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CONTENTS

Plenary Lecture

Special Sessions

Seismic Reduction of Monuments' Response Using Particle Dampers*

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Abstract—**This paper presents the results of an experimental study focusing on increasing the capacity of ancient multi-drum columns to resist lateral loading, without altering their overall appearance. The innovative approach proposed herein consists of replacing missing or heavily damaged drums by similar in-shape ones, with the difference that are internally hollow and they contain a number of steel spherical particles (particle damper). A column specimen was designed as a scaled replica of an existing ancient column made of marble and with a varying size of the empty space in the hollow drums. Different excitations, including actual earthquake recordings, were used to excite the specimen, with and without the proposed damper. It was found that a mass of particles equal to a small fraction of the mass of the column suffices to considerably reduce the vibrations induced.**

Properly designed particle dampers can reduce significantly the response of ancient multi-drum columns to earthquake loads and increase their seismic efficiency with a minimal alteration of their appearance, compared to traditional restoration techniques.

I. INTRODUCTION

Multi-drum columns are parts of historical monuments that can be found around the Mediterranean and they are often exposed to earthquake loads. Anastylosis of monuments that are damaged includes substitution of missing or damaged parts with new material that resembles the original one. Unfortunately, replacing missing parts does not improve the capacity of the monuments to resist seismic actions, while most conventional methods available for increasing the monuments' capacity to resist seismic loads alter considerably their appearance. There is a need for new ways to protect and preserve the historic heritage without altering the overall appearance of the monuments.

Several analytical and experimental studies have examined the behavior of multi-drum columns under dynamic loads ([1]-[14]). Even though all these studies have provided useful information on the behavior of monuments they have not yielded much information about how to increase their seismic safety without altering their overall appearance.

A simple method that can increase the classical columns' seismic safety is the use of particle dampers. Particle dampers are simple passive devices that have been used to attenuate the vibration of structures. Their behavior has been studied since long ([15-32]). They consist of a container with particles that it is attached on the structure to be controlled. They start operating with the motion of the structure (primary system). The particles moving inside the container hit its walls exchanging momentum with the primary system and attenuating its oscillations.

This paper studies the effectiveness of particle dampers in increasing the seismic safety of monuments respecting their overall appearance. The damper takes the form of a classical drum looking exactly like the rest of the drums, but having a hollow part containing particles. A column-model replica of an ancient column of a Greek temple is subjected to different dynamic excitations including earthquake loads. Its response is measured with and without the damper considering the influence of the system's parameters.

II. EXPERIMENTAL SET-UP AND TESTING

A small marble model replica of an ancient column from the temple of Hephaestus in Athens was used (scale 1:8). The total weight and height of the marble column was 19.8 kg and 651 mm respectively. The column consisted of seven drums each with constant diameter (120 mm) and height (93 mm). The drums were simply placed one above the other without connection. The column was supported on a marble plate (140x140x20 mm) that was glued on a steel plate attached on a 3x5

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m shake. A safety structure was built around the marble column to contain the drums in case of overturning (Fig. 1). The motion of the column was recorded using accelerometers attached on the drums while a built in accelerometer recorded the motion of the table. Three dampers of different size were used with hollow part-diameter of 90, 80 and 65 mm, respectively. Steel spherical particles of 20 mm diameter were placed in the damper. The structure, both without and with damper, was excited by dynamic signals including actual earthquake records.

