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Vibration reduction of window glass panel using viscoelastic materials

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ABSTRACT

The window is one of the most important part of the building structure, which plays a role in the function of ventilating, lighting and changing the indoor and outdoor environment. The damping property of a window glass panel has a great influence on the comfort of the occupants especially for those buildings that are close to a vibration source, such as rail tracks. In this paper, a new method to retrofit a window glass panel for vibration reduction is developed. Viscoelastic materials tape was bounded around the edge of the glass panel to increase its inherent damping and reduce its vibration when subjected to external excitations. A float glass was mounted on the surface of the viscoelastic materials to make it have a better performance to increase the damping. Experiments were carried out to demonstrate the effectiveness of the proposed method. To measure the vibration response of the window glass panel, the Lead Zirconate Titanates (PZT) patches were mounted on the four corners and the central of the window glass panel. Comparative studies were performed and the results showed clearly that the vibration of the window glass panel reduced when suffered excitations, revealing the effectiveness of the proposed retrofit method for structure damping improvement, which can provide a reference for the design and utilization of the window glass.

Keywords: Window glass panel; Vibration reduction; Viscoelastic materials; Lead Zirconate Titanates (PZT) patches; Retrofit for damping increase

Introduction

The window, the interface between the indoor and outdoor environment, plays a highly important role in creating comfort for the residents. Window glass panel has important functions such as lighting, thermal insulation and improving the living environment. Since the damping ratio of window glass panels is in a relatively low value

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such as less than 0.5%, subjected to wind or mechanical vibration, window glass often generates considerable noise, thus lowering residential comfort. To overcome the above mentioned problems, the contact between the glass panel and window is traditionally strengthened by glass rubber seal. However, the method will cause excessive vibration of the glass, and in some case, large vibration can even result in the broken off of glass and injury of people.

Over the past several decades, researches on vibration control of the civil structures and mechanical systems have attracted a lot of attentions of engineers when suffer different external excitations such as earthquake, wind or other large vibration loads. Various control methods have been presented and implemented to attenuate the vibration. Tuned mass dampers (TMDs) (Rana 1998, Sadek 1997, Hrovat 1983, Jangid 2015, Abé 2010), amongst the oldest structural vibration control devices in existence, are effective and reliable to suppress undesirable vibrations induced by winds and earthquake loads, which have been extensively utilized in tall buildings and towers. Semi-active stiffness control devices are adopted to control the stiffness of the structure to establish a non-resonant condition during earthquakes, many investigations (Kobori 1993, Nemir 1994, Agrawal 2001, Yang 2010, Ganadhi 2003) for seismic response control about these devices have been conducted, but the modification of stiffness is discontinuous, which is hard to alleviate. As the applied electric field increases, electrorheological (ER) dampers (Gavin 1996, Noresson 2002, Lim 2015, Makris 1996, Bitman 2002) become commonly practical in vibration control of the civil structures. In order to require a large range of controllable forces, small-scale ER damping walls (Gavin 1996, Gavin 1998) are proposed and Makris et al. (Makris 1995, Makris 1998, Makris 1996,) developed an electrorheological fluid damper to deal with the disadvantage that ER dampers may be too large to be practical for the sake of developing forces for seismically excited structures. Magnetorheological (MR) dampers (Cho 2005, Dyke 1996, Zhu 2014, Motra 2011, Zapateriro 2008, Dominguez 2005) are essentially magnetic analogs of ER dampers, while the control effect is differently governed by utilized of an electric field and a magnetic field. MR fluid dampers (Yang 2002, Kwok 2007,Milecki 2015), amongst controllable fluids that have a dramatic change in their rheological behavior, are one of the most widespread used vibration control devices of MR dampers. However, the control system will become complex when considerable numbers of MR dampers are applied to large-scale civil structures, thus hard to install and maintain the control system. Duo to its advantages of efficient energy dissipation capability and wide range of applications, viscous dampers (Li 2007,Liu 2012) has been widely utilized in civil structures to control seismic, wind induced and thermal expansion motions. A fluid viscous damper (Jia 2008, Marano 2015, Mcnamara 2003, Greco 2014,Lin 2002, Constantinou 1992, Hou 2008) is one of the most common and extensive utilized devices of viscous dampers, experimental and analytical investigation, parameters identification and various design methods have comprehensively conducted. Apart from other devices, viscoelastic dampers (VEDs) (Zhang 1996, Shukla 1999, Kim 2006,Park 2010) have been proved to be capable of providing structures with considerable added damping to reduce vibration produced due to wind and seismic excitations, researches of VEDs show that the response of civil structures to earthquakes can be reduced significantly because of a notable increase in the structural damping used of it. However, all these devices are connected with or installed in the civil structure, no effective devices can be used on some non-critical parts to reduce vibration, such as window glass. For the vibration reduction of the glass panel, some researches have been conducted and some methods have been complicated. M. Kasparek (Kasparek 2014) used an experimental setup consisting of microphones and 2D plane vibrometer to measure local amplitudes and phases of out-of-plane glass motion in which the vibration and noise transfer characteristics were measured using a set of microphones and vibrometer. A. S. Bagaev et al. (Bagaev 2004) applied solution of the boundary-value problem related to excitation of bending vibrations of a glass rectangular plate with a viscous coating to evaluate the possible amplitude of vibrations of atypical window glass induced by speech signals. It was found that multilayer window glass structures with polymer materials in a transient state could be recommended for decreasing of the amplitude of bending vibration of the window glass.

