Proceedings Paper:

Deastra, P. orcid.org/0000-0002-1709-4686, Wagg, D.J. orcid.org/0000-0002-7266-2105 and Sims, N.D. orcid.org/0000-0002-6292-6736 (2021) Using a tuned-inerto-viscous-hysteretic-damper (TIVhD) for vibration suppression in multi-storey building structures. In: IOP Conference Series: Earth and Environmental Science. 2nd International Conference on Disaster and Management, 30 Sep - 01 Oct 2020, Padang, West Sumatra, Indonesia (online). IOP Publishing .

https://doi.org/10.1088/1755-1315/708/1/012012

IOP Conf. Series: Earth and Environmental Science **708** (2021) 012012 doi:10.1088/1755-1315/708/1/012012

Using a Tuned-Inerto-Viscous-Hysteretic-Damper (TIVhD) for vibration suppression in multi-storey building structures

P Deastra, D J Wagg and N D Sims

Department of Mechanical Engineering, The University of Sheffield, Sheffield S1 3JD, UK

Corresponding author: pdeastra1@sheffield.ac.uk

Abstract. This paper explores the use of a novel tuned-inerto-viscous-hysteretic-damper (TIVhD) for reducing the seismic response of multi-storey building structures. The TIVhD is an inerter-based damper device consisting of a linear hysteretic damper connected in series with an inerto-viscous damper. The layout of TIVhD is similar to that of tuned-inerter-hysteretic-damper (TIhD) with an additional viscous damping element in parallel with an inerter. The design is motivated by the fact that most inerter designs cannot completely remove the parasitic damping due to friction, fluid compression, etc. Moreover, the use of linear hysteretic damping is considered to be a more realistic approach when material damping is present. In this paper, the TIVhD is installed between the ground and the first-storey and is tuned by firstly assumed the viscous damping coefficient to be zero. Then the other three parameters are optimised following the tuning procedure of the TIhD that is based on the fixed-point theory with additional fine-tuning procedure by targeting the first vibration mode of the multi-storey structure. The optimum TIVhD parameters are finally obtained using two scenarios: (1) amplifying its viscous damping coefficient and stiffness while keeping the inertance constant; (2) amplifying its inertance and stiffness while keeping the viscous damping constant. Both scenarios are aiming at the same reduction level of that given by the TIhD. Finally, the effectiveness of the TIVhD on reducing the structural response is demonstrated for both harmonic and seismic base excitation cases in the time domain. This has been made possible by a newly developed time domain response of linear hysteretic damping via the Hilbert transform and a time reversal technique.

1. Introduction

The use of the inerter, a two terminal device generating force proportional to the relative acceleration between its two terminals, as a seismic protection device has attracted many researchers in the earthquake engineering community. This is due to the fact that the inerter is capable of generating inertance − an inerter constant measured in kilograms − several times larger than its physical mass [1]. As a result, it can amplify the theoretical mass of a structure to which it is attached to without significantly increasing the physical mass of the structure.

The use of the inerter in building structures is often combined with spring and damping elements. This device is also called an inerter-based-damper (IBD). The tuned-viscous-mass- damper (TVMD) [2] is one of the first IBD systems proposed in the literature for use as a vibration suppression device in civil structures. It has also been referred to as a parallel-connected-viscous-inerter-damper (PVID), for example in [3] or as a gyro-mass damper, for example in [4]. The device consists of a spring in series with a parallel connected inerter-damper. Ikago et al. [2, 5] demonstrated how the TVMD can be used as a earthquake protection device in building structures. The effectiveness of the device has also been validated experimentally via a shake table experiment [2].

In 2014, Lazar et al. [6] introduced a device called a tuned-inerter-damper (TID). It consists of a spring and damper in parallel connected in series with an inerter. If the mass of the inerter is considered, the TID becomes a tuned-mass-damper-inerter (TMDI) [7]. The TID has been shown in [6] to have some benefit compared to a traditional tuned-mass-damper (TMD): (1) Its optimum location is on the base storey; (2) it can reduce the structural response at higher modes, not just the targeted one. Morever, due to the presence of the inerter, a large mass ratio can be easily achieved with a small physical mass, hence leading to a larger reduction around resonance.