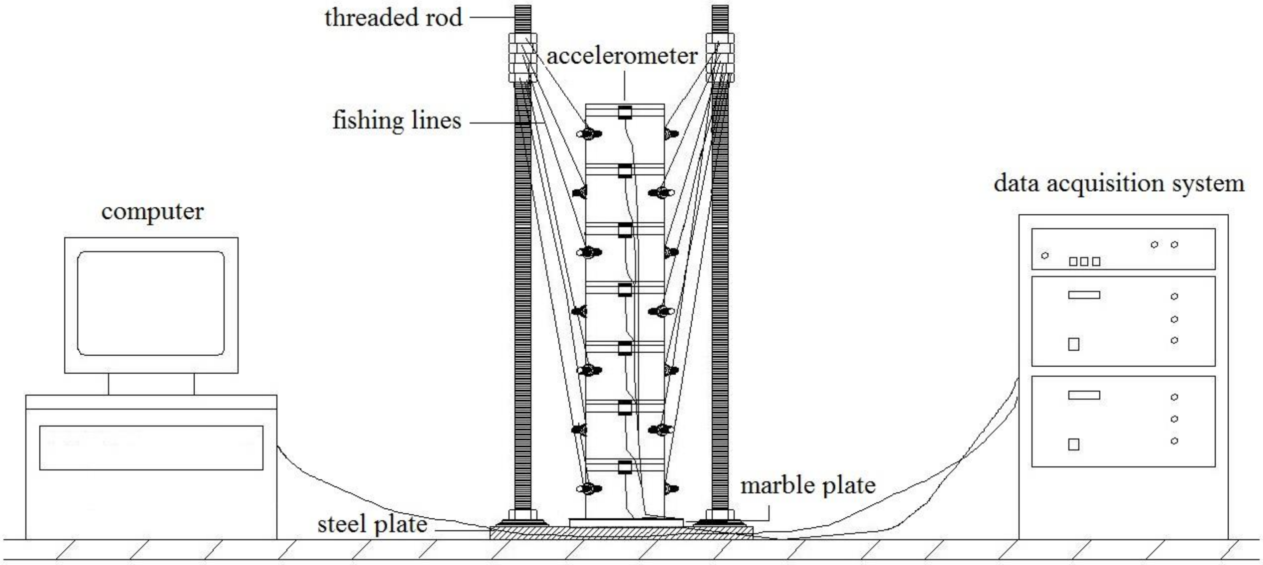

Figure 1: Experimental set-up.

III. RESPONSE OF MODEL COLUMN UNDER DYNAMIC LOADS

Initially a sinusoidal signal with frequencies in the range of 1 to 7 Hz was used to excite the column. The motion of the drums included rotation, sliding and rocking (Fig. 2). The main natural frequencies of the system were identified as 1.2, 1.6, 2.7 and 4.6 Hz, approximately (Fig. 3).

Figure 2: Deformation of model column.

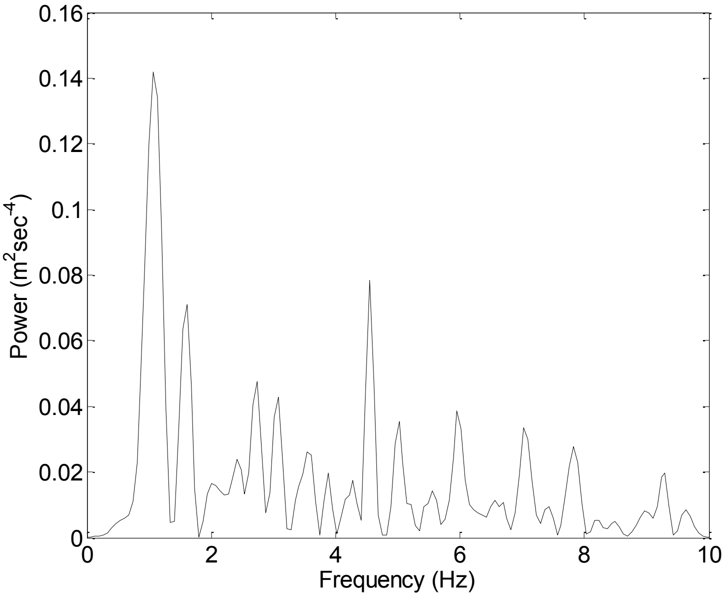

Figure 3: Frequency response of absolute acceleration at top drum under sinusoidal excitation.

A. Response of column without damper under random excitation

Subsequently, the column was excited by a random signal of 10 sec duration, containing frequencies in the range of 1-10 Hz. After a few repetitions of the test it was realized that small imperfections were considerably influencing the response and no consistent pattern of the response could be identified. To increase the robustness of the results, the test was repeated several times and the average of the response was calculated. As a measure of the response of the structure, the root mean square (RMS) of the displacement of the structure with respect to the root mean square of the displacement of the base (RMS response ratio) was selected. The average RMS response ratio for the top drum in the direction of motion was 5.55 and the standard deviation of the mean 0.48. Fig. 4(a) presents the relative displacement of the top drum of the column where the motion was higher with respect to the base for a representative experiment with mid-response (RMS response ratio 4.7). The free vibration response of the column after the end of the excitation signal continued for a few seconds before coming to rest.

