VIBRATION MITIGATION AND CONTROL OF 15 STORIED RC BUILDING VIA ACTIVE CONTROL

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ABSTRACT

The civil structures are getting slender in vertical direction over the last few decades in order to meet the need of the modern cities. Typically, those structures are often used as symbolic status of the national pride in addition to the conventional purposes. However, tall structures are prone to extreme vibration such as earthquakes. Hence it is essential to provide especial safety measure to those structures, for instance, appropriate vibration mitigation solution. The seismic hazard is a worldwide challenge, hence, in order to solve the aforementioned problem many attempts have been made over the last several decades. In this study, a reinforced building is considered to address the associated problems related to vibration mitigation. And mostly, the structures in Bangladesh are not properly designed for dynamic loads such as earthquake. Herein nonlinear dynamic analysis is performed of a 15 storied reinforced concrete building studied and performances are evaluated. It is assumed that three dampers will be placed into the building at different floors level. To do this end, an advanced modelling technique known as state space modelling is adopted. And the linear-quadratic regulator (LQR) is employed as control law. The concept of active control is adopted and numerical simulations are performed via MATLAB/SIMULINK®.

Keywords: Earthquakes; reinforced concrete buildings; nonlinear dynamic analysis; state space modeling; linear-quadratic regulator

INTRODUCTION

Modern cities around the globe are having skyscrapers due to several reasons such as to build a city inside city to save more space, to make an icon of the country, etc. Those structures incredibly prone to dynamic loads such as earthquake. The aforementioned problem is driving the engineers and scientist to find better solution for its survival by keeping the structures in safe condition. Even though, the skyscrapers are capable of solving mass accommodation problem but they cost millions. Therefore, it is essential to make those structures structurally sound by providing better technological solution. Typically, all most all of the civil structures are prone to extreme vibrations, in particular, modern structures i.e., slender/tall buildings, bridges are critical in terms of vibration mitigation. There are several alternatives available and broadly can be categories as follows; (i) passive control, (ii) active control and (iii) hybrid control. The performances may vary significantly depending on the selection of the control technology mentioned before. For instance, passive control devices are safe and reliable but these technologies are not capable of tuning in real-time. In order to avoid the aforementioned drawbacks, the active control technology has been successfully used in many structures (Dyke 1996; Preumont, 2004) as an alternative. A detail study has been performed by (Preumont, 2004) where the advantages of adopting active control as a tool for extreme vibration mitigation is reported. However, the semi-active control devices such as magnetorheological (MR) damper a particular type of hybrid control e.g. semi-active control can be used an alternative of active and passive control systems (Bhowmik, 2011; Dyke, 1996; Miah et al., 2015). There are different types of semi-active control devices and the behavior modelling of a very specific type of MR damper is studied by (Bhowmik, 2011). The possibility of implementation of a rotational type MR damper in combination with real-time model updating is studied in (Miah et al., 2015 and 2016). In order to adopt active or semi-active control scheme a control algorithm is essential. Hence, herein a simple but optimal control algorithm so called the linear-quadratic regulator (LQR) is employed. The efficacy of the LQR scheme has been verified by several researchers (Anderson and Moore, 1989; Mobaieen, et al. 2012; Miah et al., 2015; Weber and Maślanka, 2012).