Most recently, the authors proposed a tuned-inerter-hysteretic-damper (TIhD) in [8]. The device has a similar layout with the TID with the viscous damping element replaced by a linear hysteretic damping element represented by a complex stiffness. Similar with the TMDI, when the mass of the inerter is included, the TIhD becomes a tuned-mass-hysteretic-inerter-damper (TMhDI). This concept has also been validated via a shake-table experiment [9]. Despite its noncausality, the complex stiffness approach has been widely used [10] and has been proven to be an accurate and practical linearization technique for structures with nonlinear dampers [11].

In this paper, an IBD device called the tuned-inerto-viscous-hysteretic-damper (TIVhD) is proposed. The layout is similar to that of TIhD but with an additional viscous damping element in parallel with the inerter. Some of the inerter designs cannot completely eliminate the damping to achieve a pure inertance. This fact has motivated the authors to further explore the effect of the parasitic damping via a TIVhD device.

2. Structural system

A 3-storey structure adopted from [9] subjected to base excitation r(t) is given in Figure 1. The equation of motion of the structure in the Laplace domain can be written as follows:

$$\begin{cases} m_1 s^2 X_1 + k_{1,2}(X_1 - X_2) - k_{0,1}(R - X_1) - F_{1,0} = 0 \\ m_2 s^2 X_2 + k_{2,3}(X_2 - X_3) - k_{1,2}(X_1 - X_2) = 0 \\ m_3 s^2 X_3 - k_{2,3}(X_2 - X_3) = 0 \end{cases} \tag{1}$$

where $\boldsymbol{m_i}$ represents the mass concentrated on the $\boldsymbol{i}$-th storey of the structure; $\boldsymbol{X_i}$ and $\boldsymbol{R}$ represent the Laplace transform of the $\boldsymbol{i}$-th storey displacement response and base displacement; $\boldsymbol{s}$ denotes the Laplace transform variable; and $\boldsymbol{F_{1,0}}$ is the force transferred from the TIVhD to the structure given by

$$F_{1,0} = \frac{(b_d s^2 + c_d s)\big(k_d(1 + j\eta)\big)}{b_d s^2 + c_d s + k_d(1 + j\eta)}(R - X_1) \tag{2}$$

here b_d and c_d are the inertance and viscous damping parameters of the TIVhD. The linear hysteretic damping element of the TIVhD is represented by a complex stiffness $k_d(1 + j\eta)$, where η is a loss factor given by $\eta = s_h/k_d$. As previously mentioned, when $c_d = 0$ the layout of the TIVhD becomes the same as the TIhD. It can be also seen here in Equation 2 when $c_d = 0$, the $F_{1,0}$ becomes the same with the $\boldsymbol{F_{1,0}}$ derived for the TIhD in [8].

The properties of the structure in Figure 1 are given in Table 1. Note that the natural damping of the structure is ignored for simplicity.