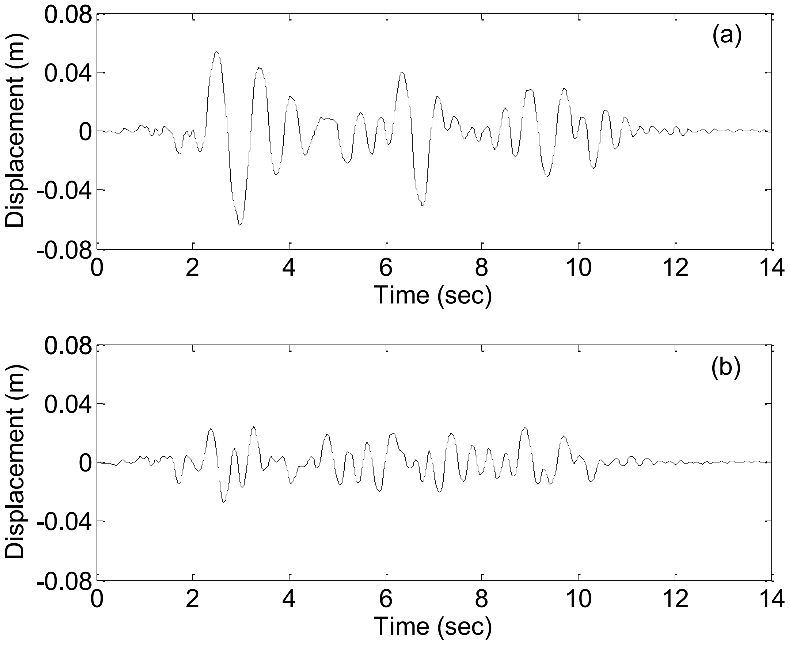

Figure 4: Displacement of column's top drum (a) without damper; (b) with damper.

B. *Response of column with damper under random excitation*

The placement of the damper along height is an important parameter for its effectiveness. Since the motion of the column was higher at the upper part, the points of insertion of the damper were at the top of the column (replacing the 7th drum) and two drums below the top (replacing the 5th drum). Initially the damper with the large diameter hollow part (90 mm) replaced the 5th drum. Eight spherical particles were placed inside the damper corresponding to 1.33% of mass ratio m/M (mass of particles (m) with respect to the initial mass of the column (M)). The response of the structure was reduced more than 40% in comparison to that without the damper and was more predictable since small imperfections of the drum set-up did not affect the response considerably. The average RMS response ratio was 3.0 with standard deviation of the mean 0.1. Fig. 4(b) presents the relative displacement of the top drum in the direction of motion for a representative experiment with mid-response (RMS response ratio 2.8). At the end of the excitation, the motion of the column decreases faster than without the damper. Increasing the number of particles (Fig. 5) to sixteen (m/M = 2.66%) and to twenty two (m/M = 3.66%) or using the dampers with the smaller diameter hollow part reduced the effectiveness of the damper owing to the lack of momentum of the congested particles. Placing the damper at the top of the column replacing the 7th drum yielded also reduced response, except for the cases in which the damper slid more than usual producing less satisfactory results. However, when the damper replaced drums lower than the top one, the increased friction seemed to control the amount of sliding and, from that point of view, the response was more consistent.

Figure 5: Damper with large diameter hollow part containing steel spherical particles.

C. *Response of column under earthquake excitation*

The model column was subjected to the Kalamata 1986 earthquake record, adjusted to the scale of the model. The frequency response of the acceleration of the top drum of the column without the particle damper is presented in Fig. 6(a) with the highest frequency response appearing below 2 Hz. The average RMS response ratio of the top column's drum without the damper was 5.82 (standard deviation of the mean 0.55). Fig. 7 presents the response displacement of the 7th, 5th, 3rd and 1st column's drum for a representative experiment with mid-response (RMS response ratio of the top drum = 4.78).

