# 動力線性化控制法對在強震下具滑動基部隔震系統建築物之反應控制

# CONTROL OF SLIDING-ISLOATED BUILDINGS SUBJECTED TO STRONG EARTHQUAKES BY USING DYNAMIC LINEARIZATION

徐一榕，楊振南
I-Rung Hsu and J.N. Yang

原著載於中華民國第二屆結構工程研討會暨
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# Control of Sliding-Isloated Buildings Subjected to Strong Earthquakes by Using Dynamic Linearization

I-Rung Hsu[1], J.N. Yang[2]

ABSTRACT

The control method of dynamic linearization for buildings equipped with a frictional-type base sliding system against strong earthquakes is presented. The dynamic behavior of a building isolated by a base sliding system is highly nonlinear. This method is to synthesize the control vector such that the response of base-isolated building matches that of a template system, whereas the dynamic behavior of the desirable template system is known. Through numerical simulations, the performance of the control method is shown to be remarkable. Furthermore, only one velocity sensor is needed to be installed on each side of the base sliding system and no other sensor is required to be installed on the building, making the control method very attractive for practical applications.

## 1. INTRODUCTION

In recent years, the applications of passive base isolation systems and active control devices to civil engineering structures have been investigated intensively for earthquake hazard mitigations. Basically, two types of base isolation systems have been demonstrated to be very attractive for practical applications; the lead-core rubber-bearing isolators [e.g., 1] and the frictional-type sliding isolators [e.g., 2-7]. The former one has been used in practice whereas the latter one has a great potential to become major base isolators. The frictional-type sliding isolation system achieves greater resistance to structural damage by permiting the structure to slide on its foundation during severe earthquakes. It decouples the motion of the building from that of the foundation using nearly frictionless teflon on stainless steel sliding plates that have a very low frictional resistance.Full-scale active control systems for civil engineering structures have been demonstrated for practical applications[e.g., 8-10]. Literature on this subject area has been available[e.g., 9, 11].

Recently, it has also been demonstrated that a combined use of base isolators and active control devices, referred to as the hybrid control system, is superior for protecting the building structures under strong earthquakes [e.g., 12-19]. The idea of hybrid control is to utilize the advantages of both active and passive control systems. The base isolation system is used to reduce the ground motion transmitted to the building, whereas the active control devices are used to either reduce the response of the building or protect the base isolation system or help the

1 Project manager,Structural Engineering Department,Moh and Associates,Inc.
2 Professor,Department of Civil Engineering,University of California,Irvine,CA92717

base isolation system to further decouple the ground motion from that of the building. Since the dynamic behavior of the base isolation systems is either highly nonlinear or inelastic, hybrid control systems involve active control of nonlinear or hysteretic structural systems. Instantaneous optimal control algorithms have been developed for control of linear, nonlinear and hysteretic structural systems [e.g., 14-19].

This paper presents the method of control for buildings equipped with the frictional-type sliding isolation system subjected to strong earthquakes. The control method presented, referred to as the dynamic linearization, is to synthesize the control vector such that the response of the base-isolated building matches that of a template system[20], whereas the dynamic behavior of the desirable template system is usually well-known.A simulation study is conducted to investigate the effectiveness of control method. It is demostrated numerically that the performatnce of the dymanic linearization method is remarkable.

## 2. FORMULATION

### 2.1 Equations of Motion

For simplicity, consider a base-isolated one-dimensional hysteretic building equipped with an active control system as shown in Fig. 2.1. The structural system is idealized by an n-degree-of-freedom system and subjected to an one-dimensional earthquake ground acceleration $\ddot{X}_0(t)$. Let $x_i(t)$ be the relative displacement between the ith floor and the i-1th floor, i.e., the deformation of the ith story unit, where the first story unit is the base isolation system. The differential equation model for the hysteretic stiffness restoring force, $F_{si}(t)$, of the ith story unit is given by [21,16-19]

$$F_{s_i}(t) = \alpha_i k_i x_i + (1-\alpha_i) k_i D_{y_i} v_i \cdots\cdots\cdots\cdots (2.1)$$

in which the subscript i represents the quantity associated with the ith story unit, the argument t for $x_i$ and $v_i$ has been dropped for simplicity and

