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SEMI-ACTIVE CONTROL OF SMART BASE ISOLATION SYSTEM WITH MAGNETORHOLOGICAL DAMPER

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ABSTRACT

One of the most widely implemented and accepted seismic protection systems is base isolation. However, because optimal design of base isolation depends on the intensity of the design level earthquake that is considered, the reduction of the seismic response is not optimal for a wide range of input ground motion intensities. In this paper, a smart base isolation system is proposed by combining traditional base isolation systems with magnetorheological (MR) dampers to achieve specified control target performance. This study employs four algorithms: discrete wavelet transform (DWT), particle swarm optimization (PSO), linear quadratic regulator LQR, and clipped-optimal control algorithm. DWT is used to obtain the local energy distribution of the motivation over the frequency bands. PSO is used to determine the gain matrices through the online update of the weighting matrices used in the LQR controller while eliminating the trial and error. A clipped-optimal control algorithm is used in order for the MR damper control force to approach the desired optimal force that is obtained from the modified LQR. Moreover, Bouc-Wen phenomenological model is utilized to investigate the nonlinear behaviour of the MR dampers. The advantage of the proposed control algorithm is the improvement of the performance of a conventional base isolation system via a semi-active MR damper that can change damping coefficient continuously. The design and control method is applied to a base-isolated two-degrees-of-freedom system implementing magnetorheological dampers subject to several historical near-fault ground motions. The results indicate that the proposed method is more effective at reducing the displacement response of the base isolation in real time when compared to a traditional base isolation systems or a base isolation system with an MR damper that employed a classical LQR control method.

INTRODUCTION

Base isolation is arguably one of the most effective solutions to protect structures subject to earthquake excitations.(Skinner et al.1993; Naeim and Kelly 1999). In base isolation systems, nonlinear devices such as lead-rubber, friction pendulum bearings, or high damping rubber bearings are often used to restore force and obtaining adequate damping capacity. However, the vibration reduction is not optimal for a wide range of external excitations as a result of the nonlinear behaviour of these devices. The effectiveness of many passive base isolation systems has been questioned when dealing with high-velocity, long period pulse or near-fault earthquakes, and when resonance occurred

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as per other passive systems. To address the shortcomings of passive control systems, semi active control systems have been introduced in the past decades (Spencer and Sain., 1997). Semi-active control has two main benefits over active and passive systems. First, it does not require much energy/power to tune the characteristics of the damping devised and significantly reduce the seismic response. Second, these systems can provide abroad range of control that a passive system, by nature, cannot. Moreover, semi-active devices cannot in principle destabilize the structure because they do not input additional energy to the system but simply absorb or store vibratory energy (Chase et al., 2006). Because of this low dependence on external power sources and the removal of instability concerns, semi–active systems may become an attractive solution for the improvement of reliability of low-damage (e.g. rocking dissipative) and base isolation systems, regardless of the uncertainties of the input ground motions. Among many other semi-active supplemental damping devices that could be used within a structural system, magnetorheological (MR) dampers can achieve high-level adaptive performance (Spencer et al 1997)(Figure 1). Mechanical simplicity, high dynamic range, low power requirements, large force capacity, high stability, robustness, and reliability are among the desirable features of MR dampers. MR dampers are capable of generating controllable damping forces by using MR fluids. MR fluids are composed of magnetized tiny particles that are scattered in a mineral liquid such as silicon oil. When a magnetic field is applied to this liquid, particle chains form in just a few milliseconds, and the fluid becomes a semi-solid which exhibits plastic behaviour.

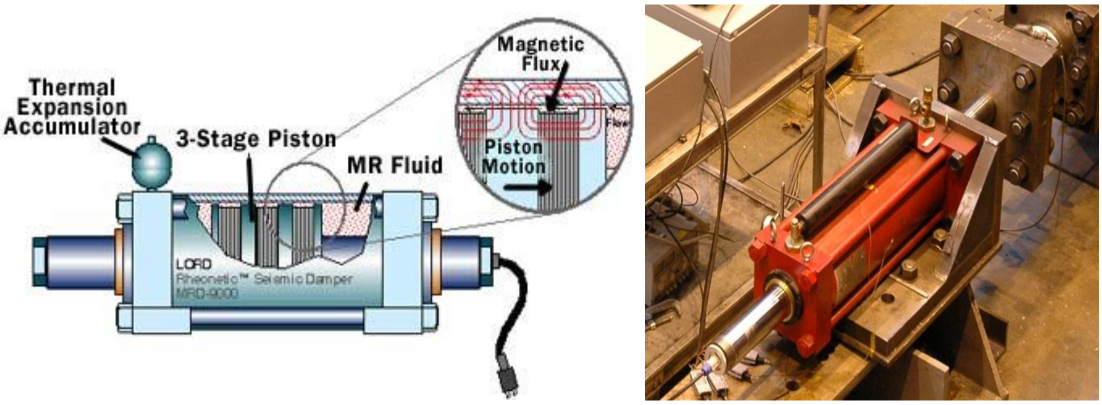

Figure 1: Large-scale semi-active damper schematic (Yang et al., 2002).