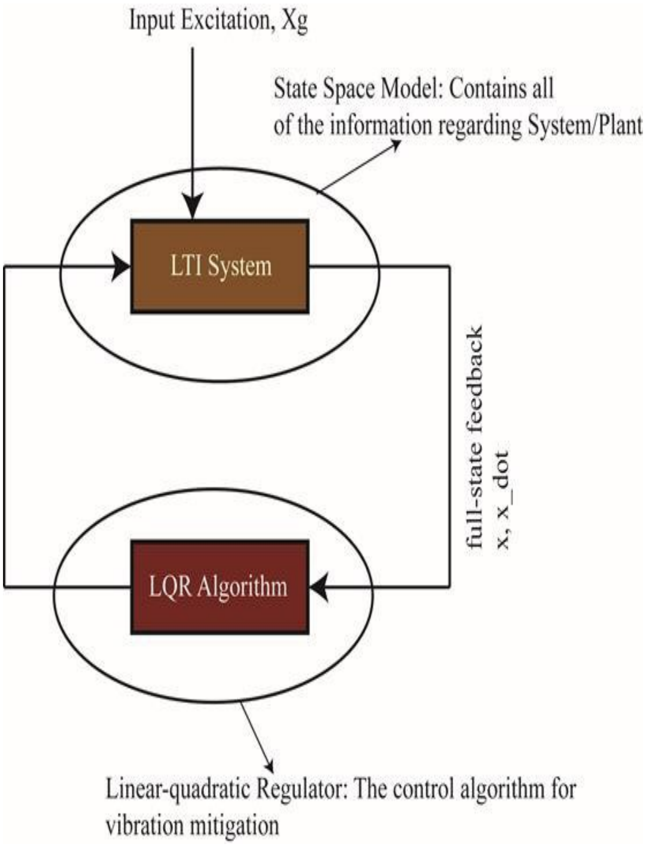

Fig. 1. Implemented control in closed-loop form.

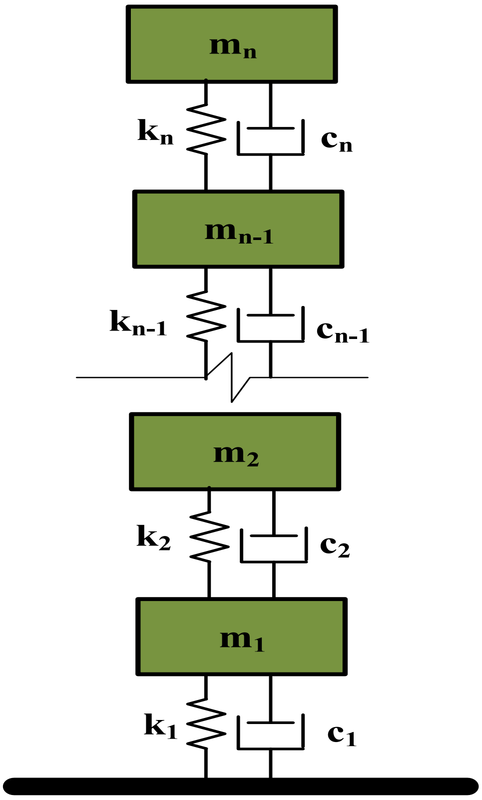

Fig. 2. The mass-spring-damper model of the 15-DOF system

Over the last few decades, due to the economic growth and the scarcity of the land has encouraged to build tall structures and it is taking serious attention all over in Bangladesh. However, the use of vibration mitigation technology is very limited in Bangladesh. Even, it is rarely that the designers are taking proper design measures for extreme dynamic loads due to several reasons; (i) project cost, (ii) lack of expertise especially in the area of vibration mitigation and control, (iii) lack of knowledge regarding nonlinear dynamic analysis and so on. Typically, the equivalent static analysis (ESA) or response spectrum analyses (RSA) are done for seismic/lateral loads analyses. The main focuses herein are to reduce the vibration of structures under seismic/dynamic loads. To do this end, the state space modelling (SSM) technique is used and linear-quadratic regulator (LQR) is employed as control law. A 15 storied reinforced concrete (RC) building frame is considered for the investigations and the response of the system is evaluated under dynamic loads.

METHODOLOGY

Problem Statement

It is mentioned in the previous section that, in this work, a sample 15 storied RC building is considered for the numerical implementations and the mass-spring-damper model is depicted in [Fig. 2]. The foregoing structure is simplified by 15 degree of freedoms (DOF) to avoid modeling complexity. Additionally, the system is presumed to be linear time-invariant (LTI) system. In order to avoid the modelling complicacy, the SSM formulation is adopted presented by Eq. (1-2). And the numerical simulations are performed via the use of MATLAB/SUMILINK®. The control loop is presented by block diagram in [Fig. 1]. The structure is subjected to dynamic loads (harmonic type excitation) as shown in [Fig. 1] by Xg. The structure is then coupled with the LQR control law where active control mechanism is employed. The aim of the control is to impose more supplementary damping to the system. The structure is assumed to be underdamped for all of the modes. There are two major equations for the SSM, the first equation is known as the system or process equation given by

