Seismic maintenance of sensible equipment by using Pseudo Negative Stiffness (PNS) algorithm

Arash Amanpour[1], Mohsen Tehranizadeh[2], Touraj Taghikhany[3], Faraj Zarei[4]

Abstract

In major earthquake not only civil engineering dealt structures are damaged, but also essential equipments that are emergent during earthquake and in rescue operation are suffered severe damage. In addition, some equipment are sensible to vibration. For these equipments, the response should be controlled in acceptable limit.

Base isolation is one of the effective methods of maintenance of sensible equipments against earthquakes. In this method by increasing the natural period of system and absorption of entrance energy, acceleration response maintains in lower level. By using control engineering and control methods, the characteristic of base isolation system can be controlled, then the performance of system is improved. By optimization the best response for system is achieved. Hybrid control systems combine the best features of both passive and active approaches, offering the reliability of passive devices and adaptability of active systems.

In this study the Pseudo Negative Stiffness(PNS) algorithm and Base isolation combined. In this algorithm damping and pseudo negative stiffness of controller modified so that causes surface of hysteresis loop to enlarge and in result period of system is increased and acceleration response is decreased. The results imply the excellent capability of this system and algorithm in maintenance of sensible equipments.

Keywords: Active Control, Base Isolation, Hybrid Control, LQR Algorithm, Pseudo Negative Stiffness(PNS)

Introduction

In thirty years, seismic base-isolation has progressed from conceptual research to extensive applications[1]. Detailed descriptions of the various base-isolation techniques and pertinent references can be found in the works of Kelly [1, 2], Buckle [3], Warburton [4] and Skinner et al. [5]. The reduction of damage is particularly important where the building contents are valuable and need to survive, such as in command centers, hospitals, nuclear power stations, etc. The fundamental action mechanisms of the base isolation are twofold: first, the increase of the fundamental vibration period of the structure beyond the energy-containing periods of earthquake ground motion, and the additional damping provided to dissipate the seismic energy[7].

However, there are still some examples such as near-fault, high-velocity, long period seismic pulses that possibly will lead to large isolator drifts and high floor accelerations. Large displacements at the isolation interface during a strong earthquake can lead to breaking up or splitting of the isolation bearing and hence total collapse. In order to reduce the large isolator drifts in the fundamental mode, it is necessary to use large level of isolator damping. However, it introduces forces into the structures, which increases structure accelerations and deformations in the higher modes and can amplify interstorey displacements, precluding the

---

[1] MSc. Student, Dept. of Civil and Environmental Engineering, University of Amirkabir. Email:arash_amanpour@aut.ac.ir

[2] Professor, Dept. of Civil and Environmental Engineering, University of Amirkabir. Email:tehz@govir.ir

[3] Assistant Professor, Dept. of Civil and Environmental Engineering, University of Amirkabir. E-mail:ttaghikhany@aut.ac.ir

[4] MSc. Student, Dept. of Petroleum Engineering, University of Amirkabir. E-mail:f_zarei@ac.ir

enhancements of base-isolation systems. Therefore, the need for new smart base-isolation system that can rapidly adjust and provide safe and effective filtering of a broad range of motions from near to far-fault seismic events is crucial. Base isolation systems which utilize semiactive controllable devices are known as smart base isolation systems. A variety of passive, active, and semiactive devices, for seismic response reduction, have been proposed [8, 9].

Control Design Model

A two-degree-of-freedom model of the structure is employed for the purpose of control design. The behavior of both the structure and the isolation bearings is assumed to be linear. The state space representation of the equation of motion for the linear base isolation system as shown in Fig. 4 is given by

$$\dot{x} = Ax + Bu + E\ddot{x}_g \tag{1}$$

The LQR algorithm has been employed both for active control and for semi-active control. Using this algorithm, the optimal control force $\{U_{\text{Optimal}}\}$ for $\{U\}$ given in Eq.(1) may be obtained by minimizing the following scalar performance index:

$$J = \int_{t_0}^{t_f} (\{x\}^T [Q]\{x\} + \{u\}^T [R]\{u\})dt \tag{2}$$

[Q] and [R] are weighting matrices and their values are selected depending on the relative importance given to the different terms in their contributions to the performance index J . Large values of [Q] represent the desire to keep the state vector close to the origin during the minimization interval $[t_0, t_f]$, whilst large values of [R] imply a moderate level of control. A thorough parametric study showed that choosing Q as diag[1,1000,1,1] with off-diagonal elements to be zero and $R=10^{-11}$ achieves better performance in reducing the deck displacement[10].