Because of the advantages of semi-active systems and the need for development of base isolation systems that can be effective for a wide range of earthquakes, smart base isolation systems that combine passive isolation systems with semi-active systems have been investigated by a number of researchers, based on the implementation of electrorheological (ER) or magnetorheological (MR) dampers (Yang et al. 1995, 1996; Makris 1997; Johnson et al. 1999; Symans and Kelly 1999; Yoshida et al. 2002; Ramallo et al. 2000a,b ; Yang and Agrawal 2001). The effectiveness of semi-active base isolation for a single span bridge model using MR dampers was experimentally shown by Nagarajaiah et al. (2000). The MR damper requires lower voltage than the ER damper which is very attractive for safety and practical reasons (Carlos et al 1996). This justifies why most practical applications use MR fluids.

There are two types of dynamic models for the MR dampers: non-parametric models and parametric models. Many non-parametric models have been used to control the dynamic behaviour of MR dampers such as neural network-based models (Wang and Liao, 2005) and fuzzy logic-based models (Kim et al., 2008). The Bingham model (Lee and Wereley, 2002), non-linear hysteretic bi-viscous model (Kamath and Wereley, 1997), hyperbolic tangent model (Christenson et al., 2008) and Bouc-Wen hysteresis model (Jansen and Dyke, 2000) are some of the parametric models that have been used to model the behaviour of MR dampers.

To characterize the behaviour of MR fluid dampers, Spencer et al. (1997) introduced the simple Bouc-Wen model. This model can predict the force-displacement and force-velocity behaviour well, and the results obtained from this model are similar to the experimental data. However, the simple Bouc-Wen model cannot capture the force roll-off when the acceleration and velocity have opposite signs and the magnitude of the velocities is small. Therefore, to overcome this drawback, Spencer et al. (1997) proposed a modified version of the Bouc-Wen model with higher level of accuracy.

Using an appropriate control algorithm is very important in order to achieve the desirable control performance via modifying the magnitude of the applied magnetic field according to a defined algorithm. Comprehensive studies have been done to determine the optimal actuator force for active-control systems. The most widespread methods are LQR, LQG, H2, and H∞ (Chin, 2013). The LQR is used widely by many researchers to determine the appropriate control force. However, classical control algorithms such as LQR suffer from some inherent shortcomings for structural applications. For instance, one of the major shortcomings of the LQR algorithm for application to forced vibration control of structures is its inability to explicitly account for the excitation. To simulate realistic circumstances, the excitation must be known prior to determining the optimal control force to achieve more reliable solutions. The effect of the specific earthquakes has been accounted for in a few studies (Wu et al., 1998, Wu et al., 1994). For example Panarillo et al. (1997) introduced a method based on updating weighting matrices from a database of earthquakes. Nonetheless, in these studies, offline databases were still required. Basu et al. (2008) and Amini et al. (2013) proposed a wavelet-based adaptive LQR and wavelet PSO-based-LQR (WPSOB-LQR) control to design the controller by updating the weighting matrices, respectively. These methods determine the time-varying gain matrices by updating the weighting matrices online, through the Ricatti equation (Basu et al 2008). Therefore, these methods do not need prior information on the external excitation, hence eliminating the need for an offline database.

In this article the feasibility and efficiency of a smart base isolation with MR dampers modelled using a modified Bouc-Wen model is discussed. Moreover, a Clipped-optimal control algorithm based on WPSOB-LQR is employed to find the optimal control force of MR dampers. The application of proposed approach to a number of pulse-like near ground motions is presented, and the efficiency of adding MR dampers in base isolation is evaluated.

MODIFIED BOUC-WEN MODEL

The schematic of the MR damper mechanical model for the modified Bouc-Wen model is shown in Figure 2b.In this case, the nonlinear force of MR damper is calculated by (Yang et al., 2002):

$$F = \alpha z + c_0 (\dot{x} + \dot{y}) + k_0 (x - y) + k_1 (x - x_0) \qquad (1)$$
$$= c_1 \dot{y} + k_1 (x - x_0)$$

Where α is Bouc-Wen model parameter related to the MR material yield stress and z is hysteretic displacement of model given by:

$$\dot{z} = -\gamma |\dot{x} - \dot{y}| \, z \, |z|^{n-1} - \beta(\dot{x} - \dot{y})|z|^n + A(\dot{x} - \dot{y}) \qquad (2)$$

$\dot{y}$ is defined as:

$$\dot{y} = \frac{1}{c_0 + c_1} \{\alpha z + c_0 \dot{x} + k_0 (x - y)\} \qquad (3)$$

Where c_0 is the viscous damping parameter at high velocities; c_1 is the viscous damping parameter for the force roll-off at low velocities; k_0 controls the stiffness at large velocities; k_1 represents the accumulator stiffness; x_0 is the initial displacement of the spring stiffness k_0; ɣ, β and A are adjustable shape parameters of the hysteresis loops, i.e., the linearity in the unloading and the transition between pre-yielding and post-yielding regions.

