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MR DAMPER-LQR CONTROL FOR EARTHQUAKE VIBRATION MITIGATION

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ABSTRACT

The use of semi-active control structural techniques has been a very interesting area of research in recent years. In this present paper, a semi active control for MR damper is proposed for suppress earthquake structural vibration. The controller design based on Linear Quadratic Regulator (LQR) with a robust feedback law to control the input energy of MR damper which minimizes a vibration of three story structure with on MR damper installed in the first floor. Under the El Centro's 1940 earthquake, the feasibility an effectiveness of the proposed algorithm is verified by a numerical simulation using Matlab. The models results comparison of controlled and uncontrolled structural vibration showed the performance of the present proposed approach.

Keywords: LQR, MR damper, Earthquake vibration, Semi-active control.

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1. INTRODUCTION

Earthquakes are one of the most destructive natural hazards that cause great loss of life (10,000 people die each year due to earthquakes). In Algeria for example, the EL-Asnam earthquake of 10 October 1980 with a magnitude of 7.2 destroyed at least 25000 housing units and rendered 300000 people homeless. The main shock, which killed about 2500 peoples (Ambraseys N.N 1981) [1]. Over the past few decades, safety of structural systems against earthquake motions is one of the most important challenges in the life cycle of a building. Therefore, the control of structural vibration mitigation has attracted several researchers from theoretical and experimental side (Cetin S et *al* 2011, Saha S & Debbarma R 2017, Li Z et *al* 2013)[2-4]. Many works have been done in the area of structural control which embraces passive, semi-active, and active cases (Buckle I.G 2000, Kumar A et *al* 2007, Fisco N.R & Adeli H 2011, Dyke S.J et *al* 1996) [5-8]. A passive control system consists of attached or embedded devices to a structure without requiring an external power source to operate with limited control performance, it's designed to reinforce or modify the structure stiffness or damping. Otherwise, an active control system required a large external power source or many, needing effectiveness and reliability consideration cost more. Semi-active control systems are a class of active control systems with small external energy requirement which can in real time tracked the motion of structure to develop the control forces guarantying the structure stability. Recently, many control algorithms and semi-active devices have been investigated to earthquake hazard mitigation especially magneto-rheological (MR) dampers due to its numerous advantages. The MR dampers are smart devices with synthetic fluids changing his viscosity from liquid to semi-solid state in milliseconds if an electric or magnetic field is applied, low-power requirements, mechanical simplicity, low cost, high dynamic range and very fast excellent control effect responses (Butz T & Von-Stryk O 2002)[9]. The control strategies applied to control MR dampers for structural vibration mitigation are ranged in two classes. The first one is the classical category which requires a mathematical model based on Lyapunov stability (Polyakov A & Fridman L 2014) [10]. The second one is the intelligent category which don't need a mathematical model of the system (Errachdi A & Benrejeb M 2014) [11]. Another category called a hybrid control is the combination of the tow precedents categories (Azadi E et *al* 2012) [12]. In this paper, a LQR controller is proposed for vibration attenuation of the systems using a MR damper subject to El Centro earthquake vibrations. The proposed controller is formulated using a cost function tradeoff between regulation performance and control effort.

2. SYSTEM MODELING:

Consider a building system with n-floor equipped with an MR damper installed in the ground floor of the structure as shown in figure 1, subjected to earthquake loads $\ddot{x}_g$ and control forces f_c.

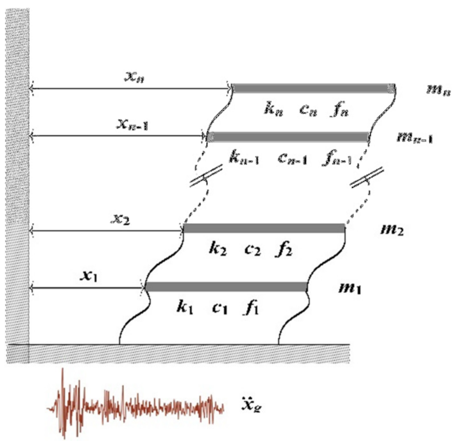

Figure 1 Typical example of n-DOF structure

The equation of the dynamic motion of the n-DOF structural system is presented by:

$$M_s\ddot{x} + C_s\dot{x} + K_s x = \Gamma \cdot f_c + M_s\Lambda\ddot{x}_g \tag{1}$$

Where x , $\dot{x}$ and $\ddot{x}$ correspond to the floor's displacements, velocities and accelerations relative to the base. M_S, C_S and K_S are mass, damping and stiffness matrix; $\ddot{x}_g$ is a ground acceleration vector; $\Gamma = [-1 \quad \dots \quad 0]^T$ is a matrix representing position of MR damper; $\Lambda = [1 \quad \dots \quad 1]^T$ is a vector showing the effect of earthquake acceleration; and f_c is the MR damper force.