However, the existing studies in vibration control of window glass panels are aimed to solve the noise problem and energy saving (Haluk 1997, Rainer 1982, Behr 1991), rather than to suppress its vibrations. In this paper, a new method to increase the damping of the window glass panel was presented. Viscoelastic materials tapes were employed to post on the edges of the window glass panel. In order to make viscoelastic materials have a better performance to increase the damping, a float glass was mounted on the surface of viscoelastic materials, which could increase the damping effect of viscoelastic materials. To measure the vibration response of the window glass panel, PZT patches were bounded on the four corners and the central part of the window glass to accept the signal and the vibration damping effect of viscoelastic materials could be analyzed. This device is simple, convenient, safe and easy to maintain, which can greatly reduce the vibration of the window glass panel.

2.Experimental setup

2.1Vibration damping enhancement through viscoelastic materials

The enhanced window glass panel with viscoelastic materials is shown in Figure.1. Viscoelastic materials tapes are posted on the edge of the window glass panel after the surface of the glass is cleaned. The damping coefficient and width of viscoelastic materials are determined according to the vibration amplitude of the window glass panel. After viscoelastic materials tapes are bounded on the window glass panel, a strip of float glass is used to cover on the viscoelastic materials layer as a constraint layer to improve the damping effect of viscoelastic materials, the size of the float glass is determined according to viscoelastic materials. To get better understanding of this setup, the specific view of the enhanced window glass panel is shown in Figure 2.

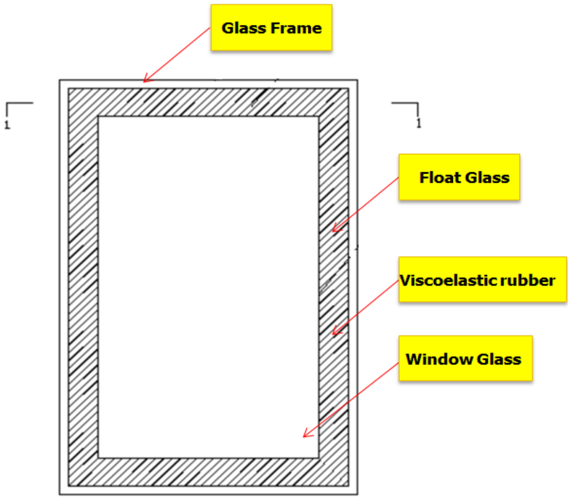

Figure 1. Enhanced window glass panel with viscoelastic materials

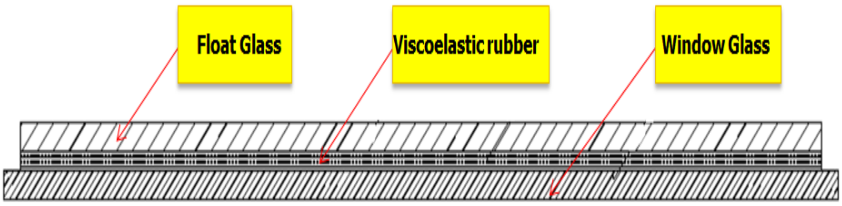

Figure 2. 1-1 Section: the sandwich structure with viscoelastic layer for damping enhancement

2.2 Window glass panel and vibration motor

A pane of float glass panel with the thickness of 5 mm was prepared at the beginning of the experiment, the dimensions of window glass panel was 1.0m×1.0m, and the window frame was fabricated by plastic-steel. Channel steel was used to restrict four sides of the window frame in the experiment. A motor was fixed on the bottom of the channel steel to simulate the external excitations. Technical parameters of this excitation motor are shown in Table 1.

