynamic can be achieved. Shimada et al. (2004) also proposed a three dimensional (3D) isolation devices for nuclear reactor buildings. In vertical direction, the system is composed of rolling seal type air springs and the hydraulic typed springs with rocking suppression system. In horizontal direction, laminated rubber bearings are used. Tsuji et al. (2014) proposed a nonlinear vertical isolation system with a post-buckled beam. The isolator is sufficiently stiff statically to support the self-weight of the isolated object and is soft dynamically to provide a low natural frequency. Araki et al. (2013) proposed a vertical quasi-zero stiffness (QZS) isolation system, which can provide an adjustable restoring force. With a high initial stiffness of the QZS, excessive static deformation of the isolated object can be avoided. With cranks and a screw jack of the QZS, the vertical restoring force is adjustable. Zhou et al. (2016) examined different types of vertical and 3D isolation systems for the potential application to modern nuclear facilities. Two vertical isolation strategies were discussed for the nuclear power plant: (1) entire building with 3D base isolation technology, and (2) entire building with horizontal base isolation, key components with vertical isolation system.

Moreover, the seismic isolation technology faces another challenge when a near-fault earthquake is encountered. Several studies have shown that near-fault ground motions, which usually accompany a strong long-period pulse waveform, may cause resonance-like response in a long-period isolation system (Jangid and Kelly 2001, Lu et al. 2013). The resonance-like response will cause an excessive isolator displacement far beyond the design level, and thus increase the failure risk of the isolation system and isolated object. Therefore, a vertical isolation system may also encounter a similar problem (Li, et al. 2007).

As an attempt to overcome the challenges mentioned above regarding vertical isolation, this study proposed a semi-active vertical isolation system called piezoelectric inertia-type vertical isolation system (PIVIS) for seismic protection of equipment. The PIVIS is composed of an inertia-type vertical isolation system (IVIS) (Lu, et al. 2016) and a piezoelectric friction damper (PFD). The IVIS has a leverage mechanism and a counterweight. The counterweight provides an uplifting force in static and an extra inertia force in dynamic, therefore, the effective vertical stiffness of the system is higher in static and lower in dynamic. The PFD can provide a controllable friction force for the PIVIS by using a non-sticking friction (NSF) control law, which can reduce displacement of the PIVIS without affecting the isolation efficiency.

**2. Dynamic Equation of PIVIS**

***2.1 Mathematic model of PIVIS***

For comparison purpose, the schematic diagram of a traditional vertical isolation system is shown in Figure 1, which is composed of a stiffness element k, a viscous damping element c, and a friction element μ. The friction element is used to simulate the inherent mechanical friction effects. To mitigate the vertical acceleration transmitted to the isolated equipment, the isolation stiffness must be soft enough to increase the vertical vibration period, meanwhile, the stiffness must be stiff enough to resist the self-weight of the isolated equipment. Figure 2 shows the mathematic model of the PIVIS, which is composed of a counterweight, a leverage mechanism, and a piezoelectric friction damper (PFD). Comparing with Figure 1, Figure 2 shows that in addition to the stiffness element, damping element and friction element, the PIVIS adds a counterweight, a leverage mechanism and a piezoelectric frication damper (PFD) into the system. When the PIVIS is vibrating, the counterweight and the leverage mechanism together provide an extra reactive force for the isolated equipment. Moreover, the excessive initial settlement due to the self-weight of the equipment can be reduced due to the existence of the counterweight. Furthermore, with a piezoelectric actuator, the PFD can provide a controllable friction force in real-time to dissipate vibration energy. Therefore, the excessive displacement could be prevented without affecting the efficiency of the isolation system. Comparison of Figures 1 and 2 reveals that the PIVIS is composed of a traditional isolation system, a counterweight, a rigid leverage mechanism and a PFD.

Equipment

Ground

Guide rail



Figure 1. Mathematical model of a traditional vertical isolation system.



Ground

Pivot

Lever arm

PFD

Equipment

Counterweight

Figure 2. Mathematical model of the PIVIS.