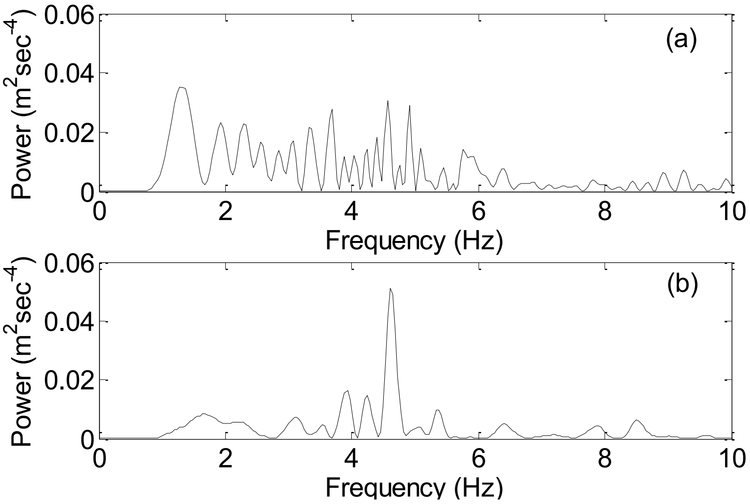

Figure 6: Frequency response of absolute acceleration of column's top drum under Kalamata earthquake record: (a) without damper; (b) with damper.

Next, the damper with the large diameter hollow part containing eight steel spherical particles replaced the 5th drum. The column's top drum average response ratio was 2.48 with standard deviation of the mean 0.10. Fig. 8 presents the response displacement of the 7th, 5th, 3rd and 1st drum of a representative experiment with mid-response (RMS response ratio of the top drum = 2.22). The response in terms of displacement was reduced more than 50% in comparison to that without the damper. In addition, the motion of the column seized much earlier than without the damper. The frequency response of the acceleration of the top drum shows reduction of the response for frequencies below 4 Hz while there was an increase for some higher frequencies (Fig. 6(b)), which though have small affect in the motion of the structure.

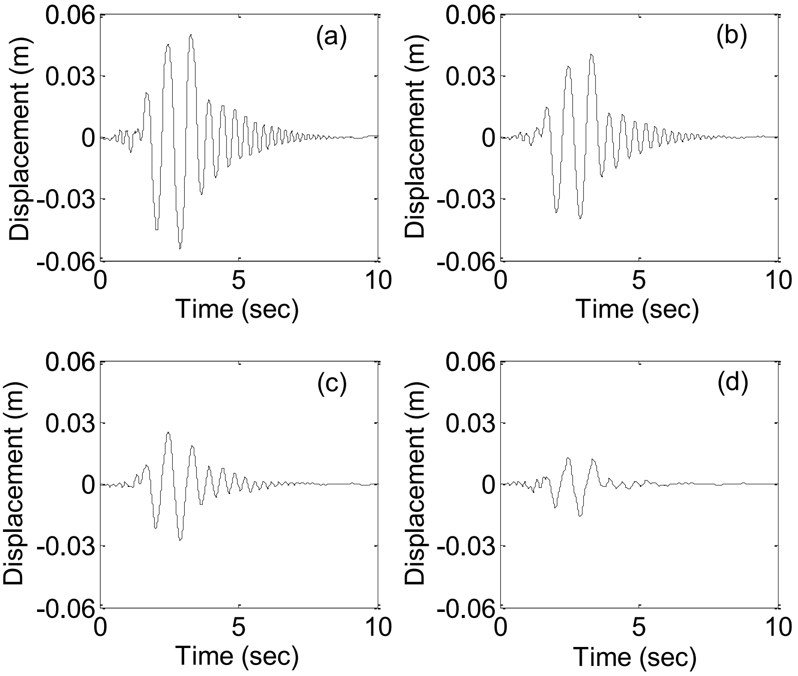

Figure 7: Displacement of column's drums without damper: (a) 7th drum; (b) 5th drum; (c) 3rd drum; (d) 1st drum.

