

# Vibration Control of Two Adjacent Structures Using a Non-Linear Damping System

Soltani Amir, Wang Xuan

**Abstract**—The advantage of using non-linear passive damping system in vibration control of two adjacent structures is investigated under their base excitation. The base excitation is El Centro earthquake record acceleration. The damping system is considered as an optimum and effective non-linear viscous damper that is connected between two adjacent structures. A MATLAB program is developed to produce the stiffness and damping matrices and to determine a time history analysis of the dynamic motion of the system. One structure is assumed to be flexible while the other has a rule as laterally supporting structure with rigid frames. The response of the structure has been calculated and the non-linear damping coefficient is determined using optimum LQR algorithm in an optimum vibration control system. The non-linear parameter of damping system is estimated and it has shown a significant advantage of application of this system device for vibration control of two adjacent tall building.

**Keywords**—Structural Control, Active and passive damping, Vibration control, Seismic isolation.

## I. INTRODUCTION

IN early 1990s, considerable attention has been paid to research and development of structural control devices, and medium and high rise structures have begun implementing energy dissipation devices or control system to reduce excessive structural vibrations [1].

The coupling of two adjacent structures with suitable mechanisms is a developing method among the various control techniques. The concept is to exert control forces upon one another to reduce the overall responses of the system. The free space available between two adjacent structures can be effectively utilized for placing the control devices and does not require additional space for the installation of such devices [1]. Such type of arrangement is also prevent the mutual pounding between two adjacent structures, occurred in the past major seismic events such as 1985 Mexico City earthquake [2], the 1989 Loma Prieta earthquake [3] and many others.

Past studies found the passive energy dissipation devices to be very effective in mitigating the dynamic responses of adjacent coupled structures as well as minimizing the chances of pounding. Control devices and specially dampers have proved to reduce the response of building efficiently in high rise buildings since these control devices can effectively dissipate the energy over the long periods of oscillation [4]-[10].

One of the best system devices for the dissipation of transferred energy to structures in various external excitations is viscous dampers. The straightforward design is achieved with a classical dashpot, when dissipation occurs by converting kinetic energy to heat as a stroke moves and deforms a thick, highly viscous fluid. The relative movement of a damper stroke to the damper housing drives the viscous damper fluid back and forth through an orifice. Energy is dissipated by the friction between the fluid and the orifice. This kind of damper can provide motion and energy dissipation in all six degrees of freedom as vibration in any direction can shake the viscous fluid [10].

It should be noted that, in seismic application, a passive control system with a constant damping coefficient is not very efficient to control a system response where there is uncertainty in response contents (maximum acceleration and frequency contents) [11]. However, the parameter of optimum damping coefficient in cannot be easily obtained by a simple calculation. Therefore, the theory of control system with linear quadratic regulation (LQR) algorithm has been used to determine the performance of an optimal damping system in vibration control of a system structure. The fundamental of this theory is satisfying all the concepts and assumptions in civil structures [14]-[17]. Recently, this method was used by Gluck and Reinhorn to find the best location of dampers in a multi-story structure and to specify their damping coefficient [12], [13].

## II. VERTICAL ISOLATION WITH A VARIABLE DAMPING SYSTEM

Fig. 1 presents a specific type of architecture called vertical isolation where a more flexible structure (left side) is connected to a more laterally stiffer (rigid) structure (right side). In this architecture the rigid structure is used for bearing the dampers reflections and to control the displacement of the other structure. In this model, the lateral force between two adjacent buildings which is transferred through the control damping device is limited to a value due to the material properties and limited connection capacity.

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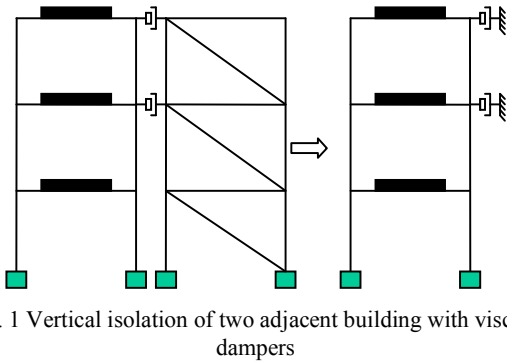


Fig. 1 Vertical isolation of two adjacent building with viscous dampers

An active control system that provides an optimum-damping coefficient can be obtained from following equation:

$$f_d(t) = C \cdot u^o \Rightarrow f_d(t)/u^o = C(t) \Rightarrow C = f(u, u^o) \quad (1)$$

where  $f_d(t)$  is the control force and  $C$  is variable optimum-damping coefficient. Also,  $u$  and  $u^o$  are the position and velocity of stroke in the damping device respectively. The optimum characteristics of this system can be determined by optimal LQR control algorithm. Optimal control deals with the problem of finding a control law (damping force) for a given system such that a certain optimality criterion (vibration control) is achieved.

