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A Novel Algorithm for Effective Vibration Control of Portal Frames

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Abstract. Severe vibrations such as earthquakes threaten to demolish or cause damage to built structures during their lifetime. Mitigation of such damage can be done by using control devices such as actuators. In this paper, an algorithm is proposed to analyze the nonlinear behavior of a portal frame supported by an actuator. The results were compared with those for a frame without actuator. The algorithm was developed in accordance with the Timoshenko beam element theory. ANSYS verified the results for the cases of a frame supported by a damper element and a frame without actuator. The results support the efficiency of the algorithm in reducing frame vibration and top-node displacement.

Keywords: *Earthquake; FAM; LQR; Timoshenko; vibration control.*

1 Introduction

Smart structures are intelligent machines that can sense environmental dynamic loading and change the characteristics of the environment to withstand extra loading because of earthquake excitation for example [1,2]. As a result of the expansion of structural control techniques over the last few decades, the interest in this field has boomed.

Numerous researches have been conducted on reducing structural vibration through classical systems such as shear walls or bracing systems against severe vibrations or loading [3]. The time line of optimal structural control is rooted in 1985, when large flexible and space structures subjected to dynamic load were optimally controlled for the first time [4]. Yang, *et al.* developed a prompt hybrid algorithm for slashing the structural response to severe earthquakes. Unlike previous methods, their algorithm determines the control vector directly from the measured response. The algorithm can be used in linear and non-linear analysis [5].

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Adeli and Saleh demonstrated a computational model for active control of large structures using distributed actuators subjected to various types of dynamic loading. The generated algorithm was used on a large bridge structure that was furnished with an active control system. Although the results were positive, a critical issue arose for the solution of the complex eigenvalue problem when the number of element grows [6]. To resolve the highlighted bottleneck, Saleh and Adeli then proposed a robust algorithm for the solution of the Riccati equations. The algorithm was applied to three large examples. The results indicated the reliability of the proposed algorithm [7].

Kim and Adeli presented a hybrid feedback controller of structures through the integration of a feedback control algorithm, Linear Quadratic Regulator (LQR), and the LQG algorithm. They applied it to an active tuned mass damper. The results revealed that the proposed algorithm minimized the error and enhanced the inherent stability [8]. Ebrahimnejad, *et al.* designed an LQR for piezoelectric actuators (PEA) in a four-story shear frame. The actuators were assembled on the columns and the MATLAB software application was employed together with the state space method. The results showed that the proposed system was efficient and reliable [9]. Chhabra, *et al.* applied PEA to a cantilever beam in different positions to identify the best control effect. They simulated it in MATLAB and used the Euler-Bernoulli beam theory [10]. The numerical results proved the increased benefit of using actuators in beam controlling. Bitaraf, *et al.* utilized a magnetorheological (MR) damper to optimize the response of a controlled structure. They benefited from a direct-adaptive-control method to control the structural response. A three-story building subjected to various earthquake loads was used to test and evaluate the results of different control methods. The outcomes indicated reliability of the proposed system [11].

Falah and Ebrahimnejad utilized a PEA in a 10-story building and shook it with 20 different excitations to minimize the structural response. They located the actuators at the bottom of the columns. The results of the controlled system in comparison with an uncontrolled one showed high capability of the employment of actuators in structural response reduction [12]. In another effort, Vashist and Chhabra tried to optimally locate the PEA on a thin plate. LQR was utilized to control the effectiveness of the system. They compared the results from their experimental test and with the computed results from the finite element code. The frequency of the response of the experiment was similar to the result from the finite element code [13].

On the other hand, considering the force analogy method (FAM) as an analytical tool for analyzing structures with material nonlinearity is an important issue for simplification of the analysis path. The original concept of

FAM was highlighted by Lin [14], using the concept of 'inelastic displacement', where the nonlinear stiffness force is replaced with the changes in displacement [14-17]. FAM uses the initial stiffness matrices, while nonlinear stiffness matrices are not used in this method. This feature is valuable during the dynamic analysis of a system that enables any algorithm to benefit from the state space theory. Thus, FAM allows the state space theory to be applied to inelastic systems as well as elastic systems [18].

Wong and Yang have reported the first implementation of FAM in a civil environment. The basis of this method for inelastic dynamic analysis is the force-deformation space. Basically, FAM formulates each inelastic deformation as one degree of freedom [19]. Subsequently, Wong and Yang derived a computational method based on FAM to signify the inelastic behavior of a structure and determine the plastic hinges from plastic energy formula [20].