$$\dot{v}_i = D_{y_i}^{-1}[A_i\dot{x}_i - \beta_i|\dot{x}_i||v_i|^{n_i-1}v_i - \gamma_i\dot{x}_i|v_i|^{n_i}] = f_i(\dot{x}_i, v_i) \cdots\cdots (2.2)$$

where $k_i$ = elastic stiffness, $\alpha_i$ = ratio of post-yielding to pre-yielding stiffness, $D_{yi}$ = yield deformation=constant, and $v_i$ is a nondimensional variable introduced to describe the hysteretic component of the deformation, with $|v_i| \le 1$. In Eq. (2.2), parameters $A_i$, $\beta_i$ and $\gamma_i$ govern the scale and general shape of the hysteresis loop, whereas the smoothness of the force-deformation curve is determined by the parameter $n_i$.

The matrix equation of motion of the entire building system can be expressed as follows [16, 17]

$$\underline{M}\ddot{\underline{X}}(t) + \underline{C}\dot{\underline{X}}(t) + \underline{K}_e\underline{X}(t) + \underline{K}_I\underline{V}(t) = \underline{H}\underline{U}(t) + \underline{F}\ddot{X}_0(t) \cdots\cdots (2.3)$$

in which a linear viscous damping model has been assumed, $\underline{X}(t) = [x_1, x_2, ..., x_n]'$ = an n vector denoting the deformation of each story unit, and $\underline{V}(t) = [v_1, v_2, ..., v_n]'$ = an n vector denoting the hysteretic variable of each story unit. For the notations above, an under bar denotes a vector or a matrix and a prime indicates the transpose of a vector or a matrix.

In Eq. (2.3), $\underline{M}$ is a (nxn) mass matrix with the i-jth element $M(i,j) = m_i$ for i = 1,2,...,n and j = 1,2,...,i, and M(i,j) = 0 for j>i, where $m_i$ is the mass of the ith floor. $\underline{C}$ is an (nxn) band-limited damping matrix with all elements equal to zero except $C(i,i) = c_i$ for i = 1,2,...,n and $C(i,i+1) = -c_{i+1}$ for i = 1,2,...,n-1, where $c_i$ is the damping coefficient of the ith story unit. $\underline{K}_e$ and $\underline{K}_I$ are (nxn) band-limited elastic stiffness matrix and hysteretic stiffness matrix, respectively. All elements of $\underline{K}_e$ and $\underline{K}_I$ are zero except $K_e(i,i) = \alpha_i k_i$, $K_I(i,i) = (1-\alpha_i)k_i D_{yi}$ for i = 1,2,...,n and $K_e(i,i+1) = -\alpha_{i+1} k_{i+1}$, $K_I(i,i+1) = -(1-\alpha_{i+1})k_{i+1} D_{yi+1}$ for i = 1,2,...,n-1. $\underline{H}$ is an (nxr) matrix denoting the location of r controllers and $\underline{F}$ is an n vector denoting the influence of the earthquake ground acceleration. It should be noted that the parameters for the sliding system are $c_1 = 0$, $\alpha_1 = 0$, and $k_1 D_{y1} = \mu \overline{m} g$.

From Eq. (2.2), the vector $\underline{V}$ appearing in Eq. (2.3) is given by

$$\dot{\underline{V}} = \underline{f}(\dot{\underline{X}}, \underline{V}) \cdots\cdots (2.4)$$

in which the ith element of $\dot{\underline{V}}$ or $\underline{f}(\dot{\underline{X}}, \underline{V})$, denoted by $\dot{V}_i = f_i(\dot{X}_i, V_i)$, is given by Eq. (2.2).