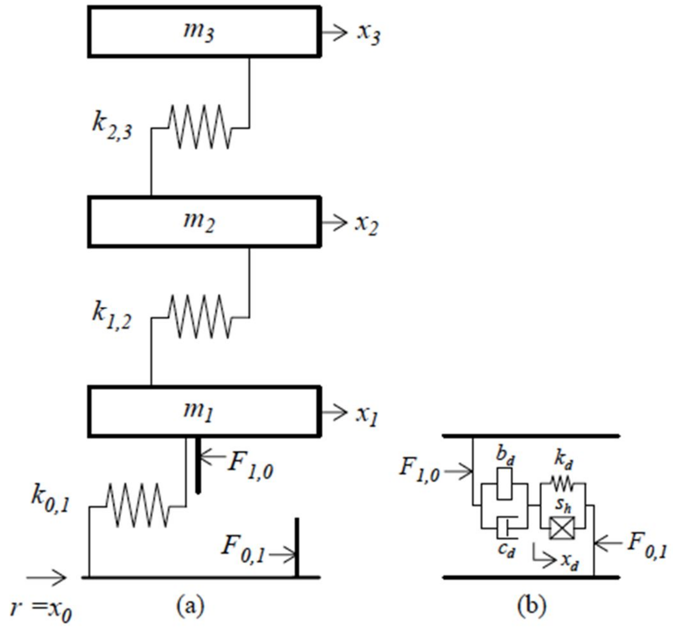


Figure 1. (a) 3-storey structure (b) TIVhD

Table 1. Structural properties [9]

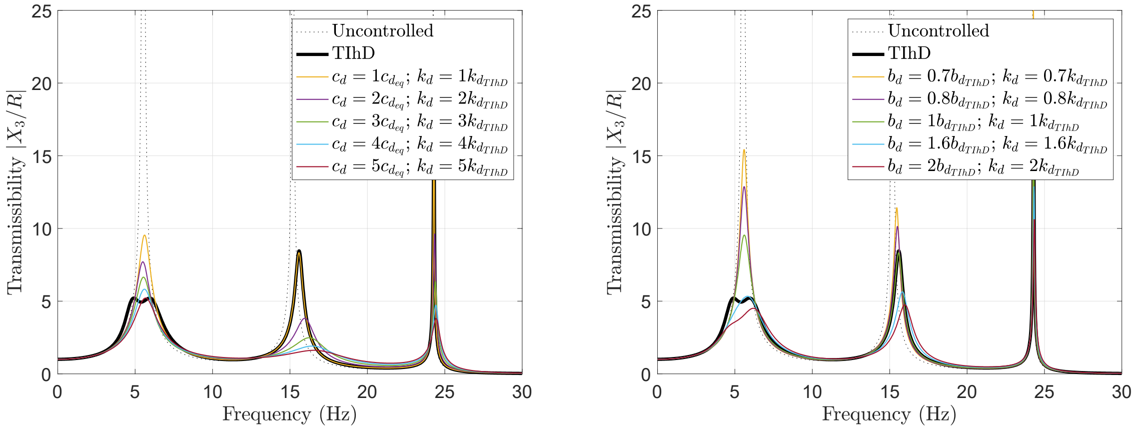
Storey	Mass (kg)	Stiffness (N/m)
1	33.15	$1.4048\ x\ 10^5$
2	24.15	$1.6858\ x\ 10^5$
3	24.15	$2.0792\ x\ 10^5$

3. Practical tuning procedure

The first step of the tuning of the TIVhD assumes that the viscous damping coefficient, c_d, is zero, so now its layout becomes the layout of the TIhD. The other parameters are then optimised via the fixed-point theory adapted from [8]. Next, two scenarios are proposed: (1) amplifying the viscous damping coefficient c_d and stiffness k_d while keeping the inertance b_d constant; (2) amplifying the inertance b_d and stiffness k_d while keeping the viscous damping c_d constant. Both scenarios use identical amplifying factor between c_d and k_d for Scenario 1 or between b_d and k_d for Scenario 2. Both procedures are aiming for a reduction level around the targeted resonant mode to be the same with that given by the TIhD. The initial viscous damping coefficient of the TIVhD is assumed to be $c_{h_{eq}} = k_d\eta/\omega_n$, where ω_n is the first natural frequency of the host structure.

Figure 2(a) shows the tuning procedure of the TIVhD via Scenario 1. In this scenario, both c_d and k_d are increased until the response around the first resonance mode reaches the same level with the TIhD. Similarly, Figure 2(b) illustrates the tuning of the TIVhD via Scenario 2. It can be seen that the response around the first resonance is reduced with the increase of both b_d and k_d. Finally, the obtained optimum parameters of the TIVhD via Scenario 1 and 2 are summarised in Table 2.