Zhao and Wong benefited from FAM to consider the P-delta effect in the geometric nonlinearity of the dynamic analysis of structures. They used the finite element method to generate the elemental stiffness matrix. Their proposed method can locate and calculate the inelastic response and separate the coupling effect between the geometric and material nonlinearity, during the analysis [21]. The accuracy and efficiency of FAM was also tested on a steel braced system to see if the state space method could be employed in inelastic conditions. In view of this, a braced frame was tested and the results clearly proved the proficiency of the method for this kind of system [22].

Li, *et al.* developed an algorithm that is able to analyze three-dimensional models and detect the biaxial local plastic machinery. The algorithm was generated based on the theory of FAM. The lumped mass and the Euler Bernoulli theory were implicated for FAM. A 3D RC piers bridge was analyzed to simulate its nonlinear shear-flexure interaction behavior and detect the rotation hinges. The efficiency of the system was validated through two tests against a numerical example [23]. To evaluate the efficiency of the algorithm based on FAM, an RC framed structure with full range factor has been considered. The excitation of the frame was raised step by step until the structural members partially failed. The extracted result endorsed the high efficiency and stability of FAM [24].

Most of the studies presented in the literature focus on analyzing the structures with lumped mass and employed the Euler Bernoulli beam theory for generation of their stiffness matrices. The current study developed an algorithm based on the Timoshenko beam element and benefits from the distributed mass.

2 Optimization Parameters of the Algorithm

Eq. (1) illustrates the main equation of motion for structures furnished with a control system.

$$M\ddot{x} + C\dot{x} + Kx = F_e + F_c \tag{1}$$

where M, C and K represent the mass, damping and stiffness of the system, respectively. $\ddot{x}$, $\dot{x}$ and x are the displacement, velocity and acceleration matrices of the system, respectively. F_e is the external force imposed on the system and F_c is its control force. In this study, the control force (F_c) was designed to optimize the vibration of the system, which in this study was a portal frame.

2.1 Force Analogy Method (FAM)

FAM is focused on the changes in displacement of the inelastic structural response, while other methods emphasize the variations of stiffness. In this method, the total displacement can be determined with Eq. (2).

$$X = X' + X'' \tag{2}$$

where X represents the total displacement, X', and X'' denote the elastic displacement and inelastic displacement vectors, respectively. Furthermore, due to determination of the plastic hinges in the system, calculation of the total moment based on Eq. (3) is required.

$$M = M' + M'' \tag{3}$$

where M represent the total moment, M' and M'' denote the elastic moment and residual moment vectors, respectively. The procedure of calculation of the residual moment is known as FAM, which replaces the plastic rotation vector θ'' with a fictitious force to generate a structure with compatible deformations. Figure 1 illustrates the FAM procedure and Eqs. (4) to (5) show the required restoring force and moment for the system.

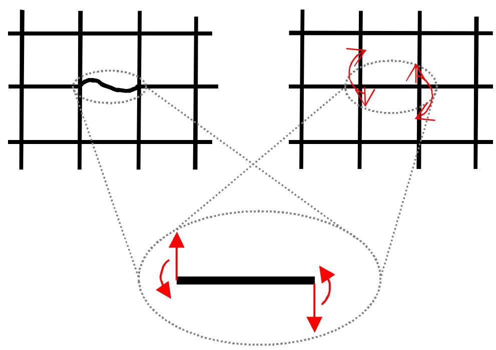


Figure 1 FAM procedure.

$$F_{RF} = -K_P\theta'' \tag{4}$$

$$M_{RF} = -K_R\theta'' \tag{5}$$

where K_P and K_R are the member force recovery and the restoring force matrix, respectively. The restoring forces can be written in equilibrium of the structure, as shown in Eq. (6).

$$X'' = K^{-1}K_p\theta'' \tag{6}$$

where K is the structural stiffness matrix.