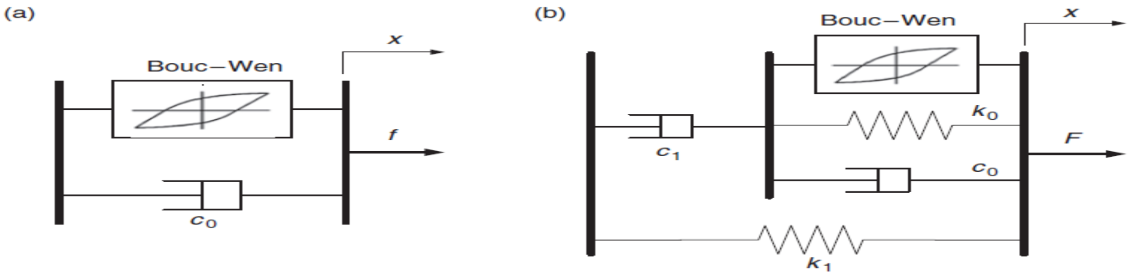

Figure 2: Mechanical model for MR damper: (a) Simple Bouc-Wen model, (b) modified Bouc-Wen model.

Optimal performance for MR damper control systems is gained by varying the applied voltage to the current driver according to the measured feedback at any moment. Thus, to determine a comprehensive model that is valid for fluctuating magnetic fields, the parameters α, c_0, c_1 and k_0 in Equations 1-3 are defined as a linear function of the efficient voltage u as given in Equation 4 to Equation 7.

$$\alpha(u) = \alpha_a + \alpha_b u \qquad (4)$$

$$k_0(u) = k_{0a} + a_b u \qquad (5)$$

$$c_0(u) = c_{0a} + c_{0b} u \qquad (6)$$

$$c_1(u) = c_{1a} + c_{1b} u \qquad (7)$$

To accommodate the dynamics involved in the MR fluid reaching rheological equilibrium, the following first order filter is employed to calculate efficient voltage, u.

$$u = -\dot{\eta}(u - v) \qquad (8)$$

Where, v and u are input and output voltages of a first-order filter, respectively; and η is the time constant of the first-order filter. Figure 3 illustrates the comparison between the response of this model and the experimental results for a 3kN MR damper in a real control condition that a damper would face during the control time. It is obvious that this model is capable of predicting MR damper nonlinear behaviour very well.

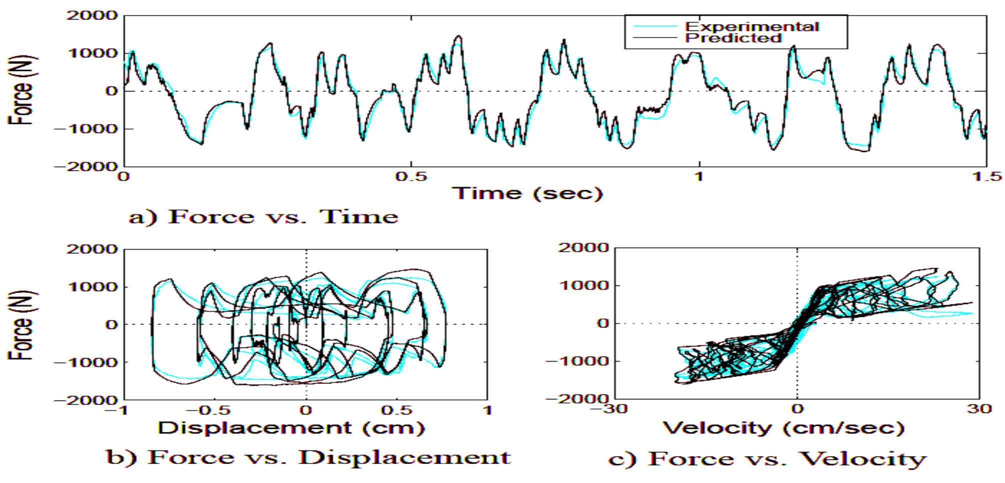

Figure 3: Predicted response by the Bouc-Wen phenomenological model in comparison with the experimental data for a 3kN MR damper in a control simulation test (Spencer et al., 1997).

INTEGRATED STRUCTURE-MR DAMPER SYSTEM

When n-degree-of-freedom (N-DOF) systems with base isolation and r MR dampers are subjected to external excitation and control forces, the governing equations of motion can be written as:

$$M\,\ddot{q}(t) + C\dot{q}(t) + Kq(t) = L.u(t) - H.f_e(t) \qquad (9)$$

where C, and K are the mass, damping, and stiffness matrices of the structure without dampers, respectively. If "q" in Equation 9 is taken as the relative displacement with respect to the ground, then mass matrix M is considered to be diagonal. The damping matrix C takes a form similar to the stiffness matrix K.