Solving the optimal control problem with J defined by Eq.(2) subjected to the constraint represented by Eq.(1) results in a control force vector $\{U_{\text{Optimal}}\}$ regulated only by the state vector {x}, such that

$$\{u_{optimal}(t)\} = [G]\{x(t)\} = -[R]^{-1}[B]^T[P]\{x(t)\} \tag{3}$$

where matrix [G] represents the gain matrix; and matrix [P] is the solution of the classical Riccati equation given by

$$[P][A] + [A]^T[P] - [P][B][R]^{-1}[B]^T[P] + [Q] = 0 \tag{4}$$

Upon substituting Eq.(3) into Eq.(1), the behaviour of the optimally controlled structure is described by

$$\{\dot{x}\} = ([A]+[B][G])\{x\}+\{E\}\ddot{x}_g \tag{5}$$

It is evident from Eq. (5) that the effect of closed-loop control becomes one of structural modifications, whereby the system matrix is changed from [A] (open-loop system) to [A]+[B][G] (closed-loop system).

Structural Model

In this research the model that Yoshoika et al. studied experimentally, was used and LQR algorithm was studied as a control method to control smart base isolation. Force saturation and time delay is not considered for damper. Figure(1) illustrates the model that Yoshoika et al studied and was used in this research.

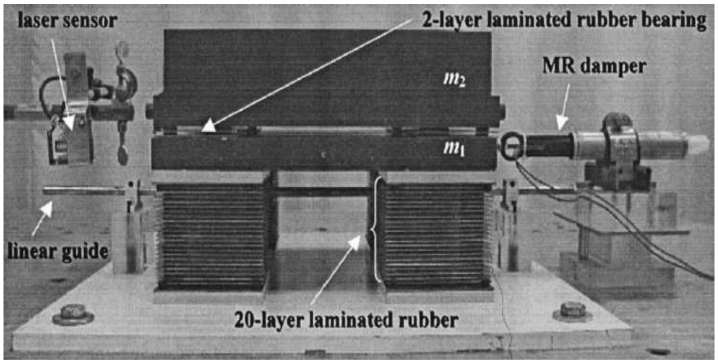

Figure 1- Experimental Model[11]

The test structure shown in Figure(1) is a two-mass model supported by laminated rubber bearings. This model represents a five-story prototype structure with an isolation period of 2s. The first mass (m_1=10.5 kg) corresponding to the isolation base of the structure. The second mass (m_2=57.5 kg) represents a single-degree-of freedom (one-mode) model of the superstructure. Twenty-layer laminated rubber bearings are employed as isolators at each of the four corners of the base. Each layer consists of three neoprene rubber disks with a height of 0.3 cm and a diameter of 1.1 cm attached to a steel plate. The experimentally verified shear modulus of the neoprene rubber is 0.11 N/mm^2. Because the vertical stiffness of the isolation bearings is relatively low, a linear guide is installed below the base to restrict vertical and torsional motion. The top mass, m_2 , was then mounted on two-layer laminated rubber bearings and attached to the lower mass, m1. This approach keeps the center of gravity of the structure low, minimizing overturning moments in the model. Therefore, only the horizontal motion of the base and the structure is considered in this experiment [11].

The similitude relations between the model and the prototype structure for time scale, mass, and length are

$$\begin{aligned} \alpha &= t'/t \\ \beta &= m'/m \\ \gamma &= x'/x \end{aligned} \tag{6}$$

where t, m, and x=time, mass, and length, respectively, in the prototype structure, and the primed quantities are those for the model structure. Table 1 shows the similitude relations for the experimental model.