2.2 State Space Solution

Eq. (1) represents a system of second-order linear deferential equations (LDE). Implementation of the state space method will change it from a second-order to a first-order LDE, which is much simpler to integrate and more accurate. Eq. (7) represents the first-order LDE of motion based on the state space method.

$$\dot{z}(t) = Az(t) + Ha(t) + F_p^c X''(t) + F(t) + Bf_c(t) \tag{7}$$

In this equation, *D* is the actuator distribution force matrix, *a* is the ground acceleration and

$z(t) = \begin{Bmatrix} x(t) \\ \dot{x}(t) \end{Bmatrix}$, $A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}$,$H = \begin{bmatrix} 0 \\ -1 \end{bmatrix}$,$F_P^c = \begin{bmatrix} 0 \\ -M^{-1}K \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ -M^{-1}D \end{bmatrix}$

2.3 Controller

To obtain the feedback gain matrix, a linear quadratic regulator (LQR) is employed. Eq. (8) shows the generated cost function for the controller [25].

$$J = \int_0^{t_c} \frac{1}{2}[z^T(t)Qz(t) + f_c^T(t)Rf_c(t)]dt \tag{8}$$

where *Q* and *R*, are symmetrically positive and known as the state weighting matrix and control weighting matrix, respectively. Increasing the value of *Q* results in prompt vibration suppression, and accumulating the value of *R* leads to more energy consumption. The t_c value is the duration over cost function. Defining the Lagrangian and Hamiltonian function for the proposed cost function is required for the minimization process. This leads to an actuator force over time *t*.

$$\lambda(t) = P(t)z(t) \tag{9}$$

$$f_{ct} = -R^{-1}G^T\lambda_{t+1} \tag{10}$$

where $\lambda(t)$ is the Lagrangian multiplier over time *t*.

A discrete algebraic Riccati equation is required to resolve P, as shown in Eq. (11) [26,27].

$$P_t z_t = Q z_t + F_s^T P_{t+1}(I + GR^{-1}G^T P_{t+1})^{-1} F_s z_t \tag{11}$$

The combination of Eqs. (9) to (11) will be ended by discovering the actuator force over time $t+1$, as shown in Eq. (12) and of Z over time $t + 1$, as illustrated in Eqs. (13) and (14).

$$f_{ct+1} = -G^T PG + R^{-1}G^T PF_s z_t \tag{12}$$

$$F_f = [I + GR^{-1}G^T P]^{-1} F_s \tag{13}$$

$$Z_{t+1} = F_f z_t + H_d^{EQ} a_t + F_P X_t^{"} \tag{14}$$

Therefore, the actuator requires the force, displacement, and velocity, so the acceleration of the system can be determined for the vibration optimization process.

2.4 Analyzing Procedure

As mentioned before, this study focused on the minimization of frame vibration, which requires computational programming. This paper proposes a new robust algorithm to calculate the nonlinear behavior of the structure and reduce it through implementation of an actuator by following Hooke's law. A brief explanation of the computational process of the employed algorithm in this study is shown in the following steps and summarized in Figure 2.

Step 1: Generate the required dynamic variable.

Finite element method is used for this algorithm. The mass of the system is generated based on the distributed mass theory, and for the stiffness of the system the Timoshenko beam theory is used in order to observe the shear effect in the algorithm precisely. To calculate the damping matrix, the Rayleigh method is used. Generation of the required matrices for FAM occurs in this step.

Step 2: Generate the required matrices for the state space method. This step requires the generation of an actuator distribution matrix.

Step 3: Set up the controller weighting matrix.

Several values of Q are tested and R is generated as below.

$$Q = \begin{bmatrix} I & 0 \\ 0 & \alpha I \end{bmatrix}, R = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}$$

Step 4: Capture the ground vibration.

Step 5: Calculate the response, such as displacement, velocity, and acceleration with the state space method.

Step 6: Check the displacement to determine the nonlinearity. If nonlinearity is identified, the inelastic displacement will be calculated for the next loop.
Step 7: Record the data and plot the results.