$$q = [\, q_1 q_2 q_3 \cdots q_{n+1}] \qquad (10)$$

The displacement vector is defined as $q(t) = (n+1)\times 1$ where q_i is the displacement of i^{th} floor relative to ground ($i = 1, 2, \ldots, N+1$); the control force vector exerted by damper, $u(t)$, is of the order $l\times 1$, and $fe(t)$ is the external dynamic force vector of dimension $r \times 1$, L and H are $(n+1) \times l$ and $(n+1) \times r$ location matrices, which define locations of the control forces and the external excitations, respectively. A state-space representation of Equation 9 can be written as:

$$\{\dot{x}\} = [A]\{x\} + [B]\{u\} + [E]f_e \qquad (11)$$

Where

$$\{x\} = \begin{bmatrix} q(t) \\ \dot{q}(t) \end{bmatrix} \qquad (12)$$

$\{x\}$ is the state vector of dimension $2n \times 1$, and

$$\{u\} = -\{G\}\{x\} \qquad (13)$$

$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix} \qquad (14)$$

$$B = \begin{bmatrix} 0 \\ M^{-1}L \end{bmatrix} \qquad (15)$$

$$E = \begin{bmatrix} 0 \\ M^{-1}H \end{bmatrix} \qquad (16)$$

$2(n+1) \times 2(n+1)$, $2(n+1) \times l$, and $2(n+1) \times r$ are the system matrix, control location, and external excitation location matrices, respectively. The matrices "0" and "I" in Equations 14 to 16 denote the zero and identity matrices of size $(n+1) \times (n+1)$, respectively. The LQR algorithm can determine the optimal control forces for the system with the aim of minimizing the cost function. The cost function is a quadratic function of the control effort and the state. The cost function is defined as

$$J = \int_0^{tf} [\{x\}^T [Q]\{x\} + \{u\}^T [\{R\}\{u\}]dt \qquad (17)$$

The matrices Q and R are referred to as the response and control energy weighting matrices, respectively. The weighting matrices Q and R are selected in classical LQR at the first step. The control force is given by Equation (13) where the gain matrix is obtained from the discrete algebraic Riccati equation.

Semi-active control systems are typically highly non-linear. One algorithm that has been shown to be effective for use with the MR damper is a clipped-optimal control approach, proposed by Dyke, et al. (1996). The clipped-optimal control approach is to design a linear optimal controller that calculates a vector of desired control forces based on the measured structural responses and the measured control force vector applied to the structure. If the magnitude of the force produced by the damper is smaller than the magnitude of the desired optimal force and the two forces have the same sign, the voltage applied to the current driver is increased to the maximum level so as to increase the force produced by the damper to match the desired control force. Otherwise, the commanded voltage is set to zero. The algorithm for selecting the command signal for the MR damper is stated as

$$v_i = V_{max} H(\{f_{ci} - f_i\} f_i) \tag{18}$$

Although a variety of approaches may be used to design the optimal controller, LQR methods are advocated because of their successful application in previous studies. The approach to optimal control design is discussed in detail in (Mohajer Rahbari 2013).