3. DYNAMIC MODEL OF MAGNETORHEOLOGICAL DAMPER

The nonlinear dynamic behavior of the MR damper was experimentally studied in (Spencer Jr.B.F et *al* 1997) [13]. The proprieties of this device are described by an augmented Bouc-Wen model shown in figure 2 developed by (Spencer Jr.B.F et *al* 1997, Dyke S.J et *al* 1996) [13-14] governed by the following equations:

$$f_{MR} = c_1\dot{y} + k_1(x - x_0) \tag{2}$$

$$c_1\dot{y} = c_0(\dot{x} - \dot{y}) + k_0(x - y) + \alpha z \tag{3}$$

$$\dot{z} = -\gamma|\dot{x} - \dot{y}|z|z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \tag{4}$$

$$\dot{y} = \frac{1}{c_0 + c_1}[\alpha z + c_0\dot{x} + k_0(x + y)] \tag{5}$$

Where x, $\dot{x}$, v, and f_{MR} are respectively the damper's displacement, velocity, supplied voltage, and output force, and z is an evolutionary variable that describes the hysteresis behavior of the output force according to the displacement and velocity of the damper. k_0 and c_0 are the accumulator stiffness and the viscous damping at low velocity and c_1 and k_1, the damping and stiffness at high velocities. The parameters γ, β, n, and A give the shape and scale of the hysteresis loop (Dyke S.J 1998) [15]. The parameters of the MR damper depending on the applied voltage are:

$$\alpha = \alpha_a + \alpha_b u \ ; \ c_0 = c_{0a} + c_{0b}u \ ; \ c_1 = c_{1a} + c_{1b}u \tag{6}$$

$$\dot{u} = -\eta(u - v) \tag{7}$$

Where u is a phenomenological variable enveloping the dynamic of the system, v is the command voltage applied to the control circuit and η is a time response factor.

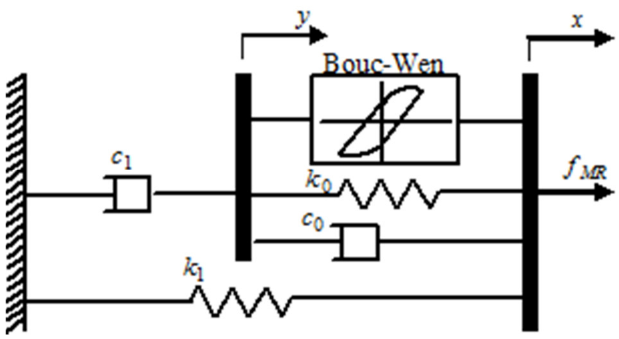

Figure 2 Modified Bouc-Wen model of the MR damper

4. SEMI-ACTIVE LQR CONTROL ALGORITHM

The Linear Quadratic Regulator, called LQ command is algorithm which make possible the calculation of the gain's control matrix by a feedback strategy created by (Kalman R.E 1960) [16]. The purpose of this control is to minimize a performance quadratic criterion $J(u)$, to bring back, preferably as quickly as possible, the state x to its equilibrium value (Barnett S & Storey C 1967, Barnett S & Storey C 1968) [17-18].

$$J(u)=\int_{t_0}^{t}\left[x(t)^T Q(t)\,x(t)+u(t)^T R(t)\,u(t)\right]dt \tag{8}$$

Where R and Q are the importance parameters of $x(t)$, $u(t)$ which are respectively the structure displacement and the control force.

$$f_c=-Kx \tag{9}$$

$$K=R^{-1}\left(N^T+B^T P\right) \tag{10}$$

Where K is the optimal gain of control find by minimizing (8) According to (Liberzon D 2012) [19] and P is the solution of the Riccati differential equation given by (Kucera V 1973) [20]:

$$-PBB^T+PA+A^T P+Q=0 \tag{11}$$

The MR damper's force can't be directly controlled by a voltage. For that, the controller generates desirable control force f_c, while an MR damper requires voltage to operate. Therefore, a unit that converts a control force into a control voltage signal integrated with the LQR system to construct the desired force. The usual algorithm for the conversion is a clipping algorithm (Ha Q.P et al 2008, Pohoryles D.A & Duffour P 2015) [21-22]:

$$v_c=v_{\max}\,H\{(f_c-f_{MR})\cdot f_{MR}\} \tag{12}$$

Where v_{max} is the maximum applied voltage, $H\{\cdot\}$ is a Heaviside step function, f_{MR} is a MR damper force, and f_c is a control force signal generated by the proposed LQR.

5. SIMULATION RESULTS AND DISCUSSIONS:

Numerical simulations were implemented and carried out in MATLAB/SIMULINK to illustrate the effectiveness of the proposed semi-active control design.