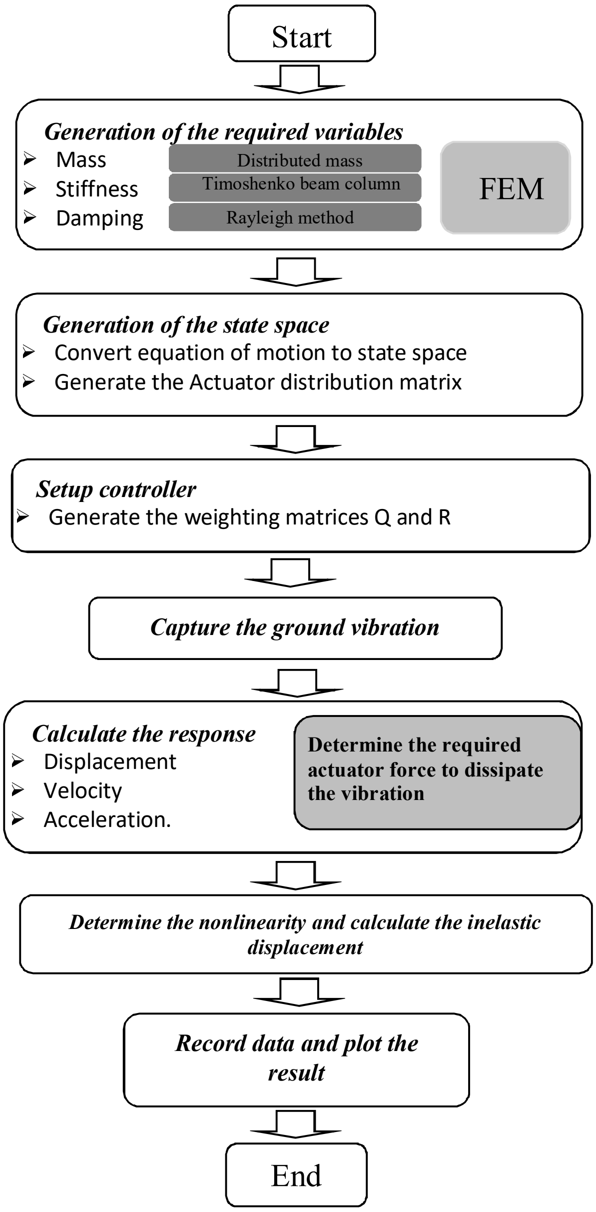
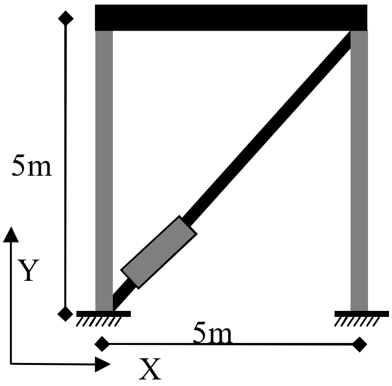


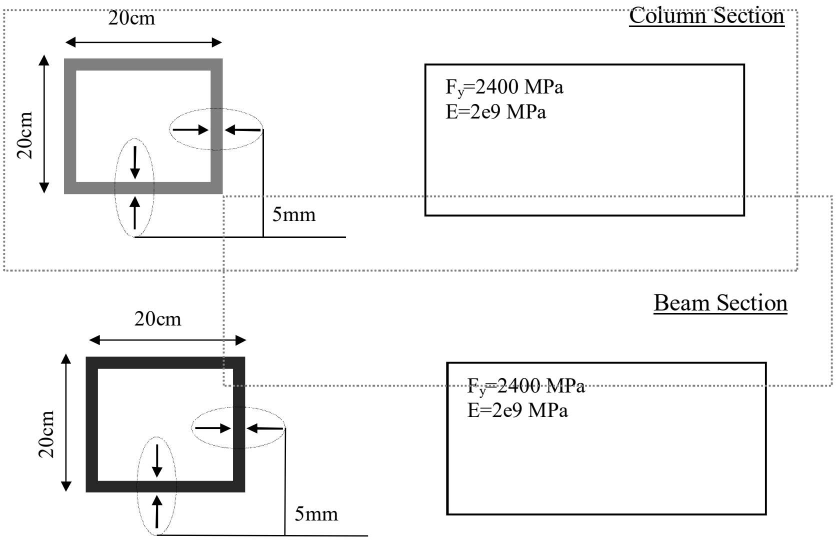
Figure 2 Flowchart of the proposed algorithm.

3 Application to a Portal Frame

The proposed algorithm was applied to a two-dimensional frame, illustrated in Figure 3(a), to control the vibration. Figure 3(b) shows the utilized columns and beam section properties.



(a) Portal frame model



(b) Column and beam section details

Figure 3 Steel portal frame model illustrating beam and column section properties.

The portal frame was subjected to ground vibration exhibited by the El-Centro East-West direction earthquake (USA, 1940) as shown in Figure 4. As the ground starts to shake, the algorithm determines the structural response for time $t + \Delta t$ and imposes the same force in the opposite direction to dissipate the external executed force. Meanwhile, the algorithm checks the displacement to determine the nonlinearity. If nonlinearity occurs, then the inelastic displacement will be calculated and considered by the algorithm.

