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THE EFFECT OF A TUNED-INERTER-DAMPER ON THE SEISMIC RESPONSE OF BASE-ISOLATED STRUCTURES

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ABSTRACT

In this paper, we asses the effectiveness of an inerter-based damper system for improving the seismic response of a multi-storey base-isolated (BI) structure. In particular we consider the tuned-inerter-damper (TID) concept that has received considerable attention in the literature recently. When placed at the base of a structure the TID can reduce peak amplitudes of displacement for all vibration modes in the structure, not just the targeted one, as in the case of a tuned-mass-damper (TMD). In this study, the performance of the TID is investigated when it is applied to a BI structure by considering two factors: (1) frequency of input excitation, and (2) damping properties of the base isolation. Through the numerical analysis using both harmonic and more realistic earthquake input excitation, it was concluded that the TID can be effectively used to help in protecting the rubber bearing base isolation from large displacements.

Keywords: Inerter-based damper; seismic response; tuned-inerter-damper; base-isolation; base-isolated structure

1 INTRODUCTION

Using rubber bearings to isolate structures is now an established method to protect the structures against unwanted vibrations. Typically rubber bearings are placed underneath the structure's columns to isolate the upper structure from ground vibrations induced by earthquake excitation. In this paper we investigate a scenario where a TID is also installed in combination with the rubber bearings. The objective of this hybrid combination is to give significantly improved isolation of the upper structure.

In particular, seismically isolated structures using rubber bearings have been found to have limitations in some particular cases. For example, it has been shown that in certain conditions, rubber bearings can cause large displacements at the base of the structure. Hence, a large clearance space is required to provide enough room for the rubber bearing to deform. Additionally, it was also found that large displacements at the top of the structure can occur during long period and long duration earthquake excitations (Kasagi et al. 2016). This scenario can occur when the location of the structure is far away from the epicenter.

The BI structure with a TID system proposed in this paper is designed specifically to overcome the above problems. The TID works as a vibration absorber that will reduce any potential large displacements due to resonance. Furthermore, the TID is tuned to effectively work when the structure is subjected to long period ground motion. This condition was simulated by using a harmonic loading with low frequency.

The layout of the new hybrid system is based on the fact that, unlike a tuned-mass-damper, the TID has been shown to work most effectively when it is installed in the base of the structure (Lazar et al. 2014). This makes it an obvious choice for being used in combination with rubber bearings, which are also installed at the base of the structure.

Several combined control strategies employing dampers and base isolation devices have been studied. Tsai (1995) studied the effect of a TMD on the response of a five-storey BI building. In this study, the TMD was installed on the base floor. The same case was also studied by Palazzo et al. (1997) who also studied the influence of TMD location on a BI structure (Palazzo et al. 1999). The TMD performance was assessed by varying its locations: on the top and base floors. An experimental study of the effectiveness of the TMD in BI structures was studied by Petti et al. (2010). Xiang and Nishitani (2014) studied a nontraditional TMD in combination with a BI system. Most recently, Hessabi et al. (2017) studied the

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performance of the TMD in BI structure by considering the nonlinearities of the isolation system.

Employing an inerter-based device on a BI structure has been discussed by Saitoh (2012) and Saitoh (2014). Several layouts were studied in combination with rubber bearings modeled as linear spring-dashpot elements. The inertance is achieved by a rack-and-pinion type of inerter which is also called a gyro-mass damper. One of the models has the inerter element in parallel with a linear spring and in series with a linear viscous damping element. This configuration of TID layout was also studied in Lazar et al. (2014) and Hu et al. (2015). However, the study was limited to a single mass BI system. The application of inerter-based devices in multi-storey BI structures was studied by Hashimoto et al. (2015). The authors considered the use of tuned-mass-damper-inerter (TMDI) to mitigate the response of multi-storey BI structures. Most recently, a combined TMDI and BI has also been studied by De Domenico and Ricciardi (2017) and De Domenico et al. (2018).

To the authors knowledge, no study has discussed the use of a TID in a multi-storey BI structure. Therefore, in this paper we study the performance of a TID on a multi-storey BI structure and also investigate the influence of its isolation damping on the effectiveness of the TID. Comparisons will be made with the same model with just base isolations, so that we can critically assess the potential performance of the new hybrid system in comparison to the existing methodology. Furthermore, results from a numerical study will be presented, in which we consider the performance of the new combined TID-BI system to more realistic earthquake inputs as well as comparing these results to a system with just base isolation.

2 STRUCTURAL SYSTEM

In order to assess the feasibility of the proposed strategy, one structural system adopted from Tsai (1995) was used in this analysis. The structure is a five-storey base-isolated building as shown in Figure 1(b). The properties of mass, stiffness, and damping for each floor of the superstructure are assumed to be the same, m_i= 3500 kg, k_i= 35000 kN/m, and c_i= 35 kNs/m, where i={2,3,4,5,6}. The mass m_b and stiffness k_b of the base isolation system are given as 3500 kg and 210 kN/m. These values are zero for the case of fixed-base structure as shown in Figure 1(a).