Mathematical Model

Two degree of freedom is considered in this study to control. Behavior of structure and base isolation assumed to be linear. State space for base isolation system is illustrated in Fig(2).

$$A = \begin{pmatrix} [0] & [I] \\ -\begin{bmatrix} \omega_1^2 + \omega_2^2\mu & -\omega_2^2\mu \\ -\omega_2^2 & \omega_2^2 \end{bmatrix} & -\begin{bmatrix} 2\zeta_1\omega_1 + 2\zeta_2\omega_2\mu & -2\zeta_2\omega_2\mu \\ -2\zeta_2\omega_2 & 2\zeta_2\omega_2 \end{bmatrix} \end{pmatrix}$$

$$\begin{gathered} B = [0 \quad 0 \quad 1/m_1 \quad 0]^T \\ E = [0 \quad 0 \quad -1 \quad -1]^T \\ \mu = \frac{m_2}{m_1},\ \omega_1^2 = \frac{k_1}{m_1},\ \omega_2^2 = \frac{k_2}{m_2},\ 2\zeta_1\omega_1 = \frac{c_1}{m_1},\ 2\zeta_2\omega_2 = \frac{c_2}{m_2} \end{gathered} \tag{7}$$

$$\begin{gathered} \dot{X} = AX + Bu + E\ddot{x}_g \\ X = [x_1 \ \ x_2 \ \ \dot{x}_1 \ \ \dot{x}_2]^T \end{gathered} \tag{8}$$

where x1 and x_2=displacement of the base and structure relative to the ground, respectively; u and x_g=control force applied by damper and the absolute ground displacement, respectively; and m_1 , m_2 , k_1 , k_2 , c_1 , and c_2=mass, stiffness, and damping coefficients for the base and the structure.

Table 1- Similitude Relations for Experimental Model[11]

	Identified experimental model	**Assumed prototype structure**	**Ratio**
Time	1	3	α=1/3
Displacement	1	20.4	γ=1/20.4
Velocity	1	6.8	γ/α
Acceleration	1	2.27	γ/α2
First mode frequency(Hz)	1.4197	0.47323	1/α
Second mode frequency(Hz)	11.65	3.8833	1/α
First mode damping(%)	1.51	1.51	1
Second mode damping(%)	2.99	2.99	1
Fundamental frequancy of fixed superstructure(Hz)	5.19	1.73	1/α
m1: Mass of the base(kg)	10.5	105000	β=.001
m2: Mass of the structure(kg)	57.5	575000	β=.001
m:m1+m2(kg)	68	680000	β=.001

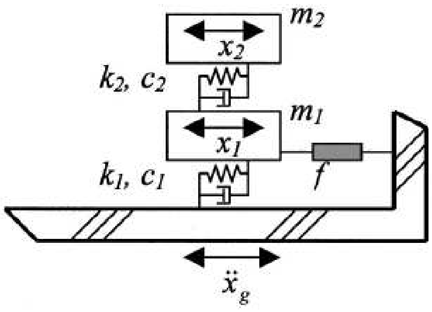

Figure 2 - 2DOF Linear base isolation model[11]

Pseudo Negative Stiffness Control Algorithm

Pseudo Negative Stiffness control algorithm was proposed by Iemura and Pradono in 2005 as a simple numerical method for LQR algorithm. They proposed a simple control force u_d, in which the force is only a function of relative displacement and velocity of the control device. Therefore, unlike the LQR control which is centralized control algorithm, this is a decentralized one, which needs only the state of device's location [12].

$$u_d = K_d x + C_d \dot{x} \tag{9}$$

The simple algorithm is called 'pseudo negative stiffness control algorithm' or simply called PNS algorithm, where K_d is a selected negative stiffness value, C_d is a selected damping coefficient, and x is stroke. The parameters K_d and C_d are adjusted to follow the hysteretic loops produced by LQR control theory to obtain the lowest seismic response[12].