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (1)$$

$$A = \begin{bmatrix} 0_{n\times n} & I_{n\times n} \\ -(M^{-1}K)_{n\times n} & -(M^{-1}C)_{n\times n} \end{bmatrix}; M = \begin{bmatrix} m_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & m_n \end{bmatrix} \quad (1a)$$

where *A* represents the system matrix which contains mass, stiffness and damping information of the structure, *B* is the input matrix that contains both exogenous excitation and control force, $\dot{x}$ is the time derivate of the state vector *x*, state vector *x* contains displacement and velocity vector of the system, *u* is the input vector, *t* is the time vector and *n* represents the number of floors. The process equation Eq.(1) requires an accompanied equation known as the measurement equation

$$y(t) = Cx(t) + Du(t) \qquad (2)$$

where C indicates the output matrix, herein all of the displacement, velocity and accelerations are observed and D represents the feed-forward matrix. The structure is assumed to have each floor weight of 50000 Kg and the stiffness of 70x10^6 N/m. The simulations are performed for 100 seconds with a sampling frequency of 500 Hz. The excitation force is applied at the first resonant frequency of the structure for the evaluation of the extreme loading case. In order to see the after load effect, the excitation was turned off after 66.67sec. And the simulations are performed for the following cases; (i) only one damper is placed at 1st floor level, (ii) two dampers are placed at 1st and 15th floor level, (iii) three dampers are placed at 1st, 5th and 15th floor level of the structure. In a nutshell, the system matrices are assumed to be in a simplified form e.g. diagonal matrix.

The Linear-Quadratic Regulator (LQR)

The linear-quadratic regulator is considered to be one of the most widely accepted full-state feedback optimal control algorithm. The simplicity and robust performance of the LQR attracts researchers and control engineers to use it for vibration mitigation and control applications. However, a serious drawback of this scheme is that all of the floors displacement and velocity information are needed which is quite difficult to get. Hence in order to maximize the performance by minimizing the cost a limited sensor information is commonly used which is known as the linear-quadratic Gaussian (LQG). The LQG is a combination of the LQR and linear Kalman filter. Herein, it is assumed that the sensors are available in all of the floors and the following cost function *J* is minimized reclusively for every time-step

$$J = \sum_{n=0}^{N}(x_n^T Q x_n + u_n^T Q u_n) \qquad (3)$$

The first part of the above equation ($x_n^T Q x_n$) represents the contribution of the system response (e.g. displacement and velocity) and the second part ($u_n^T Q u_n$) means the controller contribution. Typically, it is always expected that in order to get the most out of the controller more weight needs to be placed on the first part of the equation in comparison to the second part. The weighting factors are controlled by the parameters *Q* and *R*. Interested reader may obtain more detail about the LQR algorithm and its applications via the following articles (Anderson and Moore, 1989; Mobaieen, et al. 2012; Miah et al., 2015; Weber and Maślanka, 2012).

RESULTS AND DISCUSSIONS

The simulations are performed in a nearly real-time platform so-called SIMULINK®. In order to perform analyses, the 15-DOF system has bring into a formulation known as the SSM. Additionally, the weighting parameters *Q* and *R* of the LQR control algorithm is adjusted for the vibration mitigation of the structure. It is mentioned earlier that the simulation of the 15 storied RC building is connected with dampers at different floor levels of the structure. In Addition to the SIMULINK®, MATLAB® 2012a package is also used for numerical implementations. The results of different floors level are compared. Firstly, the displacement and velocity response of 1st floor in [Fig.3-4]. And the response of the 15th floor level is compared for different damper combinations in [Fig.5-6]. For the visualization purpose there is a full-time history 0-100 sec and a zoomed vied of 50-60 sec. In the above mentioned figures, the blue line indicates the uncontrolled case (what would happen without any damper), the black line represents the controlled case for the case damper is placed at the first floor level, the green line shows the what would happen when two dampers are used, one at first floor level and the second one is at fifteenth floor level. And the red line represents the three dampers case here three dampers are placed at 1st, 5th and 15th floor levels of the structure. It can be summarized from all of figures that two and three dampers cases are capable of mitigating the response significantly. Even, only one damper may also assist to reduce the vibration quite efficiently. Along with the aforementioned figures the 10th floor's responses e.g. displacement and velocity are compared in [Fig.7-8]. And finally, the controller's hysteretic loops for full-time history are evaluated and stable closed-loop response are observed in [Fig.9-10].