Table 1 Parameters of vibration motor

Voltage(V)	Power(W)	Rotation Speed	Motor Stall	Frequency Rang (Hz)
220	30	0 ~ 3000r/min	Level 1 ~ Level 10	0~50

2.3 The specimen and PZT

In order to study the vibration of window glass panel, a set of experiments were performed in two cases, namely without viscoelastic materials and with viscoelastic materials. In the experiments, window glass panel was fixed in the steel frame, and the steel frame was welded on a weightily iron bed which could keep it stable to simulate the boundary conditions. A vibration motor was fixed at the bottom of the steel frame, which was perpendicular to the window glass surface.

Piezoceramic belonged to energy conversion materials has the direct and the inverse piezoelectric effects. The direct piezoelectric effect can transfer the stress or strain energy into the electric energy, and the inverse piezoelectric effect can transfer the electric energy to the stress or strain energy. In this work, Lead Zirconate Titanate (PZT) was adopted to collect the vibration signal of the window glass panel due to its piezoelectric properties. Different models (such as d33, d31 or d15) of the PZT can be selected depending on the different detection cases. In the experiment, the PZT d33 mode was selected to monitor the vibration of the window glass panel due to its suitability. In order to measure the vibration of the window glass panel, five PZT patches were arranged on the four corners and the center of the window glass panel. The experimental setup of the window glass panel and the location of PZT patches were shown in Figure 3.

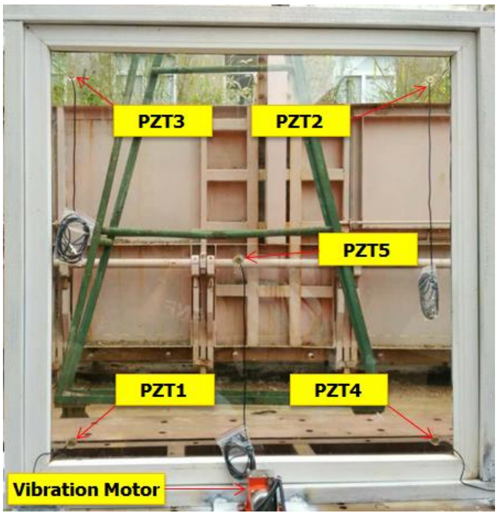

Figure 3. Experimental setup

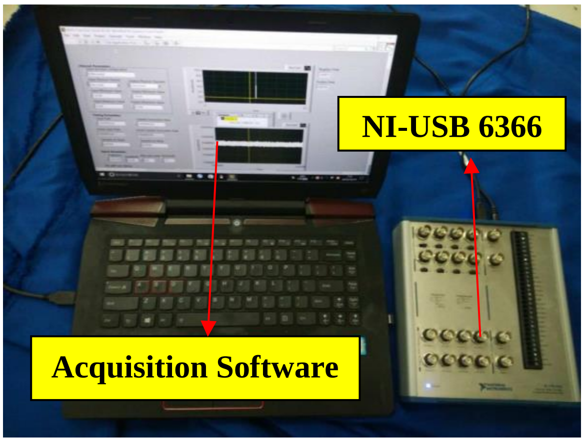

Figure 4. Instruments used in the experiment

2.4 Instrumentation

The measurement instruments consisted of a data acquisition device (NI-USB 6366) connected with a computer and an acquisition system based on LabVIEW, which was used to obtain the vibration history signal of the window glass panel. The instruments used in the experiment are shown in Figure 4.

2.5 Viscoelastic materials

Among all viscoelastic materials, ZN (one of Butyl rubber damping material) series damping materials is especially suitable to use as the damping layer since it can be directly mounted on any complex geometry surface. Furthermore, viscoelastic materials have excellent ageing durability (Guo 2016, Zhao 2001). In this paper, ZN22 was adopted to reduce the vibration of window glass panel, and the parameters of viscoelastic materials are given in Table 2. In the experimental setup, ZN22 viscoelastic materials were mounted on the surface of the window glass panel, the float glass with the thickness of 3 mm used as a constraint layer was posted on the surface of ZN22 to improve the damping ratio of the window glass panel. The configuration of the viscoelastic materials is shown in Figure 5.