By introducing a 3n state vector $\underline{Z}(t)$,

$$\underline{Z}(t) = \begin{bmatrix} \underline{X} \\ \underline{V} \\ \dot{\underline{X}} \end{bmatrix} \cdots\cdots (2.5)$$

the second-order nonlinear matrix equation of motion, Eq. (2.3), can be converted into a first order matrix equation as follows:

$$\dot{\underline{Z}}(t) = \underline{g}[\underline{Z}(t)] + \underline{B}\underline{U}(t) + \underline{W}_1 \ddot{X}_0(t) \cdots\cdots (2.6)$$

in which $\underline{B}$ is a (3nxr) matrix, $\underline{W}_1$ is a 3n vector

$$\underline{B} = \begin{bmatrix} \underline{0} \\ \underline{0} \\ \underline{M}^{-1}\underline{H} \end{bmatrix} \quad ; \quad \underline{W}_1 = \begin{bmatrix} \underline{0} \\ \underline{0} \\ \underline{M}^{-1}\underline{F} \end{bmatrix} \cdots\cdots (2.7)$$

and $\underline{g}[\underline{Z}(t)]$ is a 3n vector consisting of nonlinear functions of the components of the vector $\underline{Z}(t)$,

$$g[\underline{Z}(t)] = \begin{bmatrix} \dot{\underline{X}} \\ \hline \underline{f}(\dot{\underline{X}}, \underline{V}) \\ \hline -\underline{M}^{-1}(\underline{C}\,\dot{\underline{X}} + \underline{K}_e\,\underline{X} + \underline{K}_I\,\underline{V}) \end{bmatrix} \cdots\cdots (2.8)$$

2.2 Dynamic Linearization

For the frictional-type base sliding system as shown in Fig. 1(a), the frictional force developed in the sliding system during the sliding phase, denoted by $F_{sb}(t)$, is given by

$$F_{sb}(t) = \mu \overline{m} g\, sgn(\dot{x}_b) \cdots\cdots (2.9)$$

in which $\overline{m}\,g$ = w is the weight of the structural system above the sliding bearings and μ is the coefficient of friction. In the dynamic analysis and active control of the sliding system, the highly nonlinear frictional force is represented by the following analytical function [15-19]

$$F_{s1}(t) = \mu \overline{m} g\, v_1(t) \cdots\cdots (2.10)$$

in which $v_1(t)$ is given by Eq. (2.2) with $\alpha_1 = 0$ and $k_1 D_{y1} = \mu \overline{m} g$ in Eq. (2.1). It is mentioned that during the sliding phase, $v_1$ takes a value of either 1 or -1. During the sticking phase, the absolute value of $v_1$ is less than unity, i.e., $|v| \leq 1$. The conditions of sticking and sliding are accounted for by Eq. (2.2) automatically. The parameters governing the scale and general shape of the hysteresis loop of the sliding system are $A_1 = 1.0$, $\beta_1 = 0.5$, $n_1 = 2$, $\gamma_1 = 0.5$ and $D_{y1} =$ 0.012cm. The hysteresis loop of such a sliding system is schematically shown in Fig. 2.

The method of dynamic Linearization [20] is to synthesize the control vector $\underline{U}(t)$ so that the response of the controlled structure matches the response of a specified system, referred to as the template system. The specified template system is a stable system and its response behavior is usually well-known from either the mathematical or physical standpoint. A commonly used template system is a stable linear system.

The purpose of attaching the actuator (actuators) to the sliding system as shown in Fig. 1(b) is to overcome the frictional force in order to maintain the system in the sliding phase as much as possible, thus reducing the earthquake ground motion transmitted to the superstructure. As a result, the control vector $\underline{U}(t) = u(t)$ consists of only one element, i.e., r = 1, and the location matrix $\underline{H}$ becomes an n vector, i.e., $\underline{H} = [1,0,0,\ldots,0]'$. The matrix equation of motion, Eq. (2.6), can be written as a function of the frictional coefficient μ of the sliding system as follows

$$\dot{\underline{Z}}(t) = \underline{g}[\underline{Z}(t), \mu] + \underline{B}u(t) + \underline{W}_1 \ddot{X}_0(t) \cdots\cdots (2.11)$$

in which $\underline{B}$ becomes a 3n vector, since r = 1.

The template system is chosen to be the same nonlinear system but with a frictional coefficient $\eta$ smaller than $\mu$, i.e.,

$$\dot{\underline{Z}}_a(t) = g[\underline{Z}_a(t), \eta] + \underline{W}_1 \ddot{X}_0(t) \cdots\cdots (2.12)$$

in which $\underline{Z}_a(t)$ is a 3n response state vector of the template system.