The studied approach is a compact mathematical formulation that makes the whole process faster. Even though, very good results are observed but further investigations are essential for practical implementations. Hence, further study will investigate the performances under different alternatives for the real-time implementations.

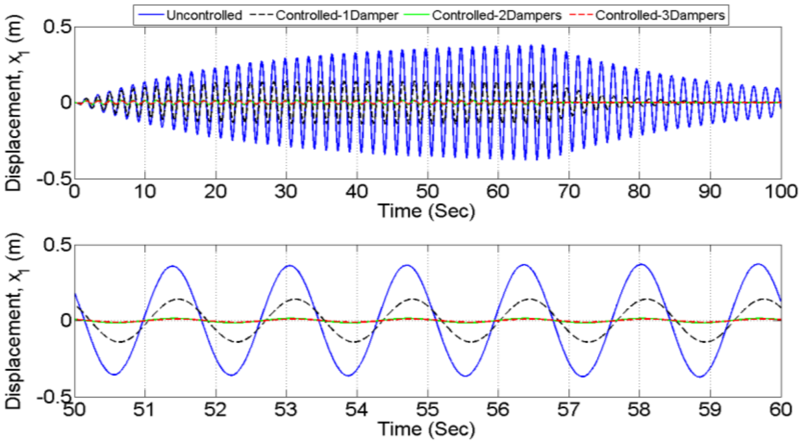

Fig. 3. The comparison of 1st floor displacement uncontrolled versus controlled cases; (a) full time history 0-100sec, (b) zoomed 50-60sec

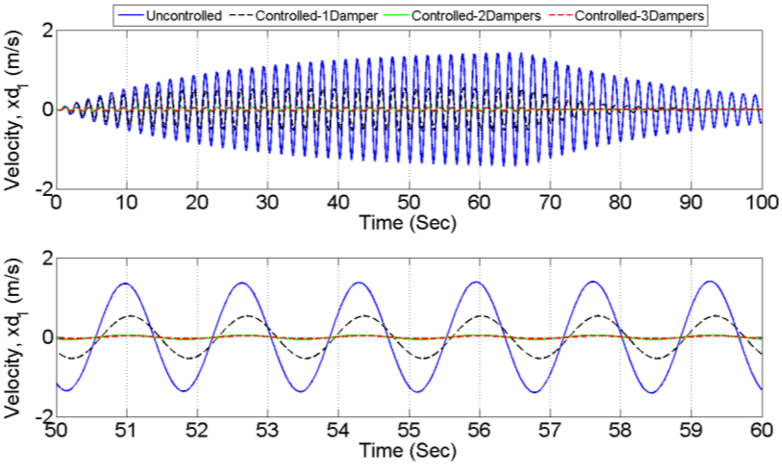

Fig. 4. The comparison of 1st floor velocity uncontrolled versus controlled cases; (a) full time history 0-100sec, (b) zoomed 50-60sec

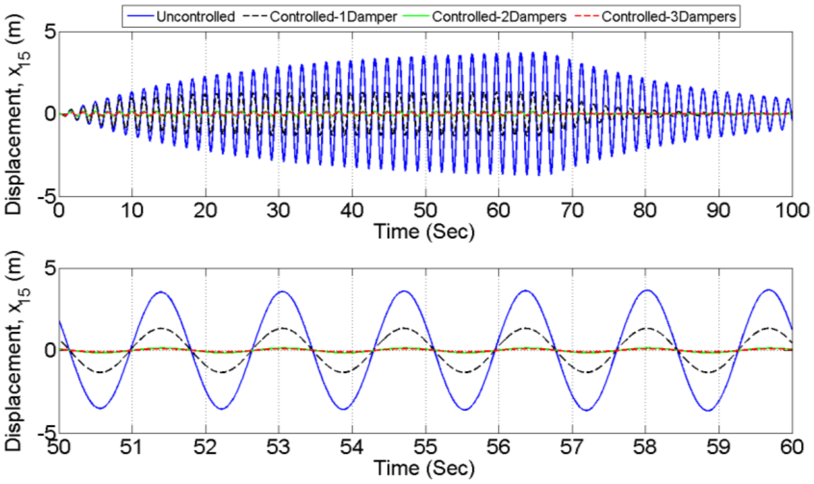

Fig. 5. The comparison of 15th floor displacement uncontrolled versus controlled cases; (a) full time history 0-100sec, (b) zoomed 50-60sec