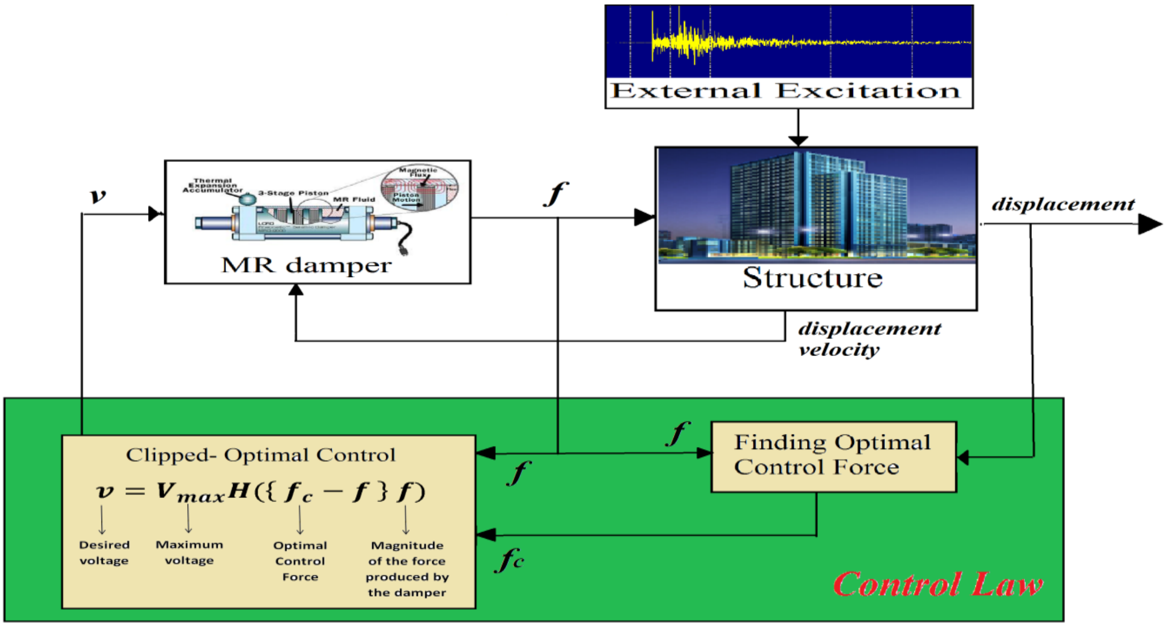

Figure.4.Block diagram of semi-active control system

MODIFIED LQR METHOD

In this study, the real time discrete wavelet transform (DWT) controller is updated at regular time steps from the initial time (t_0) until the current time (t_c) to achieve the local energy distribution of the motivation over frequency bands. The time interval under consideration [t_0, t_c] is sub-divided into time window bands. The time of i^{th} window is [t_{i-1}, t_i] of which the signal can be decomposed into time frequency bands by wavelet. Through a DWT with multi-resolution analysis (MRA) algorithm the exact decomposition of signals over a time window bands are obtained in real time. The local energy content at different frequency bands over the considered time window are given by the MRA. Obviously, the frequency containing maximum energy is the domain frequency within that window. When the domain frequency of each window is close to the natural frequency of the system, resonance can occurred in the structure. This could lead to much higher than expected displacement response (thus potential damage) in system. To mitigate the displacement response of the structural systems, a high control force is needed that can be obtained with decreasing the value of the control energy weighting matrix [R]. The advantage of this local optimal solution is that it has the ability to change the value of the matrix R on specific frequencies in contrast to the classical LQR which is a global optimal solution. To achieve this, the control energy weighting matrices are updated for every time window by a scalar multiplier and can be defined as:

$$[R]_i = \delta_i [I] \tag{19}$$

where δ_i is a scalar parameter used to scale the weighting matrix and is obtained via PSO algorithm based on the time-frequency analysis of a response state. Hence, the scalar parameter of gain matrix can be written as:

$\delta_i \neq 1$ if the frequency of the excitation is close to the natural frequency of system,

$\delta_i = 1$ otherwise.

The value of δ_i has been proposed as less than one when resonance occurs. This allows changing the weighting matrices for different frequency bands.

PSO algorithm starts with a random population (swarm) of individuals (particles) in the search space and works on the social behavior in the swarm. The position and the velocity of the i^{th} particle in the dimensional search space can be represented as $X_i = [x_{i,1}, x_{i,2}, \ldots, x_{i,d}]$ and $Vi = [v_{i,1}, v_{i,2}, \ldots, v_{i,d}]$, respectively. Each particle has its own best position (p_{best}) $P_i = [p_{i,1}, p_{i,2}, \ldots, p_{i,d}]$ corresponding to the personal best objective value obtained so far at time t. The global best particle (g_{best}) is denoted by P_g, which represents the best particle found so far at time t in the entire swarm. The new velocity of each particle is calculated as follows:

$$v_{i,j}(t+1) = wv_{i,j}(t) + c_1 r_1 \left(p_{i,j} - x_{i,j}(t)\right) + c_1 r_1 (p_{g,j} - x_{i,j}(t)) \qquad (20)$$

where $j = 1, 2, \ldots, d$; c_1 and c_2 are acceleration coefficients; w is the inertia factor; and r_1 and r_2 are two independent random numbers uniformly distributed in the range of [0, 1]. Thus, the position of each particle is updated in each generation according to the following:

$$x_{i,j}(t+1) = x_{i,j}(t) + v_{i,j}(t+1) \qquad (21)$$

The optimal control effort is obtained for each window with updated weighting matrix of the control effort [*R*] via the algebraic Riccatti equation. The updated weighting matrix and optimal control gains are obtained for each window, independent of the neighboring windows. In other words, the solution to the modified optimal control problem does not need to consider the transition conditions between two windows. In the proposed method, the total duration of the external excitation is subdivided into a number of time windows. For each of these windows, the cost function is minimized subject to the constraint given by Equation (9), by updating the weight matrices in real time. Figure 5 shows the flowchart of the PSO algorithm and proposed method for determining control energy weighting matrices and optimal control force. The fitness or objective function for the PSO algorithm for each ground motion is as follows:

$$J = \left[\frac{x_{bp}(t)}{xb_c(t)} + \frac{x_p(t) - x_{bp}(t)}{x_c(t) - x_{bc}(t)}\right] \qquad (22)$$

where X_{bp} and X_{bc} are the controlled responses of base isolation calculated using WPSOB-LQR, and classic LQR, respectively. In addition, X_p and X_c are the controlled responses of base isolation calculated using WPSOB-LQR, and classic LQR, respectively. The control energy weighting matrices are reduced when the structure has a significant high value of displacement response. This reduction of weighting matrices sets off the lesser displacement without penalty. Therefore, the positive aspect of the proposed method is that the gain matrices are calculated adaptively by using the time-varying weighting matrices depending on the online response characteristics instead of a priori (offline) choice of the weights as in the classical case (Amini et al., 2013).