The equation of motion of the BI structure (Figure 1(b)) subject to ground motion a_g is

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = -\mathbf{M}\mathbf{r}a_g \tag{1}$$

where

$$\mathbf{M} = \begin{bmatrix} m_b & 0 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_6 \end{bmatrix}; \mathbf{u} = \begin{bmatrix} u_b \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{bmatrix}; \mathbf{r} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \tag{2}$$

and

$$\mathbf{K} = \begin{bmatrix} k_b + k_2 & -k_2 & 0 & 0 & 0 & 0 \\ -k_2 & k_2 + k_3 & -k_3 & 0 & 0 & 0 \\ 0 & -k_3 & k_3 + k_4 & -k_4 & 0 & 0 \\ 0 & 0 & -k_4 & k_4 + k_5 & -k_5 & 0 \\ 0 & 0 & 0 & -k_5 & k_5 + k_6 & -k_6 \\ 0 & 0 & 0 & 0 & -k_6 & k_6 \end{bmatrix} \tag{3}$$

$$\mathbf{C} = \begin{bmatrix} c_b + c_2 & -c_2 & 0 & 0 & 0 & 0 \\ -c_2 & c_2 + c_3 & -c_3 & 0 & 0 & 0 \\ 0 & -c_3 & c_3 + c_4 & -c_4 & 0 & 0 \\ 0 & 0 & -c_4 & c_4 + c_5 & -c_5 & 0 \\ 0 & 0 & 0 & -c_5 & c_5 + c_6 & -c_6 \\ 0 & 0 & 0 & 0 & -c_6 & c_6 \end{bmatrix} \tag{4}$$

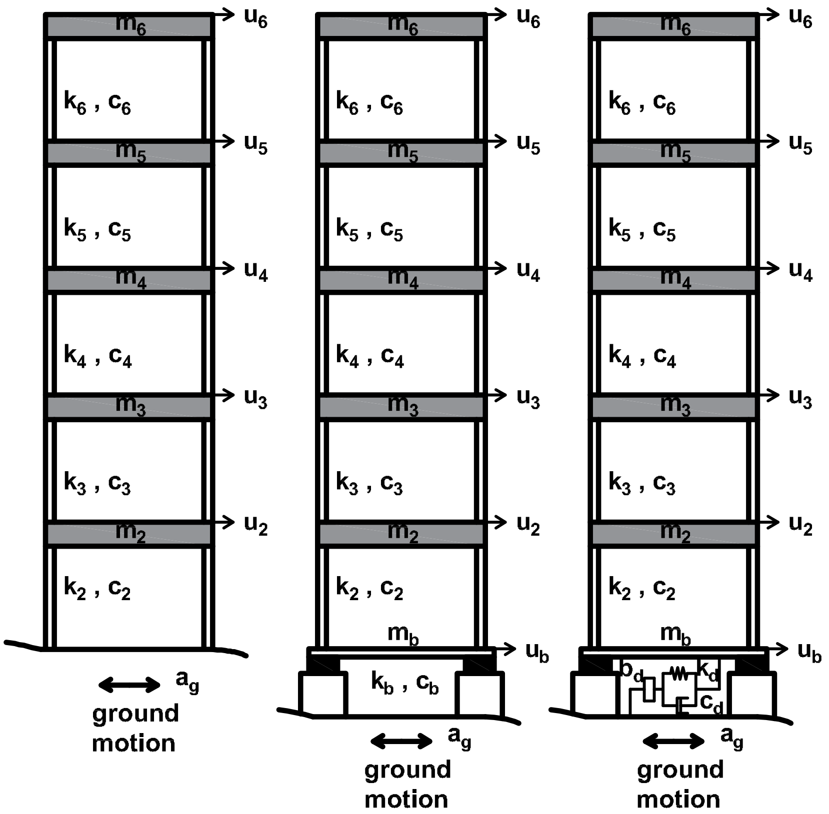


Figure 1: (a) Fixed-base structure (b) BI without TID (c) BI with a TID

M,**K**, and **C** are the the mass, stiffness, and damping matrices of the BI structure, and a_g is the ground motion. The matrix u is relative to the ground displacement. The isolation damping is c_b=2.66 kNs/m. The natural frequency of the BI structure is $\Omega = [\omega_1, \omega_2, \omega_3, \omega_4, \omega_5] = [0.5, 8.3, 15.9, 22.5, 27.5, 30.7]$ Hz. When a TID is installed into the BI structure (Figure 1(c)), the new equation of motion is given as

$$\overline{\mathbf{M}}\ddot{\mathbf{v}} + \overline{\mathbf{C}}\dot{\mathbf{v}} + \overline{\mathbf{K}}\mathbf{v} = -\overline{\mathbf{M}}\mathbf{q}a_g \tag{5}$$