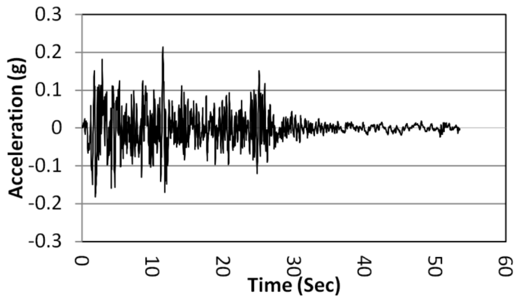


Figure 4 Earthquake record of the east-west component of the El-Centro earthquake (USA, 1940).

4 Results and discussion

The results of the proposed system required a benchmarking system for validation. For this purpose, a bare frame system was modeled with the ANSYS mechanical software application and subjected to the El-Centro earthquake. The top-node displacement of this system was recorded in the X and Y directions. In the next step, the same system was equipped with a damper device. A significant attenuation of displacement in both the X and Y direction can be seen in Figures 5 and 6, respectively. Comparing these two systems revealed 72.87% reduction for the maximum top-node displacement of the system furnished with a damper device, i.e. from 16.7 mm to 4.53 mm, in the X direction.

The maximum displacement reduction in the Y direction for these two systems was 66.67%, which is a considerable amount. The displacement reduction in the frame with damper device directly scaled down the probability of forming plastic hinges in the members of the frame. The frames analyzed by ANSYS mechanical in this study represent the analysis based on the Euler-Bernoulli element. This study aimed to replace the Euler-Bernoulli element by the Timoshenko element in FAM when analyzing the frame with controller. To pursue this aim, the algorithm written in MATLAB analyzed the same bare frame equipped with an actuator instead of a damper device.

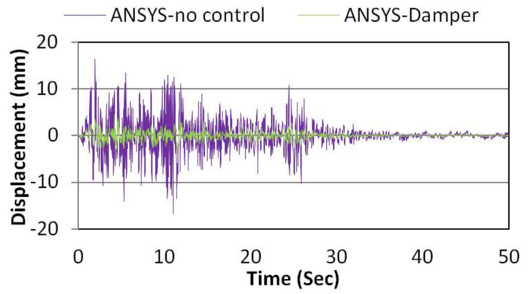


Figure 5 ANSYS comparison in the X direction.

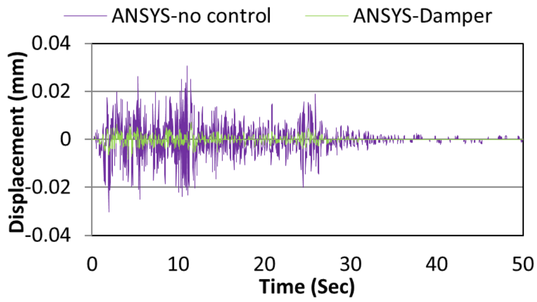


Figure 6 ANSYS comparison in the Y direction.

The top-node displacement time history of the system in the X and Y directions is shown in Figures 7 and 8, respectively. As expected, the displacement in the controlled system dramatically declined by 92.28% in the X direction. The non-controlled system faced high amplitude of fluctuation during the first 10 seconds, which greatly increased the stress, on the columns especially. Because in this study actuator saturation was not applied, there was no limit to the magnitude of the applied force to attenuate the displacement of the system. This let the authors numerically use the maximum capacity of the actuator and decrease the maximum top-node displacement in the X and Y directions to 1.76 mm and 1.18 mm, respectively.

The displacement of the controlled system in the Y direction in comparison with the frame with damper device, unfortunately, increased. This was due to the diagonal installation of the actuator in the frame. When the actuator is installed at 45°, the y-component of the actuator force slightly increases the displacement of the system in comparison with the system with damper device. Although in the proposed system the displacement in the Y direction increased, this increase was not very effective in terms of structural response.

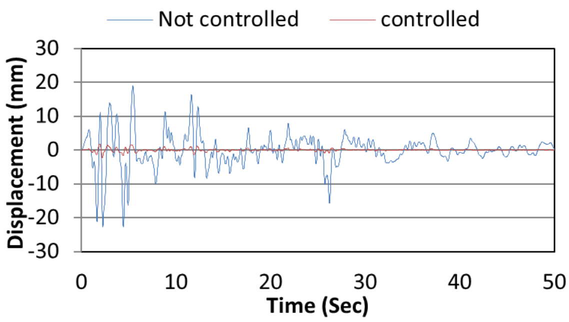


Figure 7 Displacement in the X direction.