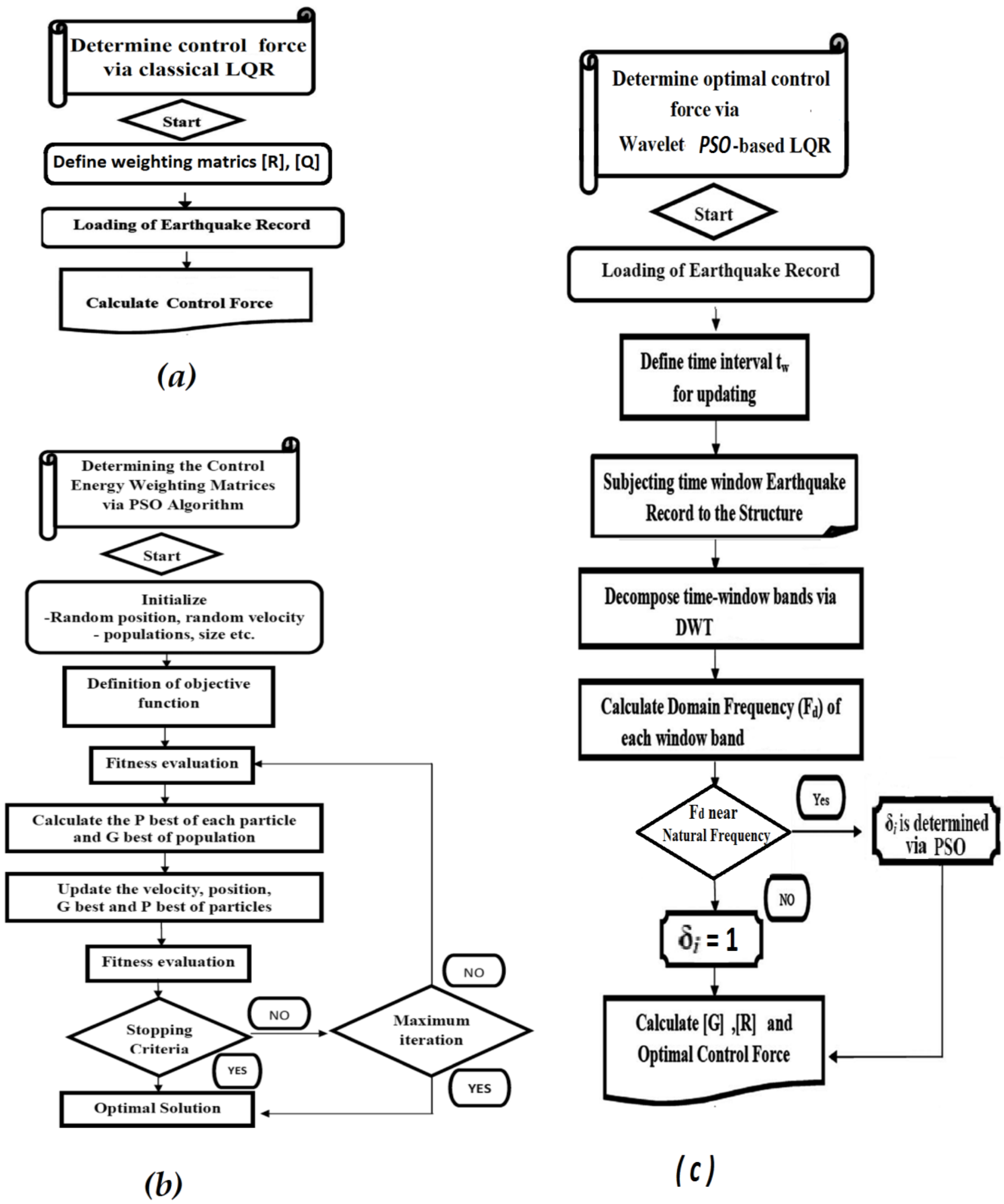

Figure 5. (a) Flowchart of the classical LQR method (b) flowchart of the PSO algorithm (Amini et al. ,2013) (c) Flowchart of the Wavelet PSO-LQR method.

NUMERICAL EXAMPLS

In this section, in order to investigate the potential application of the proposed PSO-based modified LQR control in smart base isolation, the results of linear dynamic analyses on base-isolated two-degrees-of-freedom systems excited by a number of near-fault pulse-like earthquake ground motions are discussed. The system parameters are shown in table1and Figure 6.

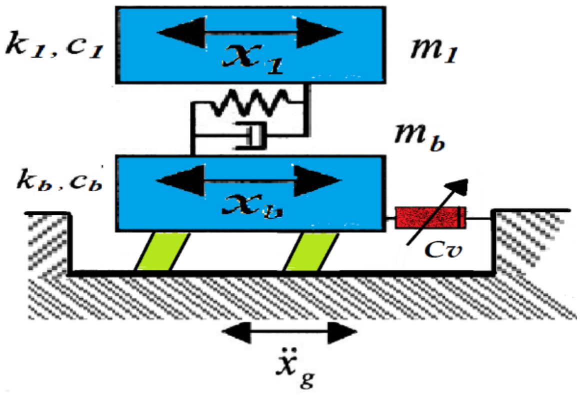

Figure.6. Smart Base Isolation Model

Table 1.System Parameters

Parameter	Mass	Stiffness	Damping
Base Isolation	10 [ton]	173.71 [KN/m]	13823 [N s /m]
First floor	100 [ton]	15791[KN/m]	25133 [N s /m]