where

$$\overline{\mathbf{M}} = \begin{bmatrix} m_b & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & b_d \end{bmatrix}; \mathbf{v} = \begin{bmatrix} u_b \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \\ u_d \end{bmatrix}; \mathbf{q} = \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 0 \end{bmatrix} \tag{6}$$

and

$$\overline{\mathbf{K}} = \begin{bmatrix} k_d + k_b + k_2 & -k_2 & 0 & 0 & 0 & 0 & -k_d \\ -k_2 & k_2 + k_3 & -k_3 & 0 & 0 & 0 & 0 \\ 0 & -k_3 & k_3 + k_4 & -k_4 & 0 & 0 & 0 \\ 0 & 0 & -k_4 & k_4 + k_5 & -k_5 & 0 & 0 \\ 0 & 0 & 0 & -k_5 & k_5 + k_6 & -k_6 & 0 \\ 0 & 0 & 0 & 0 & -k_6 & k_6 & 0 \\ -k_d & 0 & 0 & 0 & 0 & 0 & k_d \end{bmatrix} \tag{7}$$

$$\overline{\mathbf{C}} = \begin{bmatrix} c_d + c_b + c_2 & -c_2 & 0 & 0 & 0 & 0 & -c_d \\ -c_2 & c_2 + c_3 & -c_3 & 0 & 0 & 0 & 0 \\ 0 & -c_3 & c_3 + c_4 & -c_4 & 0 & 0 & 0 \\ 0 & 0 & -c_4 & c_4 + c_5 & -c_5 & 0 & 0 \\ 0 & 0 & 0 & -c_5 & c_5 + c_6 & -c_6 & 0 \\ 0 & 0 & 0 & 0 & -c_6 & c_6 & 0 \\ -c_d & 0 & 0 & 0 & 0 & 0 & c_d \end{bmatrix} \tag{8}$$

where b_d, k_d and c_d are the parameters of the TID : inertance, stiffness, and damping. u_d is the TID displacement relative to the ground.

3 COMBINED CONTROL STRATEGY : BI-TID

As shown in Figure 1(c), the TID is installed below the base floor at the same location with the isolation system. It has been previously demonstrated that the optimum location for the TID in a multi-DOF structure is at the base of the structure where the maximum acceleration occurs (Lazar et al. 2014). This is one of the benefits of applying the TID as it does not contribute on the additional mass into the upper structure as in the TMD case.

The tuning of the TID is assumed to follow the tuning rules of the TMD by Den Hartog. The tuning relations are (Lazar et al. 2014)

$$m_d = \mu_m m_{eff1} \quad ; \quad k_d = \frac{\mu_m(1-\mu_m/2)}{(1+\mu_m)^2} \quad ; \quad \zeta_{opt} = \sqrt{\frac{3\mu_m}{8(1+\mu)(1-\mu/2)}} \quad ; \quad c_d = 2\zeta\sqrt{\frac{k_d}{m_d}}m_d \tag{9}$$

In this study, the TMD mass ratio μ is given as 0.05, which gives a TMD mass of m_d=1050 kg. m_{eff1} and k_{eff1} are the effective modal mass and stiffness of the first vibration mode, and ζ is the TMD damping ratio. It has been concluded from the previous study by Lazar et al. (2014) that the TID can be designed to have a similar performance to that of a TMD by making the transfer function ratio between TID and TMD to be $\Phi^2_{n,1}/\Phi^2_{1,1}$, where $\Phi_{i,1}$ is the $i-th$ element of the first eigenvector of a n-DOF structure. Finally, the parameters of the TID are obtained and given in Table 1.

Table 1: Control system parameters

Control system	TMD	TID
$\mu_m(\mu_b)$	0.05	0.052
$m_d(b_d)(kNs^2/m)$	1.05	1.08
$k_d(kN/m)$	9.20	9.48
$c_d(kNs/m)$	0.84	0.87

It was found from the frequency response function of the system that the TID stiffness given in Table 1 does not give the optimum solution. This is because the tuning is based on an undamped structure assumption, whereas in the reality, the structure with BI is damped. Therefore, further iteration is required in order to achieve an optimum stiffness value. As illustrated in Figure 2(c), an optimum TID stiffness obtained from the iteration process is k_d = 10.28 kN/m.

3.1 Frequency-domain analysis

In the Laplace domain, the equation of motion of the BI structure with a TID can be written as

$$\overline{\mathbf{M}}s^2U + \overline{\mathbf{C}}sU + \overline{\mathbf{K}}U = -\overline{\mathbf{M}}s^2R \tag{10}$$

where U and R are Laplace transform of floor displacement and ground displacement. So, the frequency response of the system can be obtained from

$$T = \frac{-\overline{\mathbf{M}}s^2}{\overline{\mathbf{M}}s^2 + \overline{\mathbf{C}}s + \overline{\mathbf{K}}} \tag{11}$$

The frequency response of the systems is given in Figure 2. Figure 2(a) shows the frequency response of all three systems. It can be seen that the BI system can effectively shift the natural frequency of the fixed-base structure to a lower value (i.e. to the left in the Figure). The first natural frequency of the fixed-base structure is around 4.8Hz, which is reduced to be 0.5 Hz when BI system is provided. This is due to the lateral flexibility of the BI system. The BI system also makes the oscillation of the superstructure become more uniform with smaller inter-storey drift. This is the reason why its higher vibrations modes are insignificant.