***2.2 Derivation of dynamic equation***

In Figure 2, consider the free body diagrams of counterweight mass m and the equipment mass M , respectively, the dynamic force-balance equations for these two mass blocks can be written as

 (1)

 (2)

where  and represent the reaction forces applied on the counterweight and equipment, through the lever-arm, respectively;  is the vertical ground acceleration;  and denote the vertical displacements of the counterweight and equipment with respect to the ground; g is gravitational acceleration;  is the stiffness of the isolation spring;  denotes the inherent friction force due to the moving parts of the system, i.e., the sliding of guide rails and rotation of the pivot;  represents the friction force provided by the PFD.

Furthermore, considering the force-balance condition of the lever-arm and ignoring the mass of the lever-arm, we have

 (3)

where is the moment-arm ratio defined as. Additionally, from geometric condition of the lever-arm, we have

 (4)

Notably, in the above equations, symbol,,, are all defined as positive upward. Finally, substituting Equations (1), (2), (4) into Equation (3) yields the following dynamic equation for the PIVIS.

 (5)

where

 (6)

In the above equations, *R* denotes the ratio of static moments acting on the two sides of the lever-arm. Notably, Equation (5) implies that the PIVIS is a single-DOF system. If the counterweight and PFD are removed, i.e.,  and , Equation (5) will reduce to the dynamic equation of the traditional VIS shown in Figure 1. Equation (6) states that the dynamic equation of the PIVIS, particularly the inertial force terms related to mass M, can be attenuated by the changing parameters *R* and .

**3. Static vs. Dynamic Properties of PIVIS**

***3.1 Static property of PIVIS***

Let  in Equation (5) and ignore the friction effect, i.e.,  for the time being, Equation (5) can be reduced to the static equilibrium equation of the PIVIS

 (7)

where

 (8)

where represents the initial settlement of the PIVIS in static state, and  denotes the equivalent static stiffness. From above two equations, it is observed that when the value of R increases from 0 to 1, the equivalent static stiffness  will increase, while the static settlement  decreases. Therefore, a higher equivalent static stiffness () and smaller initial settlement can be achieved by adjusting *R*, so that the total stroke demand on the isolation spring can be reduced. Notably, when ,  represents a traditional VIS.

***3.2 Dynamic property of PIVIS***

To investigate the dynamic characteristics of the PIVIS more clearly, let us rewrite the dynamic equation Equation (5) as a non-dimensional one, i.e.,

 (9)

where

, , ,

, ,  (10)

In Equation (9),  represents an influential factor of the ground excitation;  is the equivalent dynamic stiffness of the PIVIS;  and  are the equivalent isolation frequency and damping ratio of the PIVIS, respectively;  and  are the original isolation frequency and damping ratio without the counterweight. Notably,  and  also represent the frequency and damping of a counterpart traditional VIS. Notably, in Equation (9),  only represents the dynamic displacement part of the PIVIS after the static settlement  is removed.

From Equation (10), the equivalent dynamic stiffness  is affected by parameters *R* and, since and  (see Equation (6)), we have

 (11)

The above equation states that the equivalent dynamic stiffness  of the PIVIS is always less than or equal to the original stiffness k due to the existence of the counterweight. In other words, in the dynamic state the PIVIS is a softer system that has a longer isolation period than that of its traditional counterpart. A longer isolation period usually implies a better isolation performance. Moreover, from Equation (9), the ground acceleration is attenuated by the factor ; therefore can be treated as an influential factor of seismic force. Since R is usually 0 < *R* < 1, from Equation (10),

 (for ) (12)

Based on the above discussions and Equations (8), (11), (12), it may be concluded that parameters *R* and are the key design parameters of the PIVIS, since both the static and dynamic properties of the system relies on these two parameters.

**4. Control of Piezoelectric Friction Damper (PFD)**

***4.1 Controllable slip force of PFD***

In Equation (9), the damper friction force  of the PFD can be written as

 (13)

where  represent the maximum friction force of the PFD,  is the friction coefficient of the PFD and  is the controllable clipping force (normal force) generated by the embedded piezoelectric actuator. The magnitude of  has to be determined by a given control law. Notably,  is also equal to the slip force of the PFD. Equation (13) also implies that while the friction force  can not be controlled directly, the slip force of the PFD is a controllable quantity.



Figure 3. Typical relationship between normal force and driving voltage of the PIVIS.

(N0=23 N, Cz=0.074 N/V) (Lu et al. 2011a)



Figure 4. Relationship between control voltage and sliding velocity for NSF controller.