The optimum parameters obtained via the Scenario 2 are considerably better than Scenario 1. As can be seen in Table 2, to achieve the same level of reduction in the first resonance, the viscous damping coefficient and the stiffness of the TIVhD from Scenario 2 are several times less than those in Scenario 1. Although the required inertance is larger, but it can be easily achieved via several mechanisms, such as rack-and-pinion, ball screw, and fluid flow mechanisms, see [12, 13]. Despite its disadvantage, Scenario 1 provides better reduction around the second and third resonances.



(a) (b)

Figure 2. Tuning of the TIVhD (a) Scenario 1 (b) Scenario 2

Table 2. Structural properties [9]

Parameters	TIhD	TIVhD, Scenario 1	TIVhD, Scenario 2
Inertance, b_d (kg)	21	21	33.6
Viscous damping coefficient, c_d (Ns/m)	0	$1.77\ x\ 10^3$	$0.353\ x\ 10^3$
Stiffness, k_d (N/m)	$2.2\ x\ 10^4$	$11\ x\ 10^4$	$3.52\ x\ 10^4$
Loss factor, η	0.53	0.53	0.53

4. Structural time-response to harmonic and seismic base excitation

It is common in practice to convert the loss factor of the linear hysteretic damping into viscous damping coefficient via the equivalent viscous damping approach [15], where $c_{h_{eq}} = k_d\eta/\omega_{n_1}$,. Here $c_{h_{eq}}$ is the viscous damping coefficient equivalent to that of loss factor η of the complex stiffness. However, this practice has been shown, for example in [8], to be only accurate around the frequency of interest, which in this case is the first resonance frequency ω_{n_1}. Therefore, the complex stiffness term must be treated in its original form for maintaining accuracy.

However, treating the complex stiffness in its original form causes a challenge in the time-response analysis. Using the conventional integration method will lead to unstable responses [11]. Therefore, some techniques have been proposed to deal with this problem, for example see [16, 17]. One of the proposed techniques was proposed by Inaudi and Makris [11]. They introduced the time reversal technique and the use of the Hilbert transform. However, the proposed method is limited by the zero-order hold method. Furthermore, it has been shown only applicable for impulse input signals.

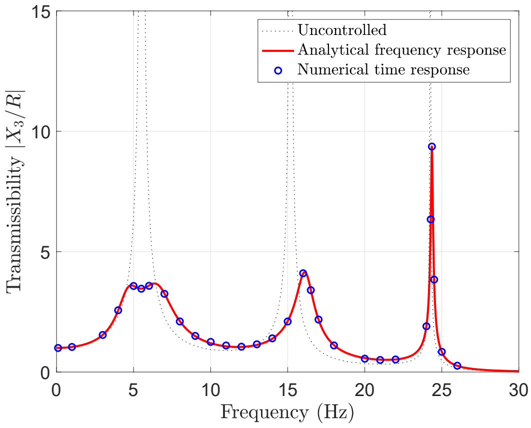
In this paper, a time domain method proposed by the authors in [8] is adapted to solve the equation of motions of the structural system with the TIVhD in the time domain. The method has been proven to be accurate for both harmonic and seismic base excitation, and for both single and multi-degree-of-freedom structural systems.

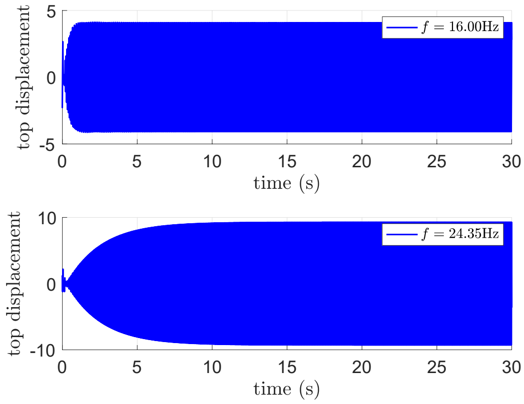
4.1. Harmonic base excitation

To demonstrate the response of the structure in the time domain, new optimum TIVhD parameters obtained via Scenario 2 with additional fine tuning are selected as given in Table 3. The frequency response of the structural system is given in Figure 3(a). This Figure also shows how the time-response of the structural system at steady states when subjected to harmonic base excitation in a good agreement with the frequency response obtained via an analytical formulation. Some examples of the time-response are given in Figure 3(b). The amplitude of the input harmonic signal $r(t)$ is 1, so they can be directly compared to the frequency response in Figure 3(a).