Despite of the superior isolation effect given by the BI system at the higher frequency vibrations, this BI structure is vulnerable to low frequency vibrations, in this case less than 1 Hz. In earthquake engineering, this is acceptable because most of the earthquakes have a predominant frequency higher than this (Tsai 1995). However, in some cases, for example for long period earthquakes whose predominant frequency are low, could be dangerous for the BI structure due to resonance. Therefore, in this paper the TID is designed to protect the BI structure from low frequency vibrations.

Figure 2(c) shows how the TID can be tuned to the first fundamental frequency of the BI structure. As a result, the peak amplitude of the response is significantly reduced. Figure 2(b) shows that the peak amplitude reduction does not only occur at the first vibration mode of the structure, but also at the higher modes, as can be seen in Figure 2(d) where the peak response at the second vibration mode is also reduced. This is one of the benefits of the TID compared to the TMD. It was concluded in Lazar et al. (2014) for the case of fixed-base MDOF structure, that the TID is capable of reducing the peak response of all the vibration modes, not just the targeted one.

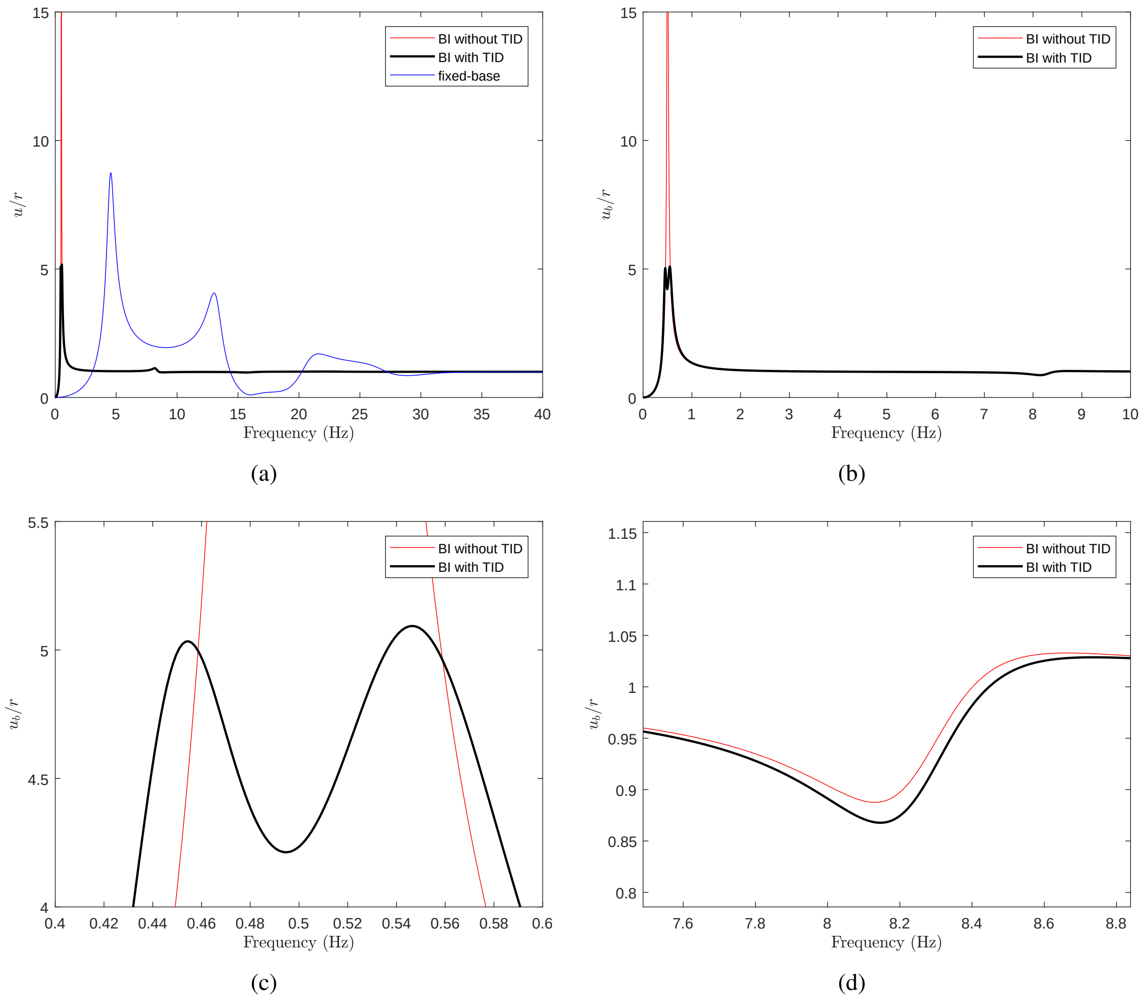


Figure 2: Frequency response functions for ground excitation (a) top storey, for all three configurations (b) base storey for BI and TID configurations (c) zoomed in at $\omega_1 = 0.5$Hz (d) zoomed in at $\omega_2 = 8.3$Hz