Table 2. Properties of viscoelastic materials

Physical Property	Tensile Strength (MPa)	15
	Elongation (%)	400
	Permanent Deformation (%)	18
	Hardness (Shore A)	72
	70℃×72h Aging Coefficient	1.09
	Specific Gravity (g/cm^3)	1.27
Damping Property	Bmax	1.4
	Tβmax(℃)	25
	Eβmax(N/M)	5×10^7
	Δtβmax=0.7(℃)	0 ~ 50
	Eβmax=0.7(N/M)	10^7 ~ 10^8

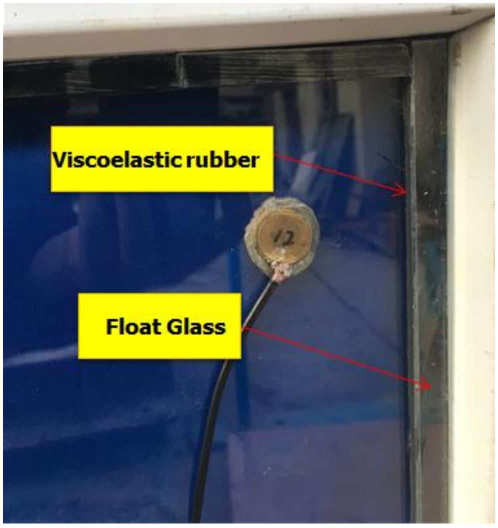

Figure 5. Detailed arrangement of viscoelastic materials

4. Experimental results and Discussion

In the experiment, level 5, level 7 and level 9 were used to provide vibration excitation, excitation frequency and the amplitude of the excitation will increase with the increases of motor stall. There were two conditions which were considered: one was without viscoelastic materials enhancement; the other one was with viscoelastic materials enhancement. The experimental data were collected by 5 PZT patches under these two conditions, and the time histories of voltage from PZT patches are shown in Figure 6 ~ 8, the results of FFT amplitude are shown in Figure 9~11.