### III. UNITS MODEL MANIFESTATION OF A TEN-STORY-MOMENT-FRAME BUILDING

The control device is considered to be connected to the top of the structure. For a ten-story-moment-frame-building the mass, stiffness and damping matrices of the structure are determined and also it is assumed that these values for each story are the same for simplifying the process.

For each story:

Stiffness (K) = 56267 N/m ,  
 Natural Damping = 500 N.m/s and  
 Seismic Mass (M) = 200,000 N

A MATLAB programming is developed to solve the Lagrangian equation of motion and obtain the response of the ten-story-building [18].

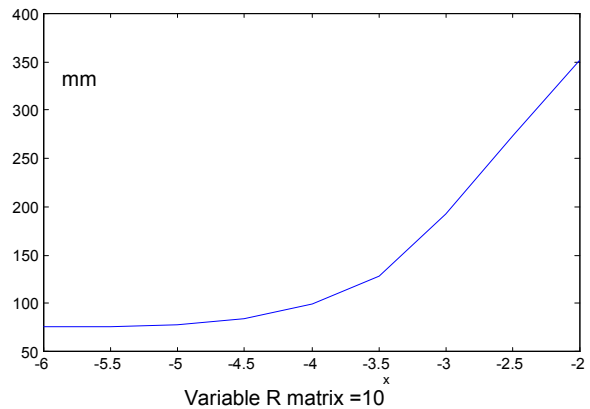
$$J = \int_{t_0}^{t_f} [X^T(t) \cdot Q \cdot X(t) + F^T(t) \cdot R \cdot F(t)] dt \quad (2)$$

In this equation,  $t_0$  and  $t_f$  are the time of the control process which is equivalent to the duration of El Centro earthquake record. Also, in this equation,  $F$  is the control force which represents the damping force. For the optimal LQR performance, the weight matrices of  $Q$  and  $R$  are investigated and selected. Where  $Q$  is the weight for the response of the building and  $R$  is the weight for the control force. The weight matrix  $Q$  is calculated for the optimal performance of the LQR algorithm.

$$Q = \begin{bmatrix} K/100 & 0 \\ 0 & m \times 1.35 \end{bmatrix} \quad (3)$$

Also the  $R$  value is optimized in a way to reduce the maximum lateral displacement of a building with 30 meters height to 150mm. Using MATLAB programming the variation of  $R$  value in respect to lateral displacement is shown in Fig. 2.

According to Fig. 2, to control the maximum displacement of a ten-story-building with 150mm maximum acceptable displacement; the  $R$  value should be equal to  $R = 10^{-3.33}$ . The responses of a ten-story-building with and without control device are shown in Fig. 3.



maximum displacement in structure

Fig. 2 The variation of  $R$  (Weight index of the control force) in respect to lateral displacement

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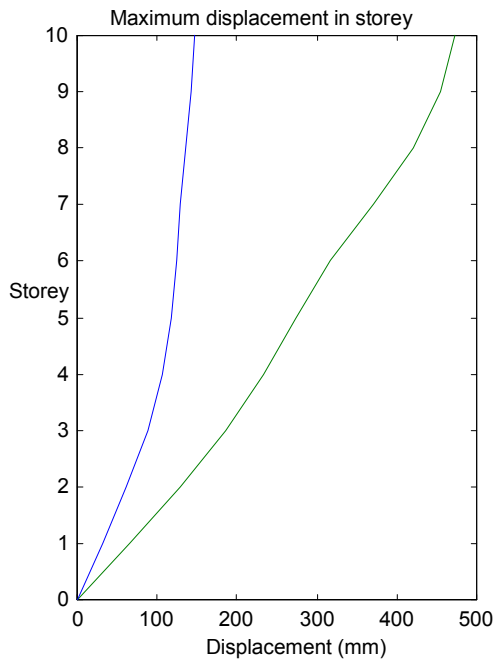


Fig. 3 Response of a ten-story-building during El Centro Earthquake using an active control system

#### IV. NON-LINEAR DAMPING COEFFICIENT

Non-linear damping coefficient changes with time and its value increases or decreases to keep the damping force within the criterion where the internal force is limited while the amount of energy dissipation is maximized. The nature of damping device inevitably applies constraints and the damping coefficient hence needs to satisfy the lower and upper bounds as the following:

$$C_{\min} < C(t) < C_{\max} \quad (4)$$

The characteristics of these dampers are provided by manufacturers as a constant damping coefficient multiplied by stroking velocity exponent.