In this study K_d and C_d are determined by Genetic algorithm without any restriction. In Genetic algorithm K_d and C_d are chosen so that the difference between area of hysteresis loops produced with LQR algorithm and PNS algorithm to be minimum, so the best numerical simulation of LQR algorithm is achieved.
Matlab's Genetic Algorithm toolbox[13] is selected to solve K_d and C_d to find the most accurate numerical approximation to LQR algorithm. The best result to be accurate that satisfies both type of earthquake is $K_d \approx 0$, $C_d \approx 383$.
In Figures(3), (4) hysteresis loops of system that is controlled by LQR and PNS algorithms are illustrated. In both earthquakes the proposed simple algorithm 'PNS' follows the LQR hysteresis loop in acceptable accuracy. In Elcentro and Kobe earthquakes area of hysteresis loop in PNS algorithm is 96% and 95% respectively close to LQR one.

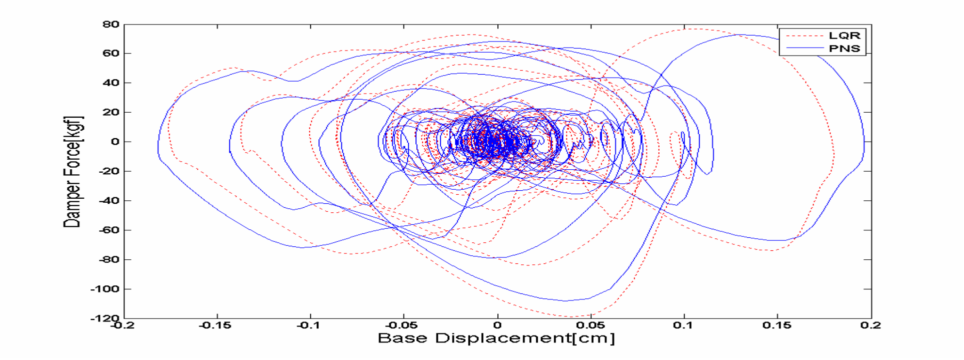

Figure 3- Hysteresis Loop for Elcentro

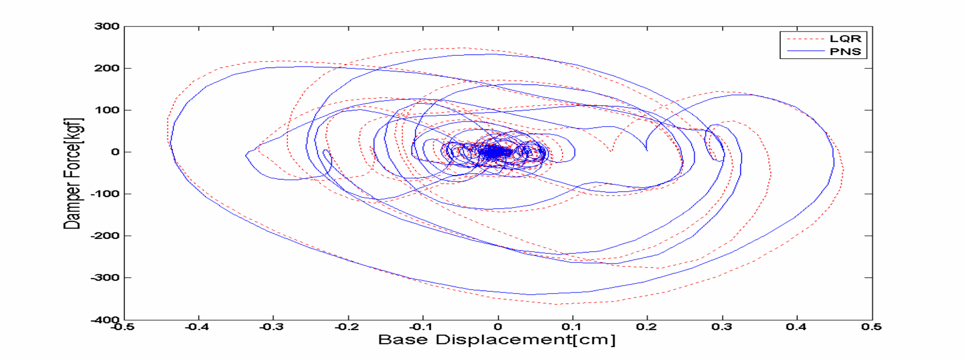

Figure 4- Hysteresis Loop for Kobe

Numerical Stimulation

In this study Elcentro and Kobe record is used for dynamic simulation. Elcentro record is selected for far-field earthquake and Kobe for near-field to compare the results. Base isolation system produce flexible floor in base that cause period of structure to be greater than previous one, in result first mode of system becomes predominant mode. In this study the model is two degree of freedom and base isolation system introduces significant flexibility in base of system, so displacement of structure is close to base displacement, it means structure is approximately rigid, respect to base. Hence, in base isolation system structure is subjected to a little deal of force that causes a little stress in structural elements. But in base isolation systems the displacement of base is large, so active control is used in base to improve the base isolation system's performance. Hence, combination of base isolation system and active control called 'Hybrid Control' is introduced to decrease the transferred force and structure displacement. PNS algorithm is used as control algorithm in this study.