The error between the controlled response, $\underline{Z}(t)$, and the response, $\underline{Z}_a(t)$, of the template system is denoted by $\underline{E}(t)$, i.e.,

$$\underline{E}(t) = \underline{Z}(t) - \underline{Z}_a(t) \cdots\cdots (2.13)$$

Taking the derivative of Eq. (2.13) and using Eqs. (2.11) and (2.12), one obtains

$$\dot{\underline{E}}(t) = g[\underline{Z}(t), \mu] + \underline{B}u(t) - g[\underline{Z}_a(t), \eta] \cdots\cdots (2.14)$$

In general, the control force u(t) may not be able to drive the response, $\underline{Z}(t)$, of the controlled structure to be identical to that of the template system, $\underline{Z}_a(t)$, and hence $\underline{E}(t)$ in Eq. (2.13) is not zero. However, one can reduce the error (mismatch) to zero asymptotically if

$$\dot{\underline{E}}(t) = \underline{S}\,\underline{E}(t) \cdots\cdots (2.15)$$

in which $\underline{S}$ is a convergence factor matrix that is asymptotically stable. In other words, $\underline{S}$ is chosen so that the real parts of all the eigenvalues of $\underline{S}$ are negative. This will guarantee the convergence of the mismatch, $\underline{E}(t)$, to zero asymptotically.

The particular template system chosen in Eq. (2.12) makes it possible to set $\dot{\underline{E}}(t) = \underline{E}(t) = 0$, so that Eq. (2.14) becomes

$$g[\underline{Z}(t), \mu] + \underline{B}u(t) - g[\underline{Z}_a(t), \eta] = 0 \cdots\cdots (2.16)$$

in which setting $\underline{Z}(t) = \underline{Z}_a(t)$, since E(t) = 0.

Substituting Eqs. (2.10), (2.3), (2.7) and (2.8) into Eq. (2.16) with $\underline{Z}(t) = \underline{Z}_a(t)$, one obtains the control force u(t) as

$$u(t) = (\mu - \eta)\overline{m}\, g v_1(t) \cdots\cdots (2.17)$$

Physically speaking, the active control force u(t) is used to reduce the frictional coefficient of the sliding system from $\mu$ to the desirable value $\eta$.

As observed from Eq. (2.17), the control force u(t) depends on the hysteretic component $v_1(t)$ of the sliding system. The hysteretic component, $v_1(t)$, is not directly measurable but it can be estimated on-line from a nonlinear observer using Eq. (2.2) and the measured relative velocity $\dot{x}_1$ as follows

$$\hat{v}_1(t) = D_{y1}^{-1}\left[A_1\dot{x}_1 - \beta_1|\dot{x}_1||\hat{v}_1|^{n_1-1}\hat{v}_1 - \gamma_1\dot{x}_1|\hat{v}_1|^{n_1}\right] \cdots\cdots (2.18)$$

In Eq. (2.18), $\hat{v}_1(t)$ is the estimate of $v_1(t)$ and the relative velocity of the sliding system $\dot{x}_1$ is measured. Thus, for the method of dynamic Linearization described above, only two velocity sensors, one on each side of the sliding isolation system, are needed to measure $\dot{x}_1$. This is a very desirable feature for practical applications.

## 3. NUMERICAL SIMULATION AND RESULTS

To investigate the performance of the control methods presented above, an eight-story building that exhibits bilinear elasto-plastic behavior is considered. The properties of the structure are as follows: (i) the mass of each floor is identical with $m_i$ = m = 345.6 metric tons; (ii) the preyielding stiffnesses of the eight-story units are $k_i$ (i=1.2,...,8) = 3.4x10$^5$, 3.26x10$^5$, 2.85x10$^5$, 2.69x10$^5$, 2.43x10$^5$, 2.07x10$^5$, 1.69x10$^5$ and 1.37x10$^5$ kN/m, respectively, and the postyielding stiffnesses are 0.1 $k_i$, i.e., $\alpha_i$ = 0.1 for i = 1,2,....,8; and (iii) the viscous damping coefficients for each story unit are $c_i$ = 490, 467, 410, 386, 348, 298, 243 and 196 kN.sec/m, respectively. The damping coefficients given above result in a damping ratio of 0.38% for the first vibrational mode. The natural frequencies of the unyielded structure are 5.24, 14.0, 22.55, 30.22, 36.89, 43.06, 49.54 and 55.96 rad./sec. The yielding level for each story unit are $D_{yi}$ = 2.4, 2.3, 2.2, 2.1, 2.0, 1.9, 1.7, and 1.5 cm. The bilinear elasto-plastic behavior can be described by the hysteretic model, Eqs. (2.1) and (2.2), with $A_i$ = 1.0, $\beta_i$ = 0.5, $n_i$ = 95 and $\gamma_i$ = 0.5 for i = 1.2,...,8. A simulated earthquake with a maximum ground acceleration of 0.3g as shown in Fig. 3 is used as the input excitation.