Table 3. Selected TIVhD optimum parameters

Inertance, b_d	Viscous damping coefficient, c_d	Stiffness, k_d	Loss factor, η
42 kg	353.47 Ns/m	$5.06\ x\ 10^4$ N/m	0.53



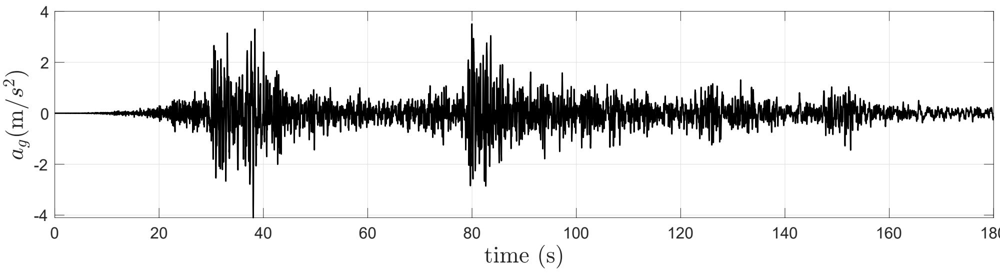


(a) (b)

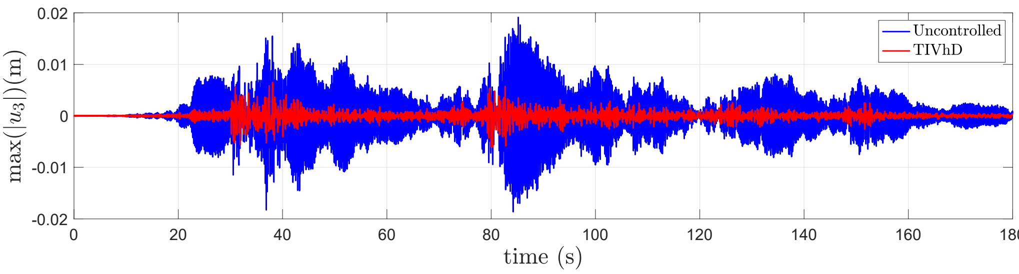
Figure 3. (a) Analytical frequency response versus numerical time-response of the structure (b) Structural time-response examples for f = 16.00Hz and f = 24.35Hz

4.2. Seismic base excitation

In order to assess the effectiveness of the TIVhD on protecting structures against earthquake, the considered 3-storey structure is simulated in case of ground motion. The Tohoku earthquake that took place in Japan on March 11th, 2011 is selected as shown in Figure 4(a). Figure 4(b) shows the time-response of the structural system when subjected to the selected ground motion.



(a)



(b)

Figure 4. (a) Ground acceleration time history (b) Relative displacement response time history

Figure 4(b) clearly shows the effectiveness of the TIVhD on reducing the structural response in case of seismic excitation. Note that for the uncontrolled structure the structural damping is no longer kept null. Small damping coefficient of 20Ns/m is assumed for each storey. The optimum parameters of the TIVhD are given in Table 3.