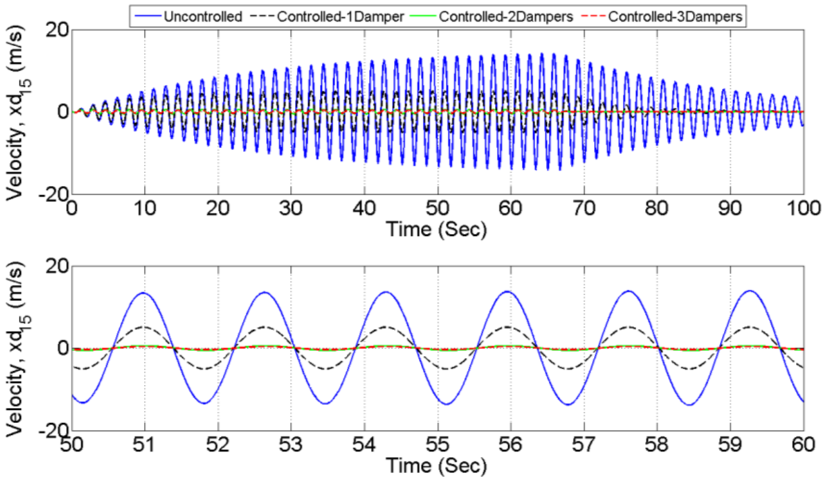

Fig. 6. The comparison of 15th floor velocity uncontrolled versus controlled cases; (a) full time history 0-100sec, (b) zoomed 50-60sec

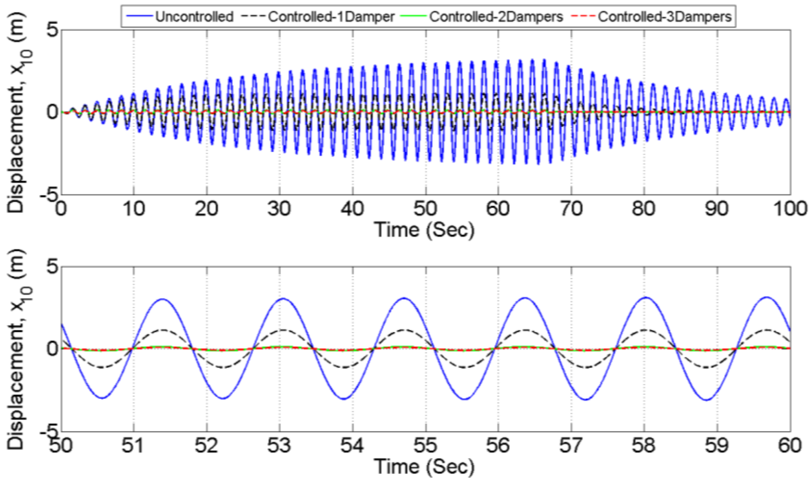

Fig. 7. The comparison of 10th floor displacement uncontrolled versus controlled cases; (a) full time history 0-100sec, (b) zoomed 50-60sec