***4.2 Control of clamping force by piezoelectric actuator***

Equation (13) states that the slip force of the PFD can be controlled through adjusting the clamping force  produced by the piezoelectric actuator. On the other hand, to generate the controllable clamping force, the piezoelectric actuator has to be driven by a voltage supplier, which is able to produce a DC voltage between 0-1000 V. Generally, the relationship between the supplied voltage and the normal force generated by the piezoelectric actuator can be expressed as (Lu et al. 2011a)

 (14)

whereis the initial compression force produced by the pre-stressed screw; is the driving voltage of the piezoelectric actuator;  is the piezoelectric coefficient (actuating force per voltage (N/V)) of the piezoelectric actuator. The value of  that greatly depends on the boundary condition of the piezoelectric actuator is usually obtained experimentally. Figure 3 shows a typical relationship between normal force and driving voltage of the PIVIS obtained by experiment (Lu et al. 2011a). In the figure, by using a regression method the values of 23 N and 0.074 N/V were obtained.

***4.3 Non-sticking friction (NSF) control law***

In this study, a control law called Non-Sticking Friction (NSF) control was employed to determine the normal force  of the PFD. This simple and efficient control law will try to maintain the friction interface of the PFD always in its sliding state and prevents the interface enters the sticking state (Yang et al., 1987). As a result, kinetic energy of the PIVIS due to the seismic excitation can be dissipated by the PFD throughout the duration of the ground motion. To achieve the goal of the NSF control law, Lu et al. (2011b) suggested the following formula to determine the driving voltageof the piezoelectric actuator

 (15)

where  denotes the required maximum voltage and β is a control sharpness parameter related to the sliding velocity . Parameter β defines how sharp that  varies along with . Equation (15) represents the NSF voltage control law used in this study. Equation (15) shows that the realization of the NSF controller requires only the feedback of the sliding velocity . Based on the control law of Equation (15), Figure 4 shows the normalized voltage  as a function of the velocity  for different values of (= 2,5,20 and 50). It is observed that when a higher β is adopted, the control voltage increases more rapidly from 0.0 to 1.0 as the velocity increases. The figure shows that the control voltage will approach zero whenever the PFD approaches its sticking state, i.e.,. Moreover, substituting Equation (15) in (14) yields

 (16)

The above equation describes that clamping force will be varied between  and . Moreover, as shown in Equation (15), the NSF control law has two control parameters, namely, the maximum driving voltage and velocity sharpness factor . In this study, these two parameters are determined by an optimal search scheme such that the isolator displacement and equipment acceleration can be minimized. During the optimal search, the vertical components of the Kobe (1995) and Loma Prieta earthquakes(1989) with PGA=0.3g were taken as the input ground motions. The optimal values  and  are listed in Table 1 that will be used in numerical simulation.

**5. Evaluation of Isolation Performance of PIVIS by Numerical Simulation**

In this section, the responses of the PIVIS subjected to 14 vertical ground motions with different characteristics and PGA levels will be simulated. To show the control efficiency, the responses of the PIVIS will be compared with those of its traditional counterpart system. The traditional system means that the PFD and leverage mechanism are all removed from PIVIS (see Figure 1). The system parameters for both systems, the PIVIS and traditional systems, are all listed in Table 1.

***5.1 Selected 14 ground accelerations***

Totally, fourteen vertical ground motions, including 7 near-fault and 7 far-field ground accelerations, are considered in the numerical simulation. Figures 5(a) and 5(b) compare the acceleration response spectra for the 7 far-field and 7 near-fault earthquakes, respectively. In this study, the classification of near-fault and far-field earthquakes is based on the average values of displacement and acceleration spectra for the range of structural period between 1s to 4s. For a specific ground motion, if the average of spectral displacement between the periods of 1-4s is larger than 0.5m and at the same time the average of spectral acceleration is larger than 0.6g, the ground motion will be classified as a near-field earthquake; otherwise, this ground motion belongs to the category of far-field earthquakes. From Figure 5, it is observed that the spectral accelerations of the 7 near-fault earthquakes in the long-period range (2-5 seconds) are higher than those of the 7 far-field earthquakes.