3.2 *Time-domain analysis*

In this time domain-analysis, the structures were investigated by applying two types of base excitations, harmonic and El Centro ground motions. The harmonic ground motion is a sine wave form, $a_g = \sin(\omega t)$, with ω is the frequency which was varied into four different scenarios: below the first natural frequency, near the first natural frequency, higher than the first natural frequency, and near the second natural frequency of the BI structure. The first three scenarios were also previously studied by Tsai (1995) for the case of TMD in BI structures.

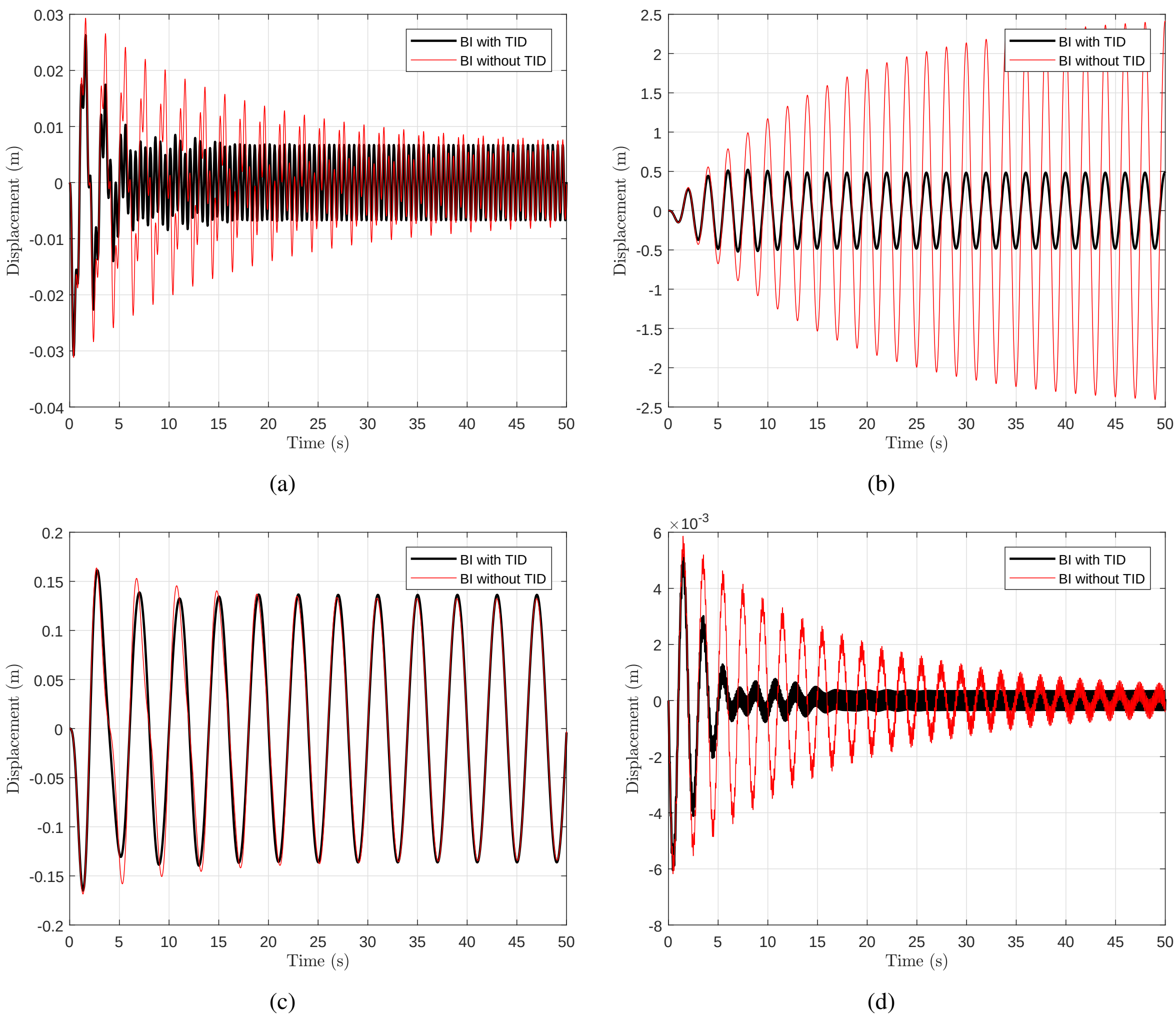


Figure 3: Base displacement subject to harmonic excitation with frequency of (a) 2Hz (b) 0.5Hz (c) 0.25Hz (d) 8.3Hz

Figure 3 illustrates how the base displacement responses vary for different scenarios. Figure 3(a) shows the displacement response to the harmonic loading with a frequency of 2Hz which is higher than the first natural frequency of the BI structure. It can be seen that the TID can effectively reduce the response for the first 25 seconds. However, its effectiveness is reduced after the first 25 seconds. Similar results were also obtained from the fourth case in Figure 3(d), where the excitation frequency is around the 2^{nd} natural frequency of the BI structure. The TID is less effective when the excitation frequency is less than the first fundamental frequency of the BI structure as can be seen in Figure 3(c).