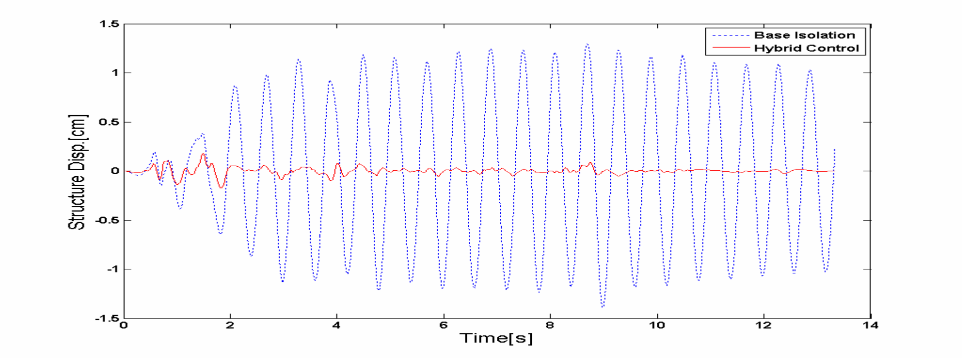

Figure 5- Displacement Response for Elcentro

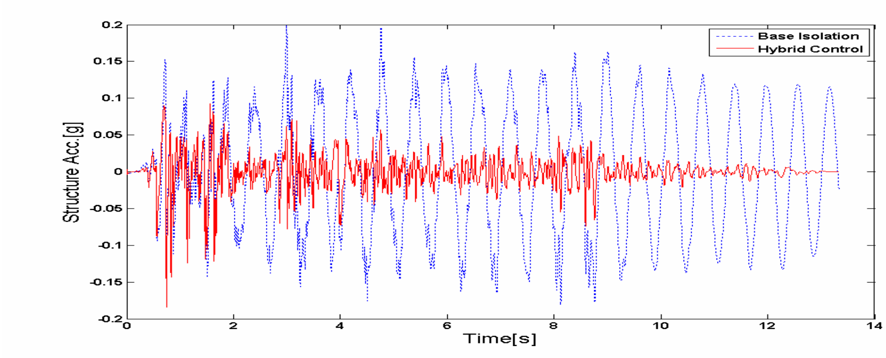

Figure 6- Acceleration Response for Elcentro

It is illustrated in Figure(5) that active control system is able to considerably reduce the displacement of base isolation system, so active control could improve the performance of base isolation system. For Elcentro earthquake as a far-field record maximum displacement is reduced 82.4% . Figure(6) shows that hybrid control has a little effect in acceleration response of system but, it is not challenging criteria in this study because the most benefits of base isolation system is to reduce acceleration response of system. Hence hybrid control using PNS algorithm is one of the best methods to reduce the displacement and acceleration response of system.

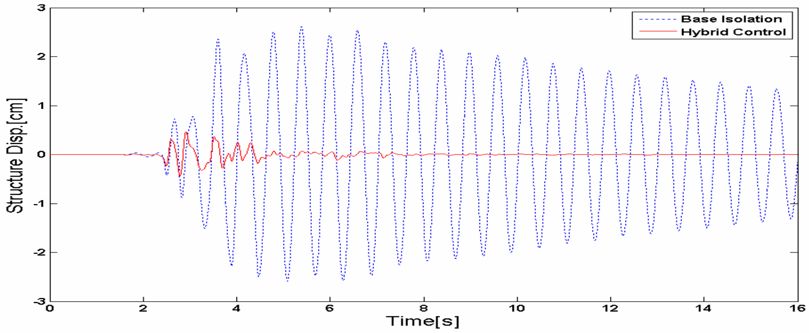

Figure 7- Displacement Response for Kobe

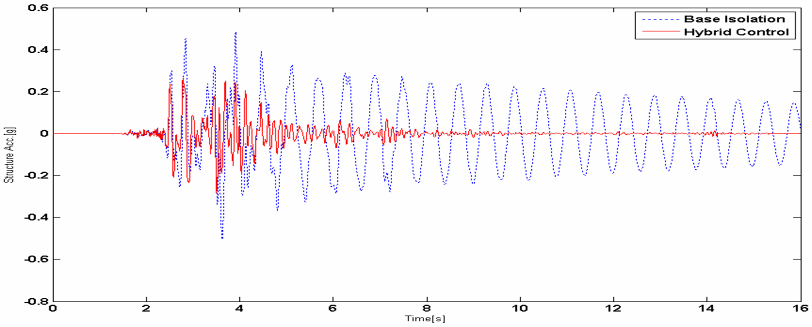

Figure 8- Acceleration Response for Kobe

Figure(7) shows that active control is also able to improve base isolation system performance for near-field earthquakes. The comparison between results of far-field and near-field responses shows that generally the results are same for two types of earthquake records. In near-filed record like far-field one the response of displacement is considerably reduced but acceleration response shows a little reduce that it is explained in former part. In Kobe earthquake as a near-field record displacement response is reduced 75%.