Table 1. Parameters of different isolation systems for numerical simulation.

|  |  |  |  |
| --- | --- | --- | --- |
| Component | Item | PIVIS | Traditional |
| Isolation System | Mass of equipment (*M*) | 16 *kg* | |
| Isolation stiffness (*k*) | 336*N/m* | |
| Original isolation period (*T)* | 1.377*s* | |
| Original isolation frequency () | 0.726 *Hz* | |
| Friction force (*ui*) | 3.87 *N* | |
| Effective frequency () | 0.66*Hz* | -- |
| Effective period () | 1.513*s* | -- |
| Ratio of moment (*R*) | 0.264 | -- |
| Ratio of moment arm (*RL*) | 0.786 | -- |
| Piezoelectric friction damper | Friction coefficient () | 0.15 | -- |
| Piezoelectric coefficient () | 0.07 *N/V* | -- |
| Preload () | 23 *N* | -- |
| NSF Controller | Maximum voltage (*Vmax*) | 500*V* | -- |
| Velocity coefficient () | 20 | -- |

 

(a) Far-field earthquakes (b) Near-fault earthquakes

Figure 5. Earthquake response spectrums of the vertical ground accelerations.

***5.2 Compared with the traditional system***

To compare the isolation performance of the PIVIS (with NSF) and the traditional system in time domain, a representative near-fault earthquake (Kobe) and a far-field earthquake (El Centro) are considered as the input ground motion in Figures 6 and 7, respectively. In these figures, the PGA of both vertical ground motions is scaled to 0.4g, and the isolation displacement, equipment acceleration and hysteresis loop of the PIVIS and traditional systems are compared. Figure 6(a) and 6(b) show that under the excitation of the near-fault Kobe earthquake, the traditional system incurs resonance-like behavior and exhibits severe oscillating response, while the PIVIS very effectively suppresses this oscillating behavior and prevents the resonance response.

|  |  |
| --- | --- |
|  |  |
| (a) Isolator displacement | (a) Isolator displacement |
|  |  |
| (b) Equipment acceleration | (b) Equipment acceleration |
|  |  |
| (c) Hysteresis loop | (c) Hysteresis loop |
| Figure 6. System responses of the PIVIS and the traditional system (El Centro, PGA = 0.4g). | Figure 7. System responses of the PIVIS and the traditional system (Kobe, PGA = 0.4g) |

Figure 6(c) shows that the typical shape of the hysteresis loop (parallelogram) for a traditional isolation system is a parallelogram, while an irregular shape is observed in the hysteresis loop of the PIVIS, because of the reactive force  resulting from the inertial force of the counterweight applied on the equipment through the lever-arm. This reactive force together with the friction force  of the PFD very effectively suppresses the motion of the equipment isolated by the PIVIS. Considering the far-field El Centro earthquake, which contains more high-frequency contents, Figure 7 shows that the PIVIS has less isolation displacement but has higher acceleration response, as compared with the traditional system. Nevertheless, the peak acceleration of the PIVIS is about 0.2g, which is only half of PGA=0.4g. This indicates that for far-field earthquake the isolation efficiency of the PIVIS is preserved even though not as efficient as that of the traditional system.

Table 2. Comparison of average peak responses of PIVIS (with NSF) and traditional systems