The most promising results of using the TID is given by Figure 3(b), which is the case of when the excitation frequency is around the first natural frequency of the BI structure. From these scenario, it can be concluded that the TID is mostly effective in reducing the structural response when the excitation is around the first fundamental frequency of the BI structure. A similar conclusion was also found in (Tsai

1995) for the case of using TMD in BI structures. This phenomenon can be explained by the frequency response discussed in previous section. As can be seen in Figure 2(b) and 2(c), the response magnitude is significantly reduced at the first vibration mode. Furthermore, some reduction also occurs almost at all vibration modes.

The performance of the structures subject to more realistic ground excitation was investigated by using El Centro ground motion. Since the vibration predominant frequency is higher than the first fundamental frequency of the structure, therefore it can be expected some reduction should occur on the time-history response of the structure. It is exactly what happens to the structures as shown in Figure 4(a). The fixed-base floor displacement is relative to the ground displacement, where the BI structure displacement is relative to the base floor displacement. The benefit of using the TID can be clearly seen in Figure 4(b) for top floor displacement and Figure 4(c) for base displacement. As discussed in the previous section, the inter-storey drift is significantly reduced in a BI structure as shown in Figure 4(d) which is the reason why only the first vibration mode is significant in a BI structure. From this Figure, it can be seen that the floor displacements relative to the base displacement (for BI structure) or ground displacement (for fixed-based structure) are significantly reduced. It is also concluded from these Figures that the TID is also capable of reducing the inter-storey drift of the BI structure.