With the eight-story bilinear elasto-plastic building structure described above and the earthquake ground acceleration shown in Fig. 3, time histories of all the response quantities have been computed numerically using the fourth order Runge-Kutta method. The time history of the first story deformation of the building is plotted in Fig. 4(a). Within 30 seconds of the earthquake episode, the maximum interstory deformation, $x_{mi}$, and the maximum absolute acceleration of each floor, $a_i$, are shown in columns (3) and (4) of Table 1, designated as "Without Control". As observed from Table 1, the deformation of the unprotected building is excessive and that yielding takes place in each story unit.

A frictional-type sliding base isolation system, as shown schematically in Fig. 1(a), is implemented to the building. The mass of the base sliding system is m = 450 metric tons and the coefficient of friction is $\mu$ = 10%. The parameter values for the hysteretic behavior of the sliding system, Eqs. (2.1) and (2.2), are $A_1$ = 1.0, $\beta_1$ = 0.5, $n_1$ = 2, $\gamma_1$ = 0.5, $D_{y1}$ = 0.012cm, $\alpha_1$ = 0 and $k_1$ = 262.8x10$^5$ kN/m. The hysteresis loop is shown in Fig. 2 and the integration time step $\Delta t$ = 0.00075 sec. is used. The time history of the first story deformation of the building is shown in Fig. 4(b) and the maximum response quantities of the structure within 30 seconds of the earthquake episode are presented in columns (5) and (6) of Table 1, designated as "With SIS". In Table 1, the results shown by the row denoted by "B" represent the maximum relative displacement, $x_{m1}$, and the maximum acceleration, $a_1$, of the base sliding system. As observed from Table 1, the interstory deformations and floor accelerations for the building are drastically reduced using the base sliding isolation system. However, the deformation of the top-story unit is still in the inelastic range.

To further reduce the structural response and to bring the deformation of the building into the elastic range, an actuator is connected to the sliding system as shown in Fig. 1(b). Assuming that the template system has a coefficient of friction of $\eta = 3\%$, we have computed all the response quantities of the structure. The time history of the deformation of the first story of the building is depicted in Fig. 4(c), whereas the time history of the required active control force is presented in Fig. 5. Within 30 seconds of the earthquake episode, the maximum response quantities are shown in columns (7) and (8) of Table 1, designated as "(A)". The maximum active control force $U_m = 2321$ kN is also presented in Table 1. A significant reduction for the building response quantities can be observed from Table 1.

Finally, the hysteresis loops of the shear force response of the top story unit are presented in Fig. 6 for comparison. With the application of the active control force, the shear force response of the top story unit is within the elastic limit as evidened by Fig. 6(c).

## 4. CONCLUSIONS

The method of dynamic linearization is presented for control of earthquake excited buildings isolated by a frictional-type base sliding system. The method of dynamic linearization is used to synthesize the control vector in order to reduce the structural response. It is most suitable for control of the buildings equipped with a base sliding system, since the control vector can be synthesized to reduce the coefficient of friction of the sliding system. Another advantage of this control method is that it requires only two velocity sensors; one to be installed on each side of the base sliding system. However, the method of dynamic linearization is not applicable to control of buildings equipped with lead-core rubber-bearing isolation systems.