under different earthquakes.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Earthquake type | (a)  PGA  (g) | Ave. peak isolation displacement | | | Ave. peak equipment acceleration | | | |
| (b)  Traditional  (mm) | (c)  PIVIS (mm) | (c)/(b)  ratio(1) | (d)  Traditional (g) | (d)/(a)  ratio(2) | (e)  PIVIS  (g) | (e)/(a)  ratio(2) |
| Near-fault  (7 records) | 0.1 | 36.7 | 2.18 | 0.060 | 0.101 | 1.01 | 0.085 | 0.846 |
| 0.2 | 119 | 20.0 | 0.171 | 0.276 | 1.38 | 0.153 | 0.763 |
| 0.3 | 210 | 50.3 | 0.239 | 0.470 | 1.57 | 0.225 | 0.751 |
| 0.4 | 303 | 91.4 | 0.302 | 0.665 | 1.66 | 0.311 | 0.778 |
| 0.5 | 402 | 137 | 0.342 | 0.877 | 1.75 | 0.413 | 0.825 |
| **Average** | | | **0.223** | **Average** | **1.47** | **Average** | **0.793** |
| Far-field  (7 records) | 0.1 | 4.45 | 0.364 | 0.082 | 0.033 | 0.330 | 0.081 | 0.813 |
| 0.2 | 38.5 | 3.49 | 0.091 | 0.105 | 0.200 | 0.130 | 0.650 |
| 0.3 | 51.4 | 6.13 | 0.119 | 0.133 | 0.442 | 0.173 | 0.578 |
| 0.4 | 81.2 | 12.0 | 0.147 | 0.196 | 0.490 | 0.217 | 0.541 |
| 0.5 | 117 | 20.1 | 0.172 | 0.271 | 0.542 | 0.260 | 0.519 |
| **Average** | | | **0.122** | **Average** | **0.401** | **Average** | **0.620** |
| Total  (14 records) | 0.1 | 20.6 | 1.27 | 0.062 | 0.067 | 0.672 | 0.083 | 0.829 |
| 0.2 | 71.8 | 11.4 | 0.159 | 0.176 | 0.879 | 0.141 | 0.706 |
| 0.3 | 131 | 28.2 | 0.216 | 0.301 | 1.00 | 0.199 | 0.664 |
| 0.4 | 192 | 51.7 | 0.269 | 0.430 | 1.08 | 0.264 | 0.660 |
| 0.5 | 260 | 78.8 | 0.304 | 0.574 | 1.16 | 0.336 | 0.672 |
| **Average** | | | **0.202** | **Average** | **0.958** | **Average** | **0.706** |

(1) The peak displacement of the PIVIS divided by that of the traditional system.

(2) The peak acceleration of the PIVIS or traditional system divided by the PGA.

***5.3 Comparison of peak response in different PGA levels***

To further evaluate the isolation performance of the PIVIS with more ground motions, Table 2 compares the average peak responses of the PIVIS and the traditional systems under the 14 chosen earthquakes with 5 different PGA levels. It is shown the average of peak isolation displacements of the PIVIS is lower than that of the traditional system in both near-fault and far-field earthquakes. Considering all 14 earthquakes, the average of the PIVIS peak displacement is only about 20% of that of the traditional system. In other words, the PIVIS reduces 80% of the isolator displacement, and will greatly reduce the demand on isolation space. On the other hand, for the equipment acceleration response, Table 2 also demonstrates that the traditional system has excellent isolation performance under the far-field earthquakes, in which it reduces the peak acceleration to about 40% of the PGA level. However, the traditional system performs poorly in the near-fault earthquakes due to the resonance-like response, since its average peak acceleration is amplified to about 147% of the PGA. In contrary, the PIVIS reduces the peak acceleration down to about 80% and 60% of the PGA level in the near-fault and far-field earthquake, respectively. This implies that the PIVIS is able to prevent the resonant behavior exerted by a near-fault earthquake, which usually has strong long-period components. Therefore, unlike the traditional system, the PIVIS is an effective isolation system regardless the earthquake types.

**6. Conclusions**

In this paper, a piezoelectric inertia-type vertical isolation system (PIVIS) is proposed for seismic protection of equipment. The PIVIS consists of a counterweight, a leverage mechanism and a piezoelectric friction damper (PFD). The lever transfers the gravity and inertia force generated by the counterweight to the equipment side, provides dynamic reactive forces, so that the equipment responses can be reduced. In static state, the counterweight and the leverage mechanism result in a higher equivalent static stiffness, which prevents exceeded initial settlement of the isolation spring due to weight of the equipment. In dynamic state, the counterweight and the leverage mechanism results in a lower dynamic stiffness. This may increase isolation performance and prevent resonant response of the system. The PFD in the PIVIS provides a controllable friction force to reduce the exceeded isolation displacement. From the numerical simulation results, the following conclusions can be obtained: (1) under the selected 14 vertical ground motions with different characteristics and PGA levels, the average peak isolation displacement of the PIVIS is much lower than that of the traditional system in all the earthquakes, regardless near-fault or far-field earthquakes. (2) The average peak acceleration of the PIVIS is slightly larger than that of the traditional system in the far-field earthquakes (still the isolation efficiency is preserved), but is significantly lower than those of the traditional system under near-fault earthquakes. (3) Due to the resonance phenomenon, the peak acceleration of the traditional system is amplified to 147% of the PGA under the near-fault earthquakes, while the PIVIS reduces the peak acceleration response to 79% of the PGA.