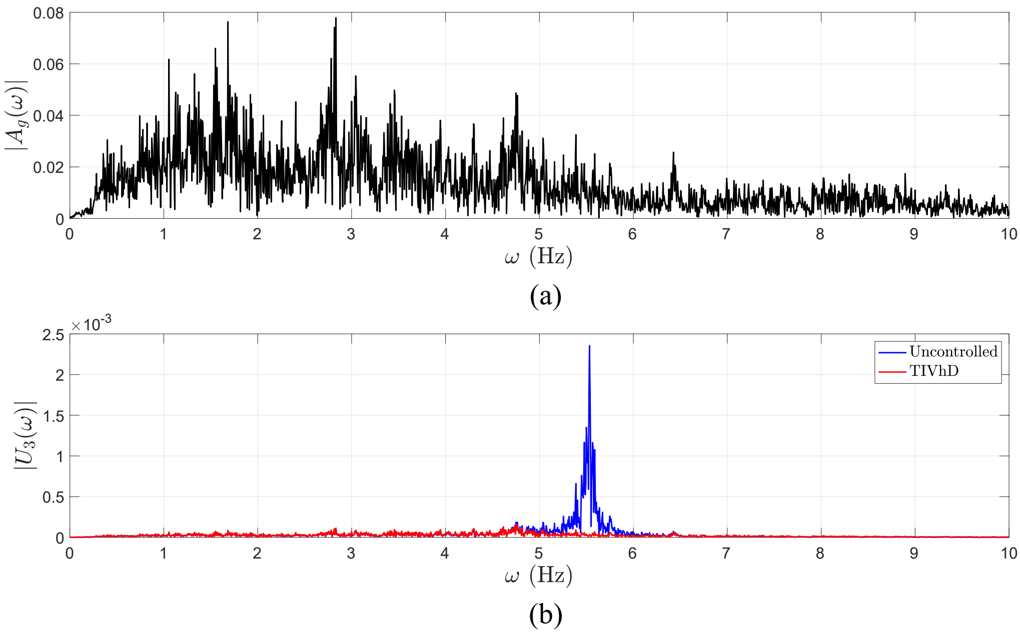


Figure 5. Single sided Fourier spectra: (a) of the ground acceleration (b) of the relative displacement response

Figure 5(a) and 5(b) shows the single sided Fourier spectra of the selected ground acceleration and the structural displacement time history, respectively. It should be noted that the first natural frequency of the structure is $\omega_{n_1} = 5.52$Hz which is in not in the region of the pre-dominant frequency of the selected ground motion. Hence, the structure is less sensitive to the chosen earthquake. However, both Figure 4(b) and 5(b) have shown how the optimised TIVhD can be effectively used to protect structures against earthquakes.

5. Conclusion

This paper discusses the use of a TIVhD for vibration suppression system in a multi-storey building structure. The layout of TIVhD is similar to that of TIhD with an additional viscous damping coefficient in parallel with the inertance. This study has been motivated by the fact that some of the proposed inerter designs cannot completely eliminate the parasitic damping due to friction, compressed fluid, etc. The coupled parallel connected inertance-damping is connected in series to a material damper. The use of a complex stiffness term is considered to be more realistic to represent the coupled stiffness-damping of the material damping. It has been proven to be an accurate and practical linearization technique for a class of nonlinear dampers. Two practical tuning procedures for the TIVhD are proposed in this paper. First the viscous damping coefficient $\boldsymbol{c_d}$ of the TIVhD is assumed to be zero, hence the TIhD tuning rule can be adapted to obtain the optimum stiffness $\boldsymbol{k_d}$ and loss factor $\boldsymbol{\eta}$ of the TIVhD for a selected inertance $\boldsymbol{b_d}$ value. Next the initial value for $\boldsymbol{c_d}$ is assumed to be equivalent to the material damper loss factor via an equivalent viscous damping approach $\boldsymbol{c_d} = \boldsymbol{c_{h_{eq}}} = \boldsymbol{k_d \eta / \omega_{n_1}}$. The optimum TIVhD parameters are then tuned based on the proposed two scenarios targeting the same reduction level with that given by the TIhD around the first resonance mode. Scenario 2 gives both $\boldsymbol{c_d}$ and $\boldsymbol{k_d}$ several times less than that given by Scenario 1. Although the required inertance is larger, but it can be easily achieved via a number of different mechanisms as discussed in the literature. Scenario 1 however, gives a better response around the second and third resonance modes. Obtaining the time response of the structure equipped with an TIVhD is challenging due the presence of the complex stiffness term. The authors have proposed an extended time domain technique for a structural system with complex stiffness in [8]. This technique is adapted in this paper to analyse the structural system in the time domain. It has been shown that the TIVhD can effectively reduce the structural response subjected to both harmonic and seismic base excitations.