Moreover a MR damper with the capacity of 1000 kN is installed to control the seismic responses of the system. Optimal values for the Bouc-Wen phenomenological model parameters for this damper are given in Table 2 and the maximum input voltage for this damper is equal to 10 V. The parameter δ used for scaling the weighting matrices is determined via PSO algorithm when the central frequency of each window band is close to the natural frequency of the MDOF system, whilst for others frequencies δ is assumed to be 1. Hence, the weighting matrix component [R], equals to δ [I] for resonance frequency bands and is kept as [I] for the rest of the frequency bands. In addition, the matrix Q is chosen as identity for each band. Daubechies wavelet of 4^{th} order (db4), is used as a mother wavelet to decompose the time history of acceleration for different window bands, to determine the frequency distribution of each band. The Daubechies wavelets have reasonably good localization in time and frequency to capture the effects of local frequency content in a time signal, and allow for fast decomposition by using MRA. The ground motion signals recorded in real time are decomposed for each interval window, which is considered as 1 second for updating. The gain matrices are updated for each window by solving the Riccatti equation. Therefore, the optimal control forces are calculated. MATLAB software has been implemented to compute the response. As a numerical example, the response of a structure with a typical (passive) base isolation system is compared with the response of a smart base isolation implementing a classical LQR to find optimal control force of the MR damper when subject to the Imperial Valley-06 (El Centro Array-06, 1979), Northridge-01 (Sylmar-Converters Station, 1994), and Kobe, Japan (Takatori site, 1995) ground motion records. Also, to illustrate the potential application of the proposed method, the response of the structure and the base isolation system are compared with congenital LQR in Table 3. The time history of the base displacement (isolator) response, by using different control methods are shown in Figures 7-9. Figures 7-9 show that the response of the base isolation system is significantly reduced using WPSOB-LQR method with almost same drift of structure.

Table 2. Parameters for MR damper model.

Parameter	value	Parameter	value
C_{0a}	110.0 KN s m^{-1}	α_a	46.2 KN m^{-1}
C_{0b}	14.3 KN s m^{-1} V^{-1}	α_b	41.2 KN m^{-1} V^{-1}
K_0	0.002 KN m^{-1}	γ	164 m^{-2}
C_{1a}	8359.2 KN s m^{-1}	β	164 m^{-2}
C_{1b}	7482.9 KN s m^{-1} V^{-1}	A	1107.2
K_1	0.0097 KN m^{-1}	n	2
X_0	0.143 m	η	100 s^{-1}

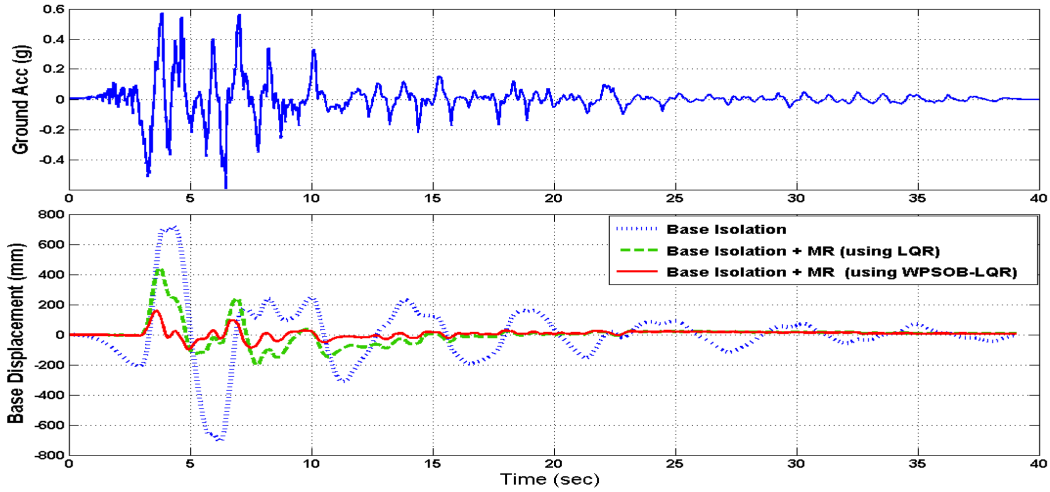

Figure 7. Acceleration time history of Northridge-01at Sylmar-Converters Station, and time history of base displacement using different control methods