**7. References**

Memari A.M., Maneetes H., and Bozorgnia Y. (2004) Study of the effect of near-source vertical ground motion on seismic design of precast concrete cladding panels. *Journal of Architectural Engineering* 10(4):167-184.

Furukawa S., Sato E., Shi Y., Becker T., Nakashima M. (2013) Full‐scale shaking table test of a base‐isolated medical facility subjected to vertical motions. *Earthquake Engineering and Structural Dynamics* 42(13): 1931-1949.

Konstantinidis D. and Makris N. (2009) Experimental and Analytical Studies on the Response of Freestanding Laboratory Equipment to Earthquake Shaking. *Earthquake Engineering and Structural Dynamics* 38(6): 827-848.

Kitamura S., Okamura S. and Takahashi K. (2005) Experimental study on vertical component seismic isolation system with coned disk spring. *ASME Pressure Vessels and Piping Division Conference*, Paper No. PVP2005-71356, 175-182.

Shimada T., Fujiwaka T., Moro S. and Ikutama S. (2004) Study on three-dimensional seismic isolation system for next-generation nuclear power plant hydraulic three-dimensional base isolation system. *Proceedings of 13th World Conference on Earthquake Engineering,* No.788.

Tsuji Y., Sasaki T., Waters T., Fujito K. and Wang D. (2014) A Nonlinear Vibration Isolator Based on a Post-buckled Inverted L-shaped Beam. *Proceedings of the Sixth World Conference on Structural Control and Monitoring*, July 15-17, Barcelona, Spain, Paper No. 376.

Araki Y., Asai T., Kimura K., Maezawa K., and Masui T. (2013) Nonlinear vibration isolator with adjustable restoring force. *Journal of Sound and Vibration* 332(23): 6063-6077.

Zhou Z., Wong J., Mahin S. (2016) Potentiality of Using Vertical and Three-Dimensional Isolation Systems in Nuclear Structures. *Nuclear Engineering and Technology* 48(5):1237-251.

Jangid R.S. and Kelly J.M. (2001) Base isolation for near-fault motion. *Earthquake Engineering and Structural Dynamics* 30: 691-707.

Lu L. Y., Lin C. C., Lin G. L. (2013) Experimental evaluation of supplemental viscous damping for a sliding isolation system under pulse-like base excitation. *Journal of Sound and Vibration* 332(8): 1982-1999.

Li X., Dou H., Zhu X (2007) Engineering characteristics of near-fault vertical ground motions and their effect on the seismic response of bridges. *Earthquake Engineering and Engineering Vibration* 6(4): 345–350.

Lu L.Y., Chen P.R., Pong K.W. (2016) Theory and experiment of an inertia-type vertical isolation system for seismic protection of equipment. *Journal of Sound and Vibration* 366: 44-61,

Lu L.Y., GL Lin, CY Lin (2011a) Experimental verification of a piezoelectric smart isolation system. *Structural Control and Health Monitoring* 18 (8):869-889.

Yang, J.N., Akbarpour A., Ghaemmaghmi P. (1987) New optimal control algorithms for structural control. *Journal of Engineering Mechanics* 113: 1369-1386.

Lu L.Y., Lin G.L., Lin C.Y. (2011b) Experiment of an ABS-type control strategy for semi-active friction isolation systems. *Smart Structures and Systems* 8(5): 501-524.

1. Professor, Dept. of Civil Eng., National Cheng Kung University, Tainan, Taiwan, [lylu@mail.ncku.edu.tw](mailto:lylu@mail.ncku.edu.tw) [↑](#footnote-ref-1)
2. Assistant Professor, National Kaohsiung Univ. of Sci. & Tech., Kaohsiung, Taiwan, [gllin@nkust.edu.tw](mailto:gllin@nkust.edu.tw) [↑](#footnote-ref-2)
3. Master of Science, National Taiwan University of Science & Technology, Taipei, Taiwan, ysc2130@gmail.com [↑](#footnote-ref-3)
4. Undergraduate student, Hong Kong Polytechnic University, Hong Kong, China, ezrealfung@gmail.com [↑](#footnote-ref-4)