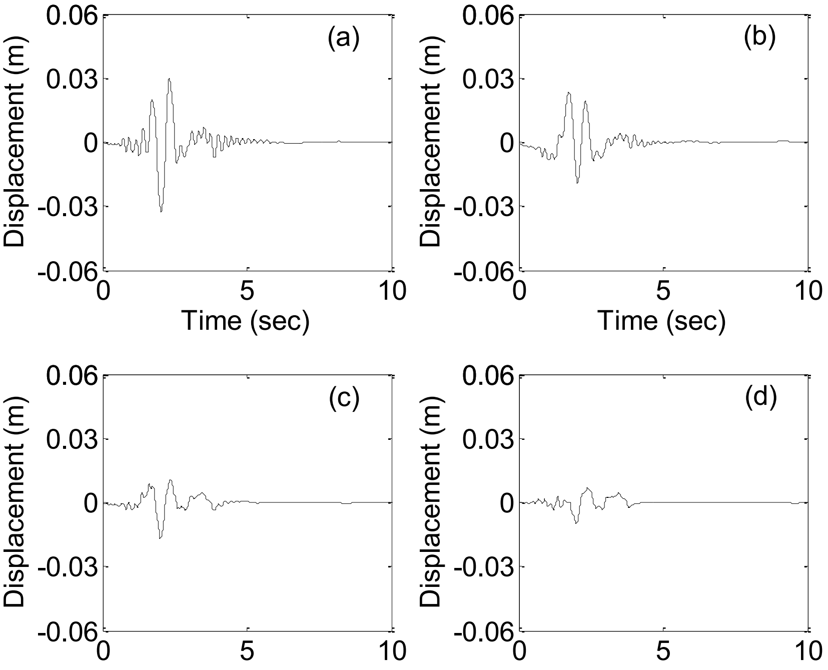

Figure 8: Displacement of column's drums with damper replacing the 5th drum: (a) 7th drum; (b) 5th drum; (c) 3rd drum; (d) 1st drum.

IV. CONCLUSIONS

This paper examined the effect of particle dampers on the response of classical columns under dynamic loads. The innovative approached used consisted of replacing an existing drum, that could have been damaged or missing, with a new one that resembled outside the original one but having a hollow inner part containing particles. It was found that when the damper is properly designed the response of the column can be reduced more than 40%. This new approach seems very promising owing to the increased seismic safety offered to monuments, without altering their overall appearance.

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REFERENCES

[1] N. Argyriou, K. Pitilakis, A. Sextos, "Numerical study of the seismic behavior of drum structures," *1st Greek National Conference of Anastylosis*, ETPAM, Thessaloniki, June 2006, pp. 14-16 [in Greek].

[2] N. Argyriou, O-J. Ktenidou, M. Manakou, P. Apostolidis, F.-J Chavez-Garcia, K. Pitilakis, "Seismic response analysis of ancient columns," *8th International Conference on Earthquake Geotechnical Engineering*, Thessaloniki, June 25-28, 2007.

[3] M.E. Dassios, I. Psyxaris, I. Vayias, "Analysis of seismic behaviour of columns and series of columns of ancient temples," *3rd Greek Conference in Seismic Mechanics and Technical Seismology*, 5-7 November, 2007 (in Greek).

[4] H.P. Mouzakis, I.N. Psycharis, D.Y. Papastamatiou, P.G. Carydis, C. Papantonopoulos, C. Zambas, "Experimental investigation of the earthquake response of a model of a marble classical column," *Journal of Earthquake Engineering and Structural Dynamics*, 31, 2002, pp. 1681-1698.

[5] M.E. Dassios, X. Mouzakis, I. Psyxaris, K. Papantonopoulos, I. Vayias, "Experimental Investigation of columns and series of columns", *3rd Greek Conference in Seismic Mechanics and Technical Seismology*, 5-7 November, 2008 (in Greek).

[6] D. Konstantinidis, N. Makris, "Seismic response analysis of multidrum classical columns," *Earthquake Engineering and Structural Dynamics*, 34, 2005, pp. 1243-1270.

[7] H.P. Mouzakis, I.N. Psycharis, D.Y. Papastamatiou, P.G. Carydis, C. Papantonopoulos, C. Zambas, "Experimental investigation of the earthquake response of the model of a marble classical column," *Earthquake Engineering and Structural Dynamics*, 31, 2002, pp. 1681-1698.

[8] K. Papadopoulos, E. Vintzileou, "The seismic response of the columns of Epikouriou Apollo's," *3rd Greek Conference in Seismic Mechanics and Technical Seismology*, 5-7 November, 2008 [in Greek].

[9] L. Papaloizou, P. Komodromos, "Planar investigation of the seismic response of ancient columns and colonnades with epistyles using a custom-made software," *Soil-Dynamics and Earthquake Engineering*, 29, 2009, pp. 1437-1454.

[10] C. Papantonopoulos, I.N. Psycharis, D.Y. Papastamatiou, J.V. Lemos, H. Mouzakis, "Numerical prediction of the earthquake response of classical columns using the distinct element method," *Earthquake Engineering and Structural Dynamics*, 31, 2002, pp. 1699 –1717.

[11] K. Pitilakis, E. Tavouktsi, "Seismic response of the columns of two ancient Greek temples in Rhodes and Lindos," *8th International Symposium on the Conservation of Monuments in the Mediterranean Basin*, Patra, 31 May-2 June, 2010.