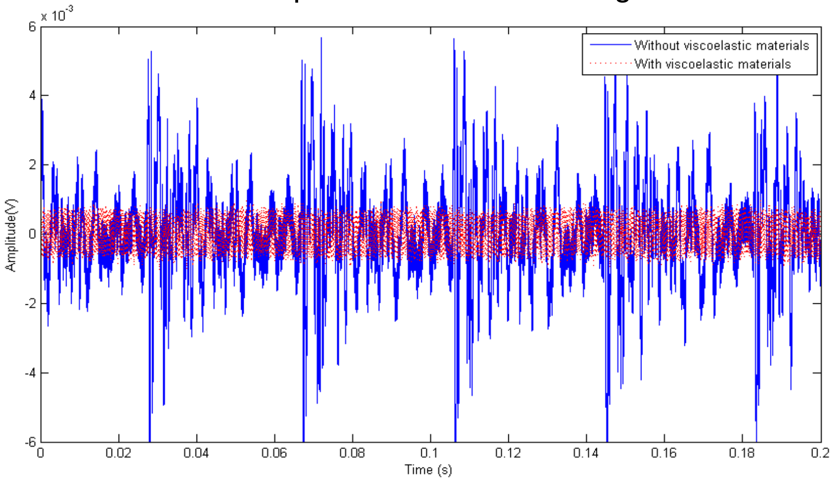

Figure 6. Time domain response curve of PZT 2 under level 5

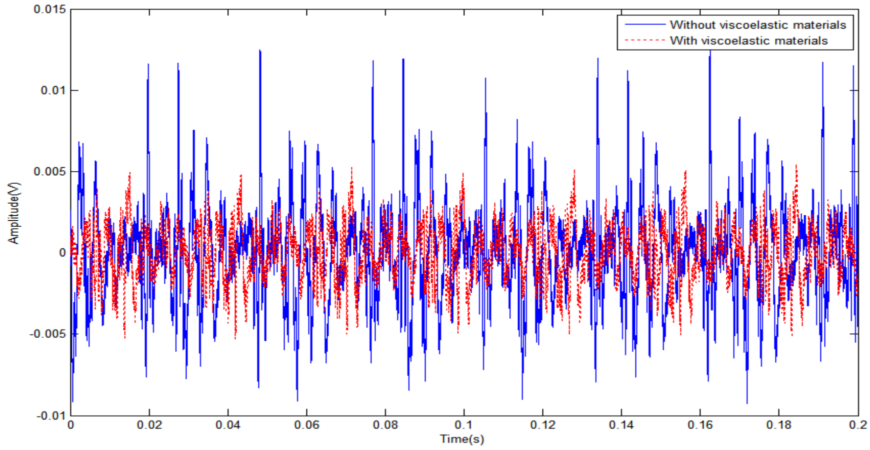

Figure 7. Time domain response curve of PZT 1 under level 7

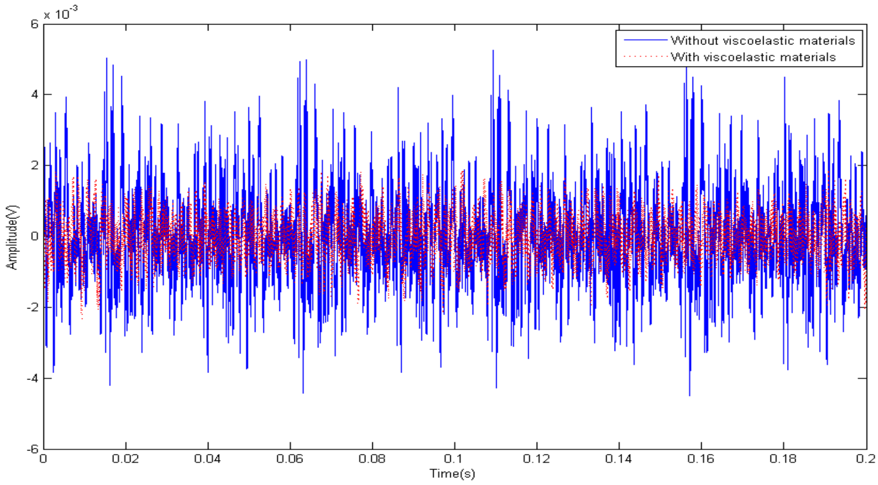

Figure 8. Time domain response curve of PZT 5 under level 9

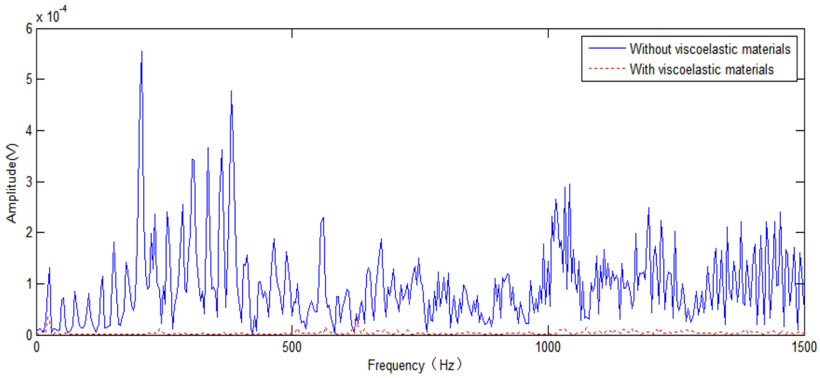

Figure 9. Frequency response curve of PZT2 under level 5

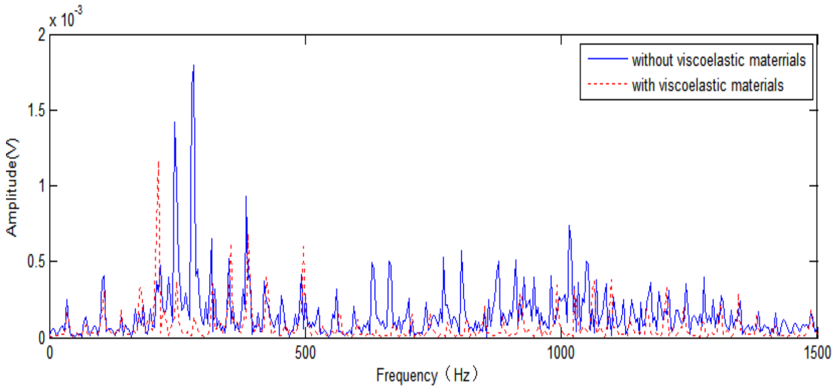

Figure 10. Frequency response curve of PZT1 under level 7

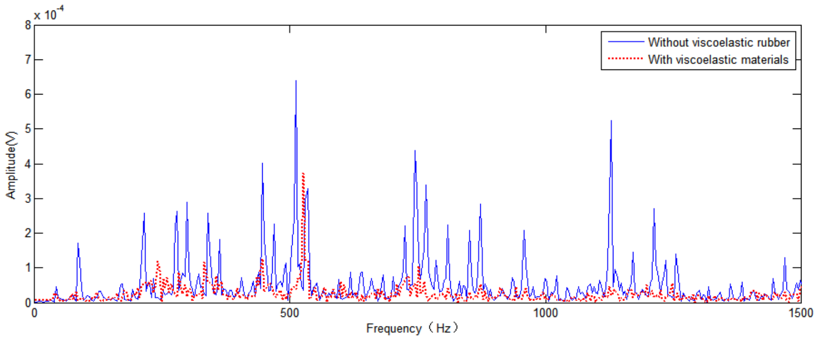

Figure 11. Frequency response curve of PZT5 under level 9

The voltage signals received by different PZT patches on window glass panel show a good correspondence with each other patches. The experiment result shows that the viscoelastic materials can increase the damping ratio of the window glass panel, and the maximum vibration reduction is up to 66.7%, the damping effect by different measuring point is different and the vibration damping effect under level 9 is the best, the vibration damping effect under level 7 is better than level 5. This can be explained by the damping mechanism of viscoelastic materials. In the practical application, its principle is based on deformation obtained by converting kinetic energy into heat energy, which can reduce resonance amplitude of structure, in order to inhibit the vibration of structure. Viscoelastic rubber will produce cycle deformation under load due to its viscoelastic property, molecular chain segments produce relative displacement. Due to inner-friction between molecules, a part of mechanical energy was converted into heat energy and dissipated, so the target for damping effect was achieved. Therefore, the larger distance between the molecules obtained from enlargement of deformation will lead to higher energy consumption. The vibration of glass under high level is large, the damping effect of viscoelastic rubber on glass is good, but damping effect under low level is poor conversely.

5.Conclusion