During the time steps of dynamic equation the active control force and the velocity of the stroke are obtained at each time steps and the results are shown in a graph in Fig. 4.

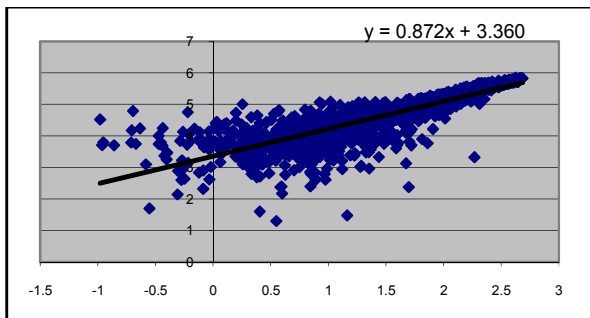


Fig. 4 The control force vs. stroke velocity of the damper

Considering damping force as a function of damping coefficient and the velocity of the stroke:

$$F = C^* \times (\dot{u})^\alpha \quad (5)$$

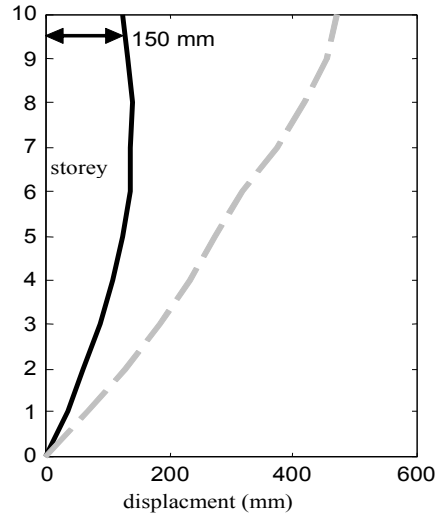
and therefore:

$$\text{Log}(F) = \text{Log}C^* + \alpha \text{Log}(\dot{u}) \quad (6)$$

Then the optimum values of  $C^*$  and  $\alpha$  can be determined from Fig. 4, where the properties of the regression line that estimates the relationship of velocity of the stroke with the damping force. Therefore the optimum damping parameter connected to the top of a ten-story-moment-frame building is determined where value of  $C$  is equal to 2294  $N.m/s$  and  $\alpha$  is equal to 0.8721.

$$F_D = 2294 \times (\dot{u})^{0.8723} \quad (7)$$

To see the performance of this non-linear damping device, a same model of a ten-story building is considered with same properties. However, instead of active control force that applies to the top of the structure, the program is modified to apply the non-linear passive damping with parameters given in equation 7 into the dynamic motion of the building. The drift and maximum displacement of the ten-story building are calculated in the MATLAB software and are shown in Fig. 5.



(a) Maximum displacement in storey

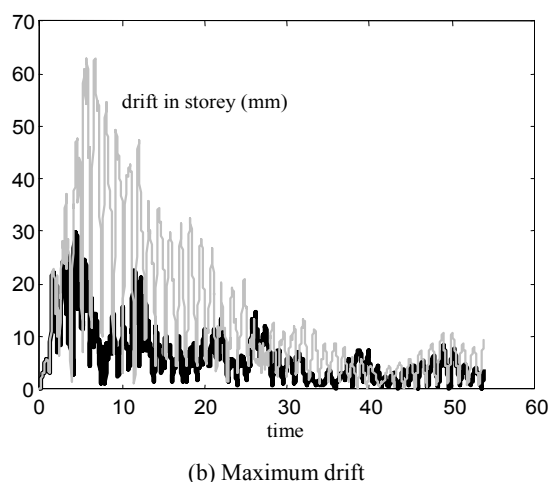


Fig. 5 Response of a ten-story-building during El Centro Earthquake with and without a non-linear passive damper

Comparing the results from Fig. 3 with response of the structure in Fig. 5, one can be concluded that the non-linear passive system has an efficient and optimum performance and the non-linear parameters ( $C^*$  and  $\alpha$ ) are optimum characteristics of a viscous damping device.

#### V. CONCLUSION

In this study an analytical model has been investigated for a ten-story-moment-frame building with simplified structural properties. This building is supported by an adjacent structure with higher lateral stiffness. The two structures are connected by an active control system. The response of structure is investigated during the El Centro excitation. It is concluded that the control system is found to be very effective in mitigating the dynamic responses of the adjacent structures and there is an optimum damping coefficient of damper for minimum responses. The optimum damping force is determined using linear quadratic regulation algorithm (LQR). Later, a relation between control force and velocity of the stroke is estimated. This estimation provides the non-linear parameter of a damping system which can control the response of the structure similar to an active control system performance.

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