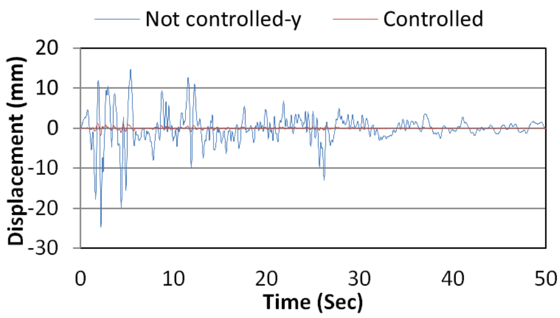


Figure 8 Displacement in the Y direction.

The actuator was diagonally connected the top right node of the frame to the bottom right and imposed compression and tension forces in an interval of 0.02 seconds. The applied force time history is shown in Figure 9. As expected, for the non-saturated actuator, the applied force time history follows the same pattern as the displacement time history record, except for the magnitude. The maximum imposed compression force recorded was 9 kN, while the maximum tension force recorded was 5.68 kN.

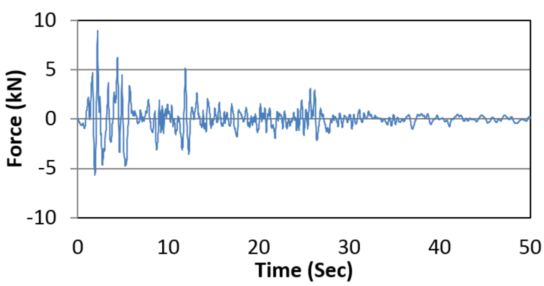


Figure 9 Force applied by the actuator.

The time history displacement of the controlled and not-controlled frame based on the proposed algorithm along with the results of the bare frame and the frame with damper device were analyzed with the ANSYS software application, as illustrated in Figure 10. The differences between the results of the proposed algorithm and ANSYS for the frames with no control system are due to the number of degrees of freedom, i.e. 3 (DOF) in the proposed algorithm and 6 (DOF) in ANSYS, condensing the stiffness and mass matrices and the applied assumptions in the analysis. However, the recorded maximum amplitudes of these systems were quite close to each other. Both damper device and actuator system significantly attenuated the X-direction displacement. This reduction was especially obvious in the first five seconds and at the 25th second of the time history record, which were the most violent periods in this study.

The results of the frame analyzed by the proposed algorithm are summarized in Table 1. More than 90% reduction was achieved in each direction, which is proof of the numerical efficiency of the algorithm. To continue this study, it is recommended to apply the saturation effect of the actuators and multiple node definitions on each frame.

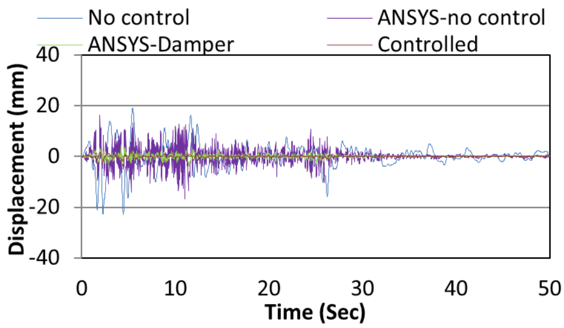


Figure 10 Comparison between the systems in the X direction.

Table 1 Summarized results of the algorithm.

	Not Controlled	Controlled	Difference
X direction	22.8mm	1.76 mm	92.28%
Y direction	24.6 mm	1.18 mm	95.2%

5 Conclusion

In this study, a robust algorithm was developed to increase the performance of portal frames that are subjected to ground vibration. The state space method along with the force analogy method were employed to determine the structural response and required actuator force. The algorithm was designed to determine the nonlinearity of the structure by using Hook's law. The generated algorithm was applied to a two-dimensional portal steel frame that was subjected to ground vibration. The results revealed that the controller reduced the top-node displacement of the frame by 92.28% in the X direction and by 95.2% in the Y direction. In comparison with a viscous damper, the displacement in the X direction was reduced by 61.14%, while in the Y direction the viscose damper performed better. These results and the comparison, as discussed above, designate that the algorithm is efficient and reliable to employ on frames.

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