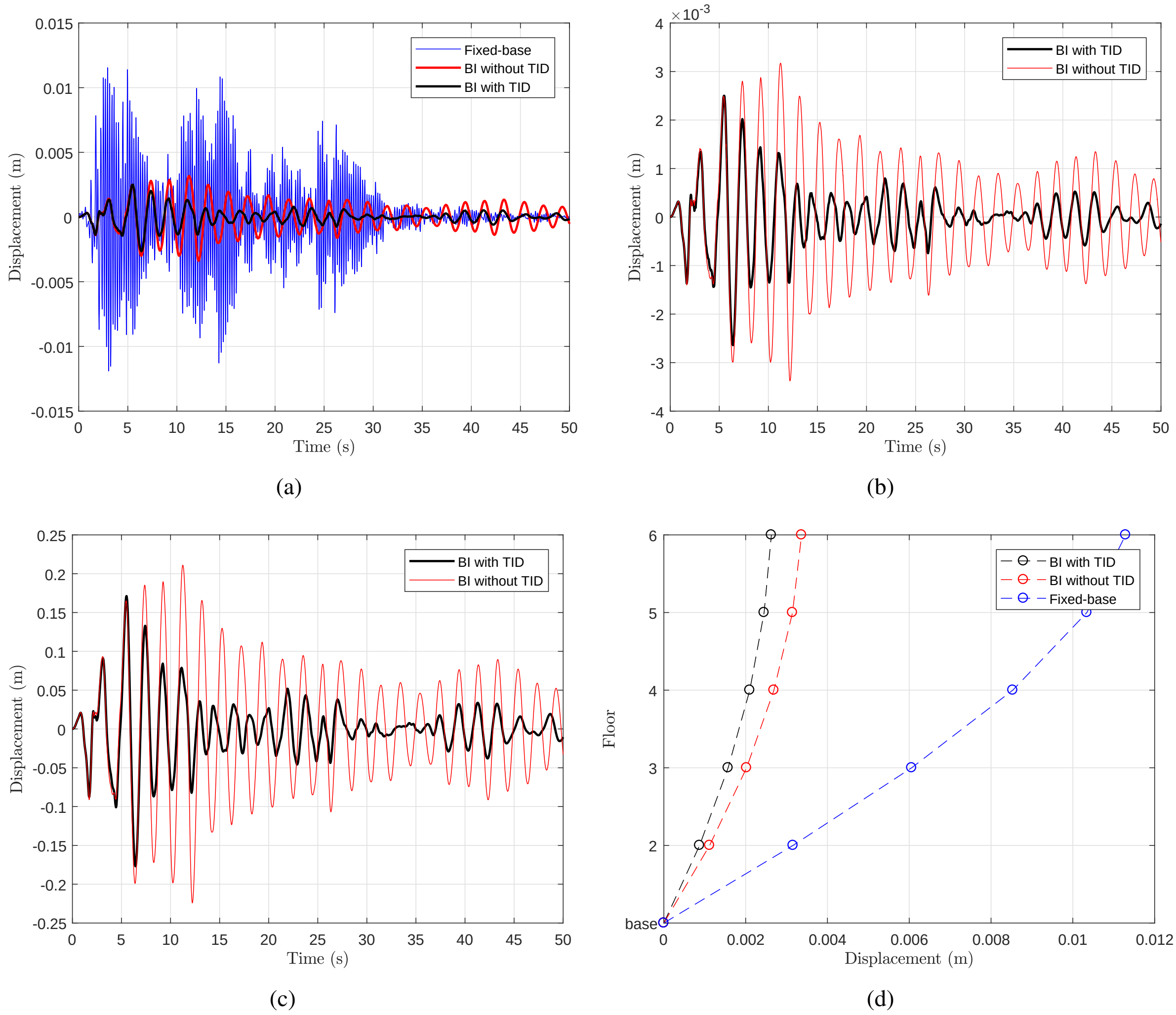
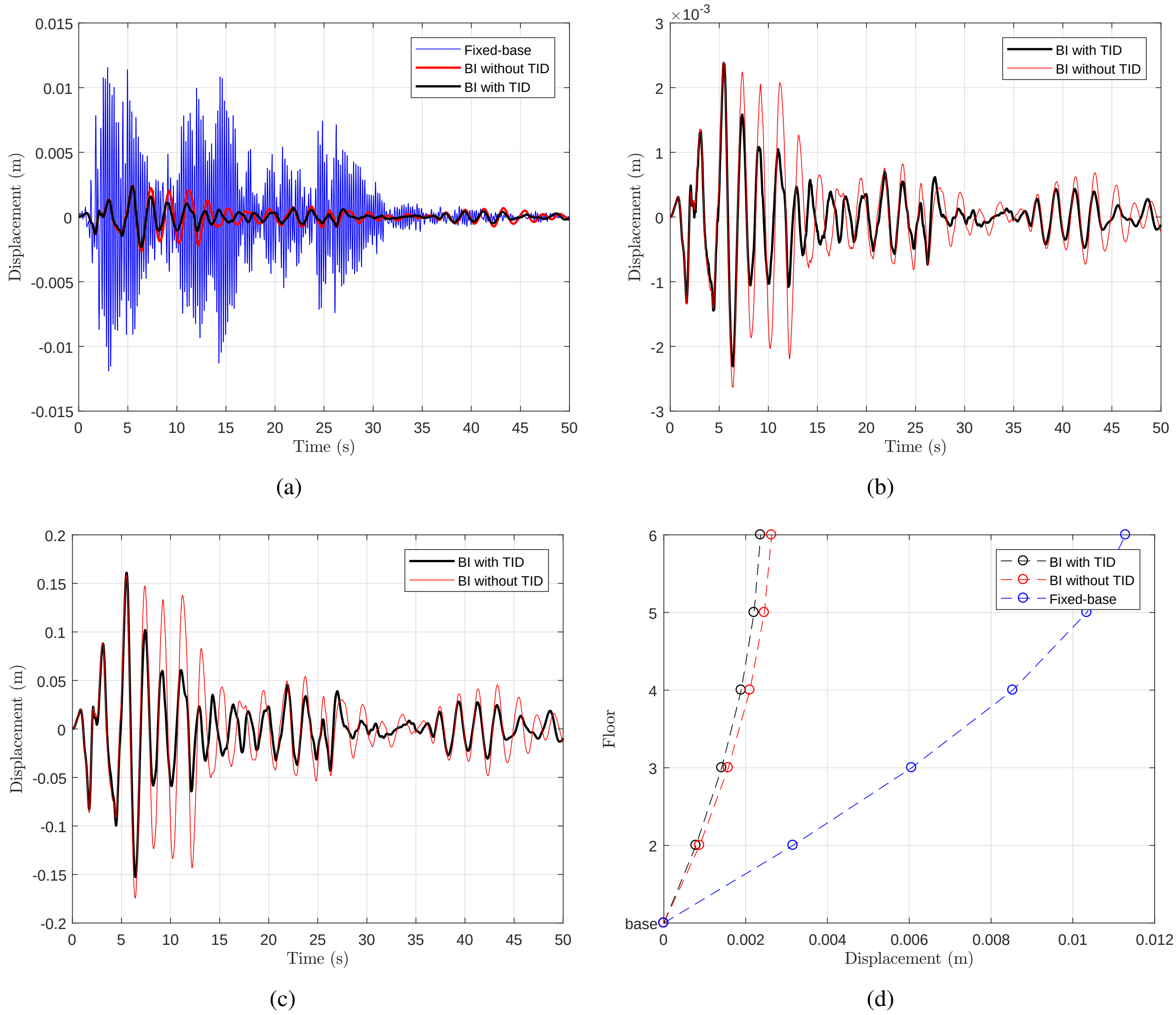


Figure 4: Structural response subject to El Centro ground motion, relative to the ground, c_b = 2.66kNs/m : (a) and (b) top displacement (c) base displacement (d) all floors displacement

Further analysis investigated the influence of the damping of the isolation system. In (Tsai 1995), it was concluded that the performance of the TMD becomes less effective when the damping of the isolation system is increased. In this study, the same conclusion also applies for the TID in BI structures. When the isolation damping c_b is increased to 6.64 kNs/m, the influence of the TID becomes less significant compared to when the isolation damping is 2.66 kNs/m. As illustrated in Figure 5(a) and 5(b), the top floor displacement of the BI structure is slightly reduced when using a TID. The similar results also applies for the best displacement and inter-storey drift as shown in Figure 5(c) and 5(d).