In this paper, a new method to increase the damping of the window glass panel is presented. Viscoelastic materials tapes are posted on the edges of the glass to reduce the vibration, and Lead Zirconate Titanates patches are bounded on the four corners and the central point of the window glass panel to measure its vibration response. The effect of the viscoelastic materials is verified by the experiments which shows that the large amplitude vibration of the window glass panel is prohibited. The damping effect of viscoelastic materials under high frequency was excellent, however, was not well under low frequency. The experimental results had a good actual reference value, which could be applied in damping reduction of glass window panel under large vibration circumstances. However, there are still some other works to do, further research is needed on the mechanism of vibration reduction, effect of viscoelastic materials with different thickness on the damping effect of the window glass panel needs further study. To make a better understanding of vibration damping effect of viscoelastic materials, numerical simulation will be conducted in the next step.

Reference

Rana, R. and Soong, T.T. (1998), “Parametric study and simplified design of tuned mass dampers.” *Eng. Struct.,* **20**(3), 193-204.

Sadek, F., Mohraz, B. and Taylor, A. W. et al. (1997), “A method of estimating the parameters of tuned mass dampers for seismic application.” *Earthq. Eng. Struct. D.,* **26**(6), 617-635.

Hrovat, D., Barak, P. and Rabins, M. (1983), “Semi-Active versus Passive or Active Tuned Mass Dampers for Structural Control.” *J. Eng. Mech., ASCE,* **109**(3), 691-705.

Jangid, R. S. and Datta, T.K. (2015) “Performance of multiple tuned mass dampers for torsionally coupled system.” *Earthq. Eng. Struct. D.,* **26**(3), 307-317.

Abé, M. and Fujino, Y. (2010), “Dynamic characterization of multiple tuned mass dampers and some design formulas.” *Earthq. Eng. Struct. D.,* **23**(8), 813-835.

Kobori, T., Takahashi, M., and Nasu, T. et al. (1993), “Seismic response controlled structure with Active Variable Stiffness system.” *Earthq. Eng. Struct. D.,* **22**(11), 925-941.

Nemir, D.C., Lin, Y. and Osegueda, R. A. (1994), “Semi-active Motion Control Using Variable Stiffness.” *J. Struct. Eng.,* **120**(4), 1291-1306.

Agrawal, A.K. and He, W.L. (2001), “Control of seismically excited cable-stayed bridge using a resetting semi-active stiffness damper.” *J. Bridge Eng.,* **6**(6), 376-384.