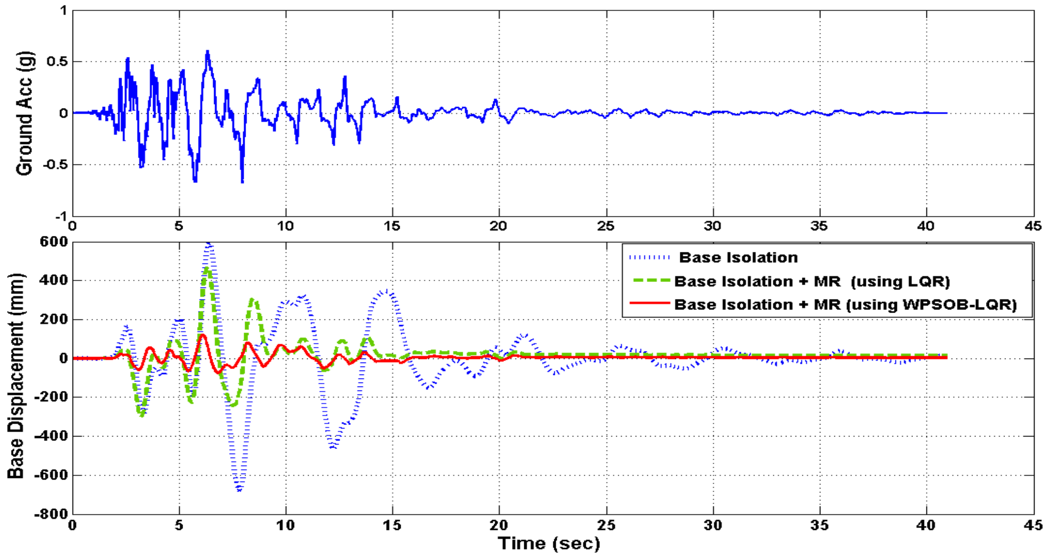

Figure 8. Acceleration time history of Kobe, Japan at Takarazuka site, and time history of base displacement using different control methods

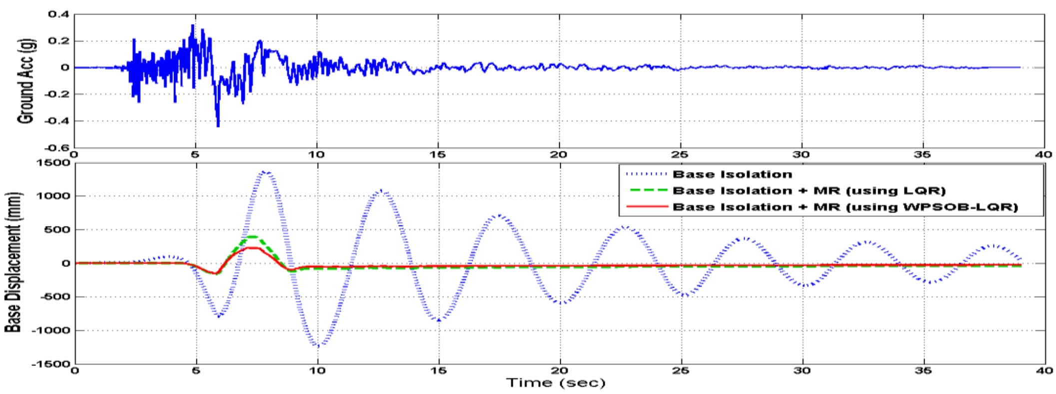

Figure 9. Acceleration time history of Imperial Valley-06 at El Centro Array-06, and time history of base displacement using different control methods

Table 3. Comparison of Effectiveness of Using Typical Base Isolation, Smart Base Isolation-1 (Using Classical LQR Control Algorithm), and Smart Base Isolation-2 (Using WPSOB-LQR Control Algorithm)

	Typical Base Isolation		Smart Base Isolation-1 (LQR)		Smart BaseIsolation-2 (WPSO-LQR)	
Earthquake	Base Displacement (cm)	Superstructure Drift (cm)	Base Displacement (cm)	Superstructure Drift (cm)	Base Displacement (cm)	Superstructure Drift (cm)
Northridge Converter Station	72.03	0.73	44.26	1.43	15.7	2.9
Imperial Valley Array#6	136.21	1.37	39.27	1.07	22.81	1.17
Kobe, Takatori site	59	0.62	46.7	1.75	11.9	4.43

Interestingly, it can be noted that under the Kobe earthquake the base isolation system-1 which uses a MR damper that employed conventional LQR algorithm control method does not decrease the base response (around 0.5 meter). On the other hand, the proposed method decreases the base displacement significantly, while maintaining same level of maximum drift at the first floor (representing the extent of the structural damage). Therefore with the proposed method, an optimal response of both the superstructure and of the base isolation systems is achieved under the considered ground motion records.

CONCLUSIONS

The performance of a smart base isolation system using PSO and DWT methods to find control force of MR damper has been investigated. DWT has been used as a powerful time-frequency tool to provide time-varying energy in different frequency bands. Also, the optimal active control force has been derived using PSO algorithm based on minimization of the gain matrices in LQR controller. This method determines the time-varying gain matrices by online updating the weighting matrices, through PSO algorithm in each frequency band. Therefore, this method does not need prior information about external excitation, thus, eliminating the need for an offline database. The efficacy of this smart base isolation system in reducing the base displacement for several near field ground motions has been demonstrated. The results are compared with traditional passive base isolation systems and with base isolation systems in combination with MR damper employing LQR algorithm to find optimal control force. Based on the limited numerical analyses, the proposed method to derive the optimal control force appears to perform better than the conventional method in reducing base displacements and can be a promising solution for improving the seismic response control of building structures Moreover, this method can be efficiently used to reduce the residual displacements of non-re-entering base isolation systems. The results show that this method is practicable and worthwhile for vibration control of building structures.

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