## 5. ACKNOWLEDGEMENTS

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## 動力線性化控制法對在強震下具滑動基部隔震系統建築物之反應控制

徐一榕[1] ，楊振楠[2]

### 摘 要

本文係介紹如何使用動力線性化法( Dynamic Linearization )使具滑動部隔震系統之建築物在強震下所產生之反應予以控制。本法係整合作用於上述建築物之控制力( Control Vector )使其因強震而產生之非線性動力行爲與某一特定之穩定、線性系統之動力行爲相吻合。此法經數值模擬結果顯示其對上述建築物在強震下之反應控制，頗具顯著之效果，此外使用本法僅需2 個速度計測器( sensers )，甚爲實用。

1.亞新工程顧問公司結構部計畫經理 ； 2.美國加州大學爾灣分校土木系教授

TABLE 1: Maximum Response Quantities of A Base-Isolated Building Using Frictional-Type Sliding Isolators

| FLOOR NO (1) | Yield Displ $D_{yi}$ (cm) (2) | without control $x_{mi}$ (cm) (3) | without control $a_i$ (cm/s²) (4) | with SIS Alone $x_{mi}$ (cm) (5) | with SIS Alone $a_i$ (cm/s²) (6) | (A) Um=2321 kN $x_{mi}$ (cm) (7) | (A) Um=2321 kN $a_i$ (cm/s²) (8) |
|---|---|---|---|---|---|---|---|
| B | - | - | - | 11.54 | 658 | 44.86 | 380 |
| 1 | 2.4 | 3.05 | 486 | 1.30 | 370 | 0.50 | 214 |
| 2 | 2.3 | 2.80 | 456 | 1.23 | 547 | 0.50 | 239 |
| 3 | 2.2 | 3.14 | 571 | 1.38 | 531 | 0.56 | 230 |
| 4 | 2.1 | 2.95 | 529 | 1.40 | 404 | 0.68 | 217 |
| 5 | 2.0 | 2.70 | 558 | 1.50 | 424 | 0.78 | 242 |
| 6 | 1.9 | 2.91 | 720 | 1.72 | 462 | 0.74 | 298 |
| 7 | 1.7 | 2.90 | 580 | 1.82 | 541 | 0.93 | 218 |
| 8 | 1.5 | 2.08 | 617 | 1.64 | 601 | 0.87 | 344 |

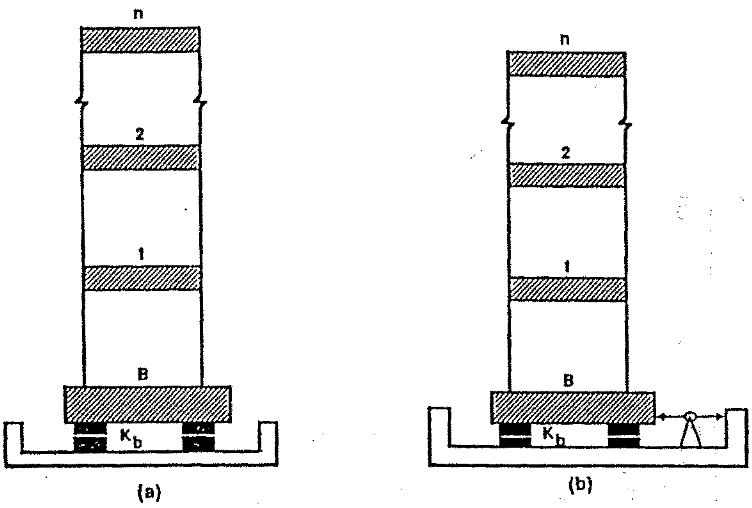


**Figure 1** Structure Model of a Multi-Story Building : (a) With Base Sliding System; (b) With Base Sliding System and Actuator

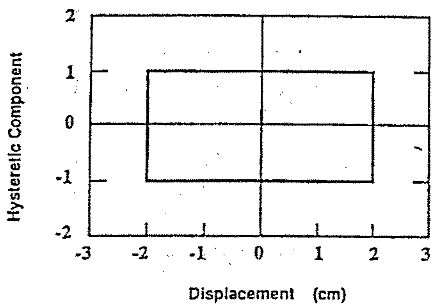


Fig.2 Hysteresis Loop of Base Sliding Isolation System