Yang, J.N., Bobrow, J. and Jabbari, F. et al. (2010), “Full-scale experimental verification of resetable semi-active stiffness dampers.” *Earthq. Eng. Struct. D.,* **36**(9), 1255-1273.

Gandhi, F. and Anusonti-Inthra, P. (2003), “Adaptive Control of Semi-Active Variable Stiffness Devices for Narrow-Band Disturbance Rejection.” *J. Intel. Mat. Syst. Struct.,* **14**(3), 191-201.

Gavin, H.P., Hanson, R.D. and Filisko, F.E. (1996), “Electrorheological Dampers, Part I: Analysis and Design.” *J. Appl. Mech.,* **63**(3).

Gavin, H.P., Hanson, R.D. and Filisko, F.E. (1996), “Electrorheological Dampers, Part II: Testing and Modeling.” *J. Appl. Mech.,* **63**(3), 676-682.

Noresson, V., Ohlson, N.G. and Nilsson, M. (2002), “Design of electrorheological dampers by means of finite element analysis: theory and applications.” *Mater. Design*, **23**(4), 361-369.
Lim, K.H., Choi, S. B. and Lee, Y.S., et al. (2015), “Discrete-time fuzzy sliding mode control of vehicle suspension system featuring electrorheological damper.” *Smart Mater. Struct.,* **16**(3), 798-808.
Makris, N., Burton, S.A. and Taylor, D.P. (1996), “Electrorheological damper with annular ducts for seismic protection applications.” *Smart Mater. Struct.,* **5**(5), 551.
Bitman, L. (2002), “Electrorheological Damper Analysis Using an Eyring Constitutive Relationship.” *J. Intel. Mater. Syst. Struct.,* **13**(10), 633-639.
Gavin, H.P. (1998), “Design method for high-force electrorheological dampers.” *Smart Mater. Struct.,* **7**(7), 664.
Makris, N., Hill, D. and Burton, S., et al. (1995), “Electrorheological fluid damper for seismic protection of structures.” *Proce. Spie.,* **2443**(1), 184-194.
Makris, N., Roussos, Y. and Whittaker, A., et al. (1998), “Seismic protection with fluid dampers and the issue of viscous heating.” Structural Engineers World Congress, San Francisco.
Makris, N. and Mcmahon, S. (1996), “Structural Control with Controllable Fluid Dampers: Design and Implementation Issues.” International Workshop on Structural Control, Hong Kong.
Makris, N., Burton, S.A. and Hill, D., et al. (1996), “Analysis and Design of ER Damper for Seismic Protection of Structures.” *J. Eng. Mech.,* **122**(10), 1003-1011.
Cho, S.W., Jung, H.J. and Lee, I.W. (2005), “Smart passive system based on magnetorheological damper.” *Smart Mater. Struct.,* **14**(4), 707-714.
Dyke, S.J., Spencer, B.F. and Sain, M.K., et al. (1996), “Modeling and control of magnetorheological dampers for seismic response reduction.” *Smart Mater. Struct.,* **5**(5), 565.
Zhu, W. and Rui, X. (2014), “Semiactive Vibration Control Using a Magnetorheological Damper and a Magnetorheological Elastomer Based on the Bouc-Wen Model.” *Shock Vib.,* **2014**(2), 1-10.
Motra, G.B., Mallik, W. and Chandiramani, N.K. (2011), “Semi-active vibration control of connected buildings using magnetorheological dampers.” *J. Intel. Mater. Syst. Struct.,* **22**(16), 1811-1827.
Zapateiro, M. (2008), “Semiactive control of a base isolated building using magnetorheological dampers.” *Inter. J. Model. Ident. Control*, **7**(7), 41-48(8).
Dominguez, A., Sedaghati, R. and Stiharu, I. (2005), “Semi-Active Vibration Control of Adaptive Structures Using Magnetorheological Dampers.” *Aiaa. J.,* **44**(7), 1563-1571.
Yang, G., Jr, B.F.S. and Carlson, J. D., et al. (2002), “Large-scale MR fluid dampers: modeling and dynamic performance considerations.” *Eng. Struct.,* **24**(3), 309-323.
Kwok, N.M., Ha, Q.P. and Nguyen, M.T., et al. (2007), “Bouc–Wen model parameter identification for a MR fluid damper using computationally efficient GA.” *Isa T.,* **46**(2), 167.
Milecki, A., Myszkowski, A. and Sędziak, D. (2015), “Investigation of dynamic properties and control method influences on MR fluid dampers performance.” *J. Intel. Mater. Syst. Struct.,* **13**(7-8), 453-458.
Li, B. and Liang, X. (2007), “Seismic Design of Supplemental Viscous Dampers to