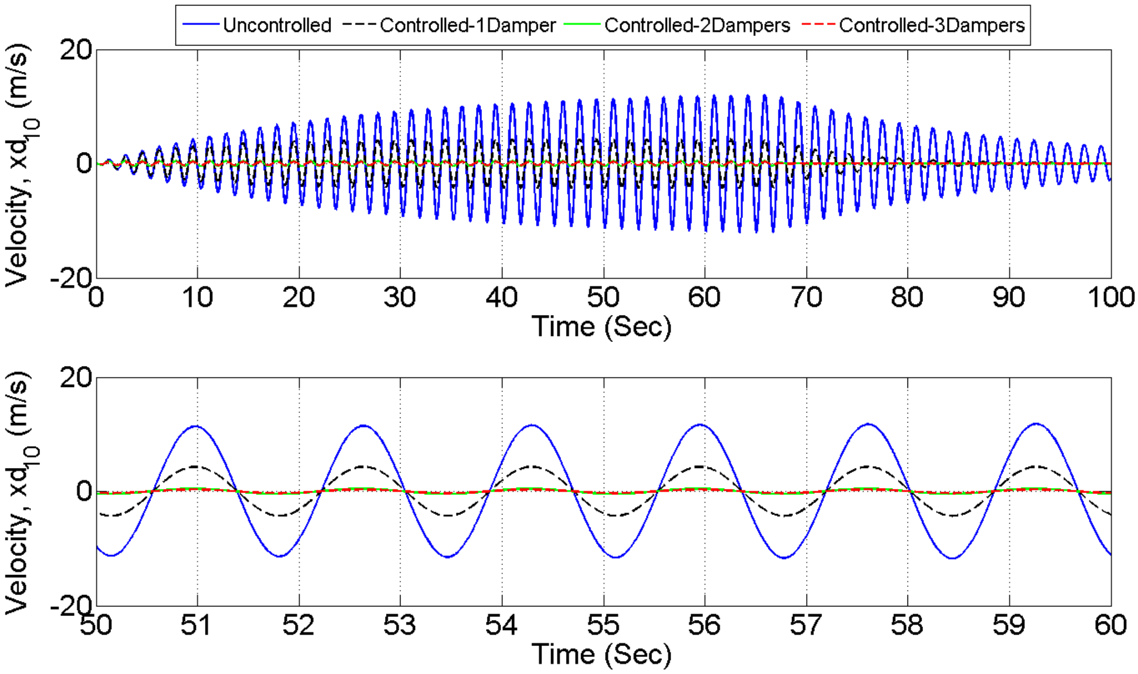

Fig. 8. The comparison of 10th floor velocity uncontrolled versus controlled cases; (a) full time history 0-100sec, (b) zoomed 50-60sec