(a) (b) (c) (d)

Figure 5: Structural response subject to El Centro ground motion, relative to the ground, c_b = 6.64kNs/m : (a) and (b) top displacement (c) base displacement (d) all floors displacement

4 CONCLUSIONS

This paper shows the performance of a TID in a multi-storey BI structure. The combination of the TID absorber and isolation effect from the isolation system (rubber bearings), significantly decreases the storey drift amplitude around the resonant frequency by (i) splitting the peak as a TMD would, and (ii) reducing the maximum amplitude on the split peaks. Two factors were considered in the analysis: (1) the frequency of the input excitation, and (2) damping properties of the isolation. Through the numerical analysis, the TID has been found to be more effective when the structure is subject to input excitation whose frequency is near or higher than the natural frequency of the BI structure. However, it shows little effect when the excitation frequency is below the natural frequency of the structure. A similar insignificant effect also occurs when the isolation has more damping. These results have confirmed the capabilities of the TID in protecting the base isolation system from large displacements due to resonance. These results demonstrate that this combined control strategy of TID-BI systems should be developed further for potential applications in structural engineering.

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REFERENCES

De Domenico, D., Impollonia, N., and Ricciardi, G. (2018). Soil-dependent optimum design of a new passive vibration control system combining seismic base isolation with tuned inerter damper, *Soil Dynamics and Earthquake Engineering*; 105, pp.37-53

De Domenico, D., and Ricciardi, G. (2017). An enhanced base isolation system equipped with optimal tuned mass damper inerter (TMDI), *Earthquake Engineering and Structural Dynamics*; Wiley Online Library

Hashimoto, Takuya, Fujita, Kohei, Tsuji, Masaaki, Takewaki, and Izuru (2015). Innovative base-isolated building with large mass-ratio TMD at basement for greater earthquake resilience, *Future Cities and Environment*; vol.1, no.1, pp.9

Hessabi, R.M., Mercan, O., and Ozturk, B. (2017). Exploring the effects of tuned mass dampers on the seismic performance of structures with nonlinear base isolation systems, *Earthquakes and Structures*, vol.12, no.3, pp.285-296

Kasagi, M., Fujita, M., Tsuji, M., & Takewaki, I.(2016). Automatic generation of smart earthquake-resistant building system: Hybrid system of base-isolation and building-connection, *Heliyon*, vol.2, no.2, p.e00069

Lazar, I., Neild, S., & Wagg, D.(2014). Using an inerter-based device for structural vibration suppression, *Earthquake Engineering and Structural Dynamics*, vol.43. no.8, pp.1129-1147

Lazar, I., Neild, S., & Wagg, D.(2014). Design and performance analysis of inerter-based vibration control systems, *Dynamics of Civil Structures*, vol.43. pp.493-500

Palazzo, B., Petti, L and De Ligio, M.(1997). Response of base isolated systems equipped with tuned mass dampers to random excitations, *Structural Control and Health Monitoring*, vol.4, no.1, pp.9-22

Palazzo, Bruno, Petti, and Luigi, B.(1999). Combined control strategy: base isolation and tuned mass damping, *ISET Journal of Earthquake Technology*, vol.36, no.2-4, pp.121-137

Petti, L., Giannattasio, G., De Iuliis, M., and Palazzo, B.(2010). Small scale experimental testing to verify the effectiveness of the base isolation and tuned mass dampers combined control strategy, *Smart Structures and Systems*, vol.6,no.1,pp.57-72

Saitoh, M. (2012). On the performance of gyro-mass devices for displacement mitigation in base isolation systems, *Structural Control and Health Monitoring*, vol.19, no.2, pp.246-259

Saitoh, M. (2014). An external rotary friction device for displacement mitigation in base isolation systems, *Structural Control and Health Monitoring*, vol.21,no.2,pp.173-188

Tsai, H.-C. (1995). The effect of tuned-mass dampers on the seismic response of base-isolated structures, *International journal of solids and structures*, vol.32, no.8-9, pp.1195-1210

Xiang,P and Nishitani, A. (2014). Optimum design for more effective tuned mass damper system and its application to base-isolated buildings, *Structural Control and Health Monitoring*, vol.21, no.1, pp.98-114

Y. Hu, M. Z. Chen, Z. Shu, and L. Huang. (2015). Analysis and optimisation for inerter-based isolators via fixed-point theory and algebraic solution, *Journal of Sound and Vibration*, vol.346, pp.17-36