[12] I.N. Psycharis, D.Y. Papastamatiou, A.P. Alexandris, "Parametric investigation of the stability of classical columns under harmonic and earthquake excitations," *Earthquake Engineering and Structural Dynamics*, 29, 2000, pp. 1093–1109.

[13] I. Psycharis, J. Lemos, D. Papastamatiou, C. Zambas, C. Papantonopoulos, "Numerical study of the seismic behaviour of a part of the Parthenon Pronaos," *Earthquake Engineering and Structural Dynamics*, 32, 2003, pp. 2063-2084.

[14] G.C. Manos, "The dynamic performance of ancient columns and colonnades with and without the insertion of wires made of shape memory alloy," *International Conference Structural Studies, Repairs and Maintenance of Historical Buildings,* Dresden, Allemagne, 1999.

[15] A. Papalou A., S.F. Masri, "Performance of particle dampers under random excitation," *ASME Journal of Vibration and Acoustics* Vol. 118, 1996, pp. 614-621.

[16] A. Papalou A., S.F. Masri, "Response of impact dampers with granular materials under random excitation," *International Journal of Earthquake Engineering and Structural Dynamics*, Vol. 25, 1996, pp. 253-267.

[17] A. Papalou, S.F. Masri, "An experimental investigation of particle dampers under harmonic excitation," *Journal of Vibration and Control*, 4, 1998, pp. 361-379.

[18] C.N. Bapat, S. Sankar, Multi unit impact damper—re-examined, Journal of Sound and Vibration, 103 (1985), 457–469

[19] N. Popplewell, S.E. Semercigil, Performance the bean bag impact damper for a sinusoidal external force, Journal of Sound and Vibration, 133 (2) (1989), 193-223

[20] Y. Araki, Y. Yuhki, I. Yokomichi, Y. Jinnouchi, "Impact damper with granular materials," *Bulletin of JSME 28 (240)*, 1985, pp. 1121-1217.

[21] M.Y. Yang, G.A. Lesieutre, S.A. Hambric, G.H. Koopmann, "Development of a design curve for particle impact dampers," *Noise Control Engineering Journal*, 53 (1), 2005, pp. 5-13.

[22] Z. Xu, K. Chan, W. Liao, "An empirical method for particle damping design," *Shock and Vibration* 11, 2004, pp. 647-664.

[23] M. Saeki, "Impact damping with granular materials in a horizontally vibrating system," *Journal of Sound and Vibration*, 251 (1), 2002, pp. 153–161.

[24] K. Mao, M.Y. Wang, Z. Xu, T. Chen, "DEM simulation of particle damping," *Powder Technology*, 142 (2–3), 2004, pp. 154–165.

[25] L.Hu, Q. Huang, Z. Liu, "A non-obstructive particle damping model of DEM," *International Journal of Mechanics and Materials Design*, 4 (1), 2008, pp. 45–51.

[26] C. Wong, M.C. Daniel, J.A. Rongong, "Energy dissipation prediction of particle dampers," *Journal of Sound and Vibration*, 319 (1-2), 2009, pp. 91-118.

[27] Z. Lu, S.F. Masri, X. Lu, "Parametric studies of the performance of particle damper under harmonic excitation," *Sturctural Control and Health Monitoring*, 18 (1), 2011, pp. 79-98.

[28] R.D. Friend, V.K. Kinra, "Particle impacting damping," *Journal of Sound and Vibration*, 233 (1), 2000, pp. 93–118.

[29] K.S. Marhadi, V.K. Kinra, "Particle impact damping: effect of mass ratio ratio, material and shape," *Journal of Sound and Vibration*, 283 (1), 2005, pp. 433–448.

[30] Z. Xu, M.Y. Chen, T. Chen, "Particle damping for passive vibration suppression: numerical modelling and experimental investigation," *Journal of Sound and Vibration*, 279 (3–5), 2005, pp. 1097–1120.

[31] Z. Lu, X. Lu, S.F. Masri, "Studies of the performance of particle dampers under dynamic loads," *Journal of Sound and Vibration*, 329 (26), 2010, pp. 5415–5433.

[32] Z. Lu, X. Lu, W. Lu, S.F. Masri, "Experimental studies of the effects of buffered particle dampers attached to a multi-degree-of-freedom system under dynamic loads," *Journal of Sound and Vibration*, 331, 2012, pp. 2007–2022