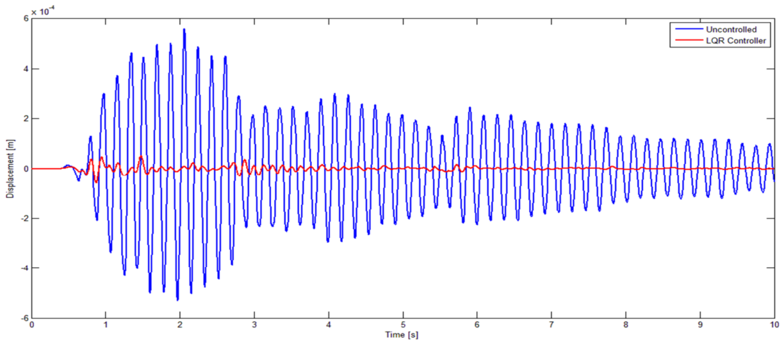

Figure 3 Displacement responses of 1st floor under the 1940 El-Centro earthquake

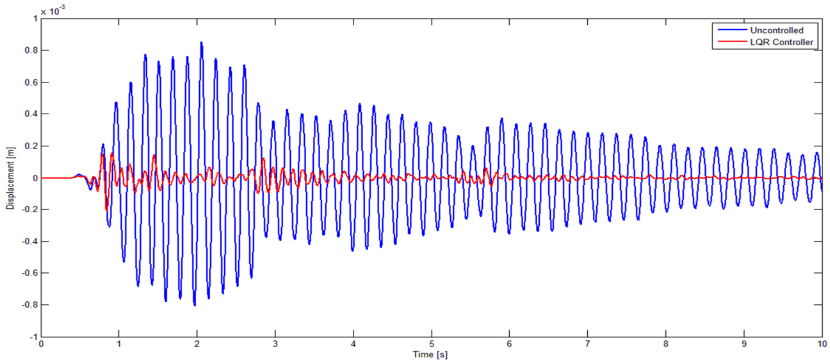

Figure 4 Displacement responses of 2nd floor under the 1940 El-Centro earthquake

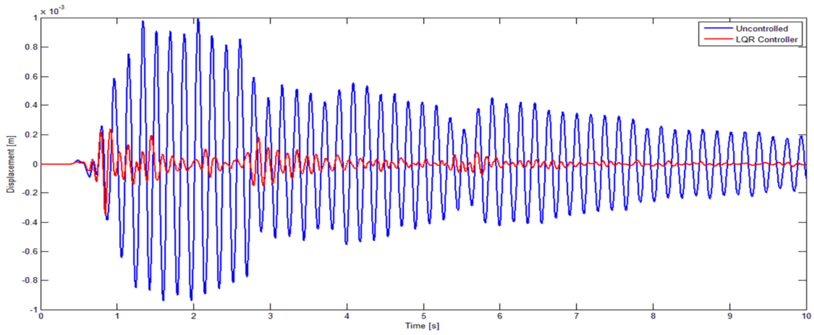

Figure 5 Displacement responses of 3rd floor under the 1940 El-Centro earthquake

The mass *Ms*, damping *Cs* and stiffness *Ks* matrices of the three-storey building model are given as:

$$[\mathbf{M}_s] = \begin{bmatrix} 98.3 & 0 & 0 \\ 0 & 98.3 & 0 \\ 0 & 0 & 98.3 \end{bmatrix} [\mathrm{kg}] \; ; \quad [\mathbf{C}_s] = \begin{bmatrix} 175 & -50 & 0 \\ -50 & 100 & -50 \\ 0 & -50 & 50 \end{bmatrix} [\mathrm{N.s/m}]$$

$$[\mathbf{K}_s] = 10^5 \times \begin{bmatrix} 12.0 & -6.84 & 0 \\ -6.84 & 13.7 & -6.84 \\ 0 & -6.84 & 6.84 \end{bmatrix} [\mathrm{N/m}]$$

The parameters are defined as:

$c_{0a} = 21\, N \cdot s/cm$; $c_{0b} = 3.5\, N \cdot s/cm$; $k_0 = 46.9\, N/cm$; $k_1 = 5\, N/cm$;
$c_{1a} = 283\, N \cdot s/cm$; $c_{1b} = 2.95\, N \cdot s/cm$; $\alpha_a = 140\, N/cm$; $\alpha_b = 695\, N/cm$;
$\gamma = 363\, cm^{-2}$; $\beta = 363\, cm^{-2}$; $A = 301$; $n = 2$; $\eta = 190\, s^{-1}$; $x_0 = 14.3\, cm$

6. CONCLUSION

The proposed approach provides a robust control strategy that can be used to mitigate vibrations of the structures subjected to seismic excitations. To demonstrate the effectiveness and robustness of the proposed LQR strategy coupled with the clipping control to command the voltage of MR damper, a simulation results are showed and compared which evinced that the developed control strategy can achieve good performances and can significantly reduce the vibration.

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