It can be concluded from response of hybrid control and base isolation:

- PNS algorithm is effective and simple method to simulate LQR algorithm as a optimum control strategy.
- In hybrid control as a smart control displacement response of system is considerably reduced in comparison to passive base isolation that is challenging problem in base isolation system. Hence, smart control is of the effective methods to improve the performance of base isolation system.
- In far-field earthquake the response of displacement shows more reduction than near-field one. In contrast, in near-field earthquake the response of acceleration shows more reduction than far-field one.

Conclusion

Base isolation reduces acceleration response of system that decrease severe damage during earthquake, but displacement of base is large that is not desirable. To reduce displacement of base and improve the performance of system one the most effective methods is smart control.
In base isolation system, acceleration of structure is reduced by increasing flexibility of base besides, control system modify properties of structure that in result the both acceleration and displacement response decreases to desirable level.
Results of system analysis show that PNS algorithm as a simple method to approximate LQR algorithm is responsible for both type of earthquake record.

Table 2- Analysis Result

		Elcentro	**Kobe**
Ground Acc. (g)		0.1378	0.3618
Base Acc. (g)	**Base Isolation**	0.2	0.5034
	Hybrid Control	0.1714	0.326
Storey Displacement (cm)	**Base Isolation**	1.3894	2.6088
	Hybrid Control	0.2449	0.6525

Reference

1. Luco, E. J. "Response of a double-wedge base-isolation device"; Earthquake Eng. Struct. Dyn., 33, p.p.1271-1286, 2004.

2. Kelly JM. Aseismic base isolation: review and bibliography. Soil Dynamics and Earthquake Engineering 1986; 5(3):202–217.

3. Kelly JM. Earthquake Resistant Design with Rubber. Springer-Verlag: New York, 1993.

4. Buckle I. The application of response modi_cation technologies to performance-based design of highway bridges. Proceedings of the Seminar on Response Modi_cation Technologies for Performance-based Seismic Design, ATC-17-2, Los Angeles, CA, 2002.

5. Warburton GB. Reduction of Vibrations, The 3rd Mallet–Milne Lecture. Wiley: Chichester, 1992.

6. Skinner RI, Robinson WH, McVerry GH. An Introduction to Seismic Isolation. Wiley: Chichester, 1993.

7. Fragiacomo M., Rajgelj S., Cimadom F. "Design of bilinear hysteretic isolation systems"; Earthquake Eng. Struct. Dyn., 32, p.p.1333-1352, 2003.

8. Spencer BF, Nagarajaiah S. State of the art structural control. Journal of Structural Engineering 2003; 129(7):845–856.

9. Nagarajaiah S., Sahasrabudhe S; "Seismic response control of smart sliding isolated buildings using variable stiffness systems: An experimental and numerical study", Earthquake Eng. Struct. Dyn., 35, p.p.177-197, 2006

10. Lee, T. Y., and Kawashima, K.; "Effectiveness of seismic displacement response control for nonlinear isolated bridge", J. Struct. Mech. Earthquake Eng., JSCE, 808/I-74, p.p. 1–15. 2006.

11. Yoshioka H., Ramallo J. C., Spencer Jr. B. F.; "Smart Base Isolation Strategies Employing Magnetorheological Dampers", Journal of Engineering Mechanics (ASCE), 128(5), p.p. 540-551, 2002.

12. Iemua H., Pradono M. H., "Simple Algorithm For Semi-Active Seismic Response Control of Cable-Stayed Bridges"; Earthquake Eng. Struct. Dyn., 34, p.p.409-423, 2005.

13. MathWorks. 2006. MATLAB User's Guide. MathWorks.