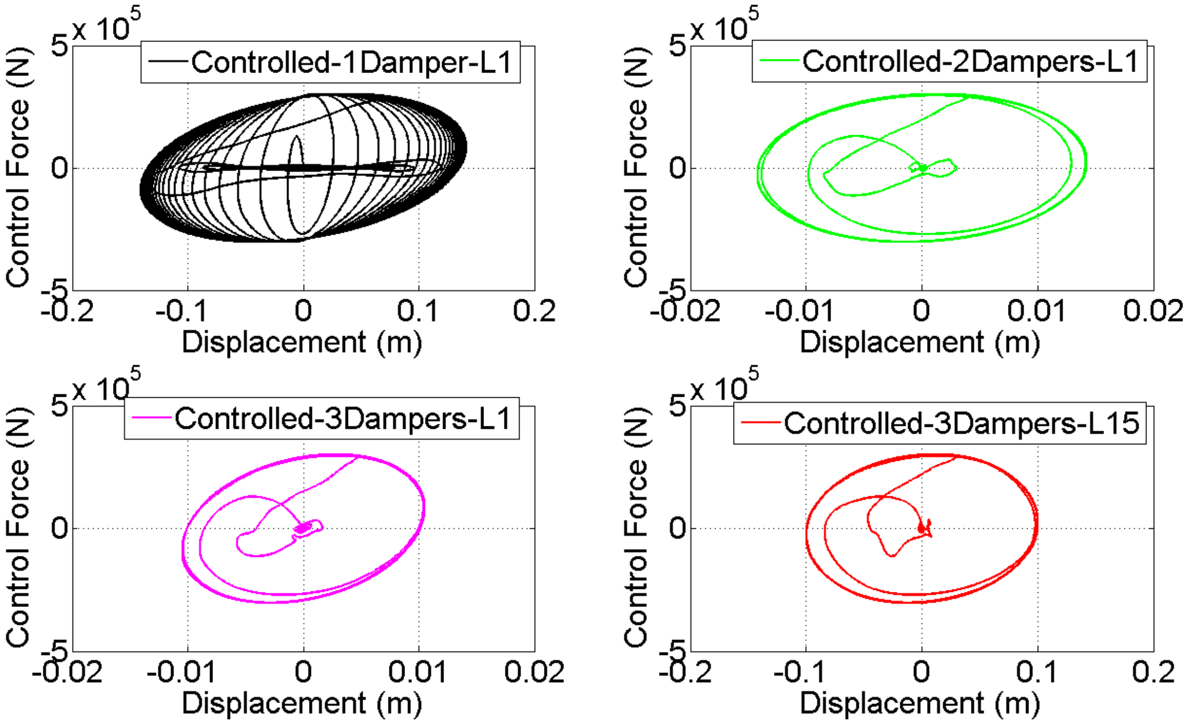

Fig. 9. The control force versus collocated displacement trajectory

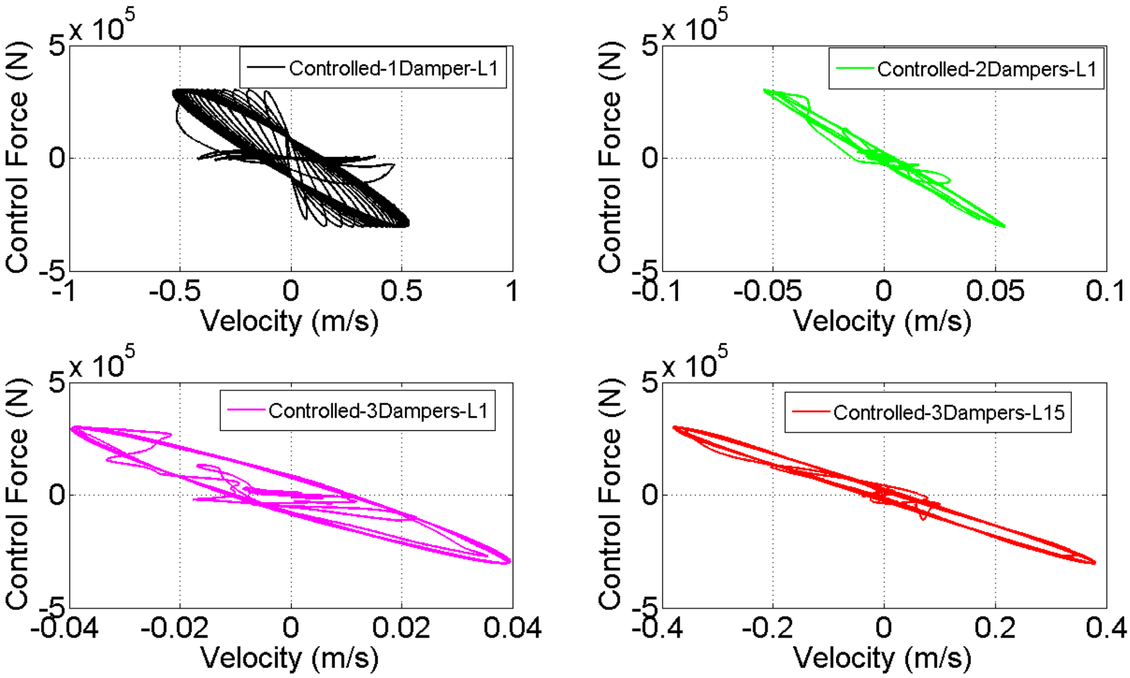

Fig. 10. The control force versus collocated velocity hysteresis

CONCLUSIONS

This paper addresses the vibration mitigation and control problem which is quite crucial in the area of structural engineering in general. The aforementioned problem even more serious issue in Bangladesh due to the lack of proper analysis and design for dynamic loads as well as vibration mitigation and control. Hence keeping the above mentioned issues in mind herein a 15 storied RC building is studied and active control is employed for vibration mitigation. The goal is achieved by combining the system with the LQR scheme. And all of the floors information are assumed to be measured and feed into the controller in order to produce the active control force. The overall outcome of the work shows that a significant reduction of structural vibration is possible. The choice of the number of dampers and their locations may have a significant impact on overall performance of the structure in terms of vibration mitigation. Designer may choose the option according to his/her project needs. Herein a full-state feedback type control scheme has been deployed, however, in future a more realistic scenario i.e., limited sensors scenario will be investigated.

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