References

[1] Smith MC 2002 Synthesis of mechanical networks: The inerter. *IEEE Transactions on Automatic Control* **47**(10) 1648-1662.
[2] Ikago K, Saito K, Inoue N 2012 Seismic control of single-degree-of-freedom structure using tuned viscous mass damper. *Earthquake Engineering and Structural Dynamics* **41**(3) 453-474.
[3] Pan C, Zhang R, Luo H, Li C, Shen H 2017 Demand-based optimal design of oscillator with parallel-layout viscous inerter damper. *Structural Control and Health Monitoring* **25**(1) e2051.
[4] Hessabi RM, Mercan O 2016 Investigations of the application of gyro-mass dampers with various types of supplemental dampers for vibration control of building structures. *Engineering Structures* **126** 174-186.
[5] Ikago K, Sugimura Y, Saito K, Inoue N 2012 *Modal response characteristics of a multiple-degree-of-freedom structure incorporated with tuned viscous mass dampers*. *Journal of Asian Architecture and Building Engineering* **11**(2) 375-382.
[6] Lazar IF, Neild SA, Wagg DJ 2014 Using an inerter-based device for structural vibration suppression. *Earthquake Engineering and Structural Dynamics* **43**(8) 1129-1147.
[7] Marian L, Giaralis A 2014 Optimal design of a novel Tuned Mass-Damper-Inerter (TMDI) passive vibration control configuration for stochastically support-excited structural systems. *Probabilistic Engineering Mechanics* **38** 156-164.
[8] Deastra P, Wagg D, Sims N, Akbar M 2020 Tuned inerter dampers with linear hysteretic damping. *Earthquake Engineering and Structural Dynamics* **49**(12) 1216-1235.
[9] Deastra P,Wagg D, Sims N 2020 Shake table tests of a three-storey structure with an inerter-based-hysteretic-damper. *17th World Conference on Earthquake Engineering* (Accepted).
[10] Beards CF. Structural Vibration. Butterworth-Heinemann; 1996. ISBN 9780340645802.
[11] Inaudi, JOSE A and Makris, Nicos 1996 Time-domain analysis of linear hysteretic damping. *Earthquake Engineering and Structural Dynamics* **25** 529-546.
[12] Wang FC, Hong MF, Lin TC 2011 *Designing and testing a hydraulic inerter*. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **225**(1) 66-72.
[13] Saitoh M. 2012 On the performance of gyro-mass devices for displacement mitigation in base isolation systems. *Structural Control and Health Monitoring* **19**(2) 246-259.
[14] Deastra P, Wagg DJ, Sims ND 2019 The realisation of an inerter-based system using fluid inerter. *Dynamics of Civil Structures* 127-134.
[15] Chopra AK. Dynamics of structures: theory and applications to earthquake engineering. Pearson/Prentice Hall; 2007. ISBN 10: 0-13-285803-7.
[16] Muscolino G, Palmeri A, Ricciardelli F 2005 Time-domain response of linear hysteretic systems to deterministic and random excitations. *Earthquake engineering and structural dynamics* **34**(9) 1129-1147.
[17] Bae, SH and Cho, JR and Jeong, WB 2016 Free and transient responses of linear complex stiffness system by Hilbert transform and convolution integral. *Smart Structures and Systems* **17** 753-771.

Acknowledgement

PD would like to acknowledge the support from Indonesia Endowment Fund for Education (LPDP).