Structure." *Tech. Earthq. Disaster Prev.,* **2**(1), 1-10.
Liu, C., Wei, J.G. and Wang, S.L. (2012), "Seismic vibration control of space frame structures with viscous dampers." *J. Agri. Univer. Hebei,* **35**(1), 94-97.
Jia, J., Du, J. and Yu, W., et al. (2008), "Design method for fluid viscous dampers." *Arch. Appl. Mech.,* **78**(9), 737-746.
Marano, G.C. (2015), "Identification of parameters of Maxwell and Kelvin–Voigt generalized models for fluid viscous dampers." *J. Vib. Control*, **21**(2), 260–274.
Mcnamara, R.J. and Taylor, D.P. (2003), "Fluid viscous dampers for high‐rise buildings." *Struct. Des. Tall Spec.,* **12**(2), 145-154.
Greco, R. and Marano, G.C. (2014), "Parameter identification of fluid viscous dampers." *Astrono. Astrophys.,* **420**(2), 589-594.
Lin, W.H. and Chopra, A.K. (2002), "Earthquake response of elastic SDF systems with non-linear fluid viscous dampers." *Earthq. Eng. Struct. Dyn.,* **31**(9), 1623-1642.
Constantinou, M. C. and Symans, M.D. (1992), "Experimental and Analytical Investigation of Seismic Response of Structures with Supplemental Fluid Viscous Dampers." *Tech. Rep.*, nceer-92-0032.
Hou, C.Y. (2008), "Fluid Dynamics and Behavior of Nonlinear Viscous Fluid Dampers." *J. Struct. Eng.,* **134**(1), 56-63.
Zhang, R.H., Soong, T.T. and Mahmoodi, P. (1996), "Seismic response of steel frame structures with added viscoelastic dampers." *Earthq. Eng. Struct. Dyn.,* **18**(3), 389-396.
Shukla, A.K. and Datta, T.K. (1999), "Optimal Use of Viscoelastic Dampers in Building Frames for Seismic Force." *J. Struct. Eng.,* **125**(4), 401-409.
Kim, J., Ryu, J. and Chung, L. (2006), "Seismic performance of structures connected by viscoelastic dampers." *Eng. Struct.,* **28**(2), 183-195.
Park, J.H., Kim, J. and Min, K.W. (2010), "Optimal design of added viscoelastic dampers and supporting braces." *Earthq. Eng. Struct. Dyn.,* **33**(4), 465-484.
Kasparek, M. (2014), "Glass window vibrations analysis used for positioning of piezoelectric damping elements." *Control Conference. IEEE*.
Bagaev, A.S., Vasilieva, I.E. and Gerasimenko, V.G., et al. (2004), "Damping of Window Glass Vibrations Caused by Speech Signals Circulating in the Room." *Telecommun. Radio Eng.,* **62**(10), 903-909.
Haluk, S., Girija, C.V. and Vallabhan. (1997), "Behaviour of window glass panels during earthquake." *Eng. Struct.,* **19**(8),685-694.
Rainer, J.H. (1982), "Effect of Vibrations on Historic Buildings: An Overview." *Bul. Assoc. Preserv. Tech.,* **14**(1), 2-10.
Behr, R.A., Karson, M.J. and Minor, J.E. (1991), "Reliability analysis of window glass failure pressure data." *Struct. Safe.,* **11**(1), 43-58.
Class, J.B. and Chu, S.G. (2003), "The viscoelastic properties of rubber–resin blends. I. The effect of resin structure." *J. Appl. Poly. Sc.,* **30**(2), 805-814.
Miehe, C. and Göktepe, S. (2005), "A micro–macro approach to rubber-like materials. Part II: The micro-sphere model of finite rubber viscoelasticity." *J. Mech. Phys. Sol.,* **53**(10), 2231-2258.
Class, J.B. and Chu, S.G. (1985), "The viscoelastic properties of rubber–resin blends. III. The effect of resin concentration." *J. Appl. Poly. Sci.,* **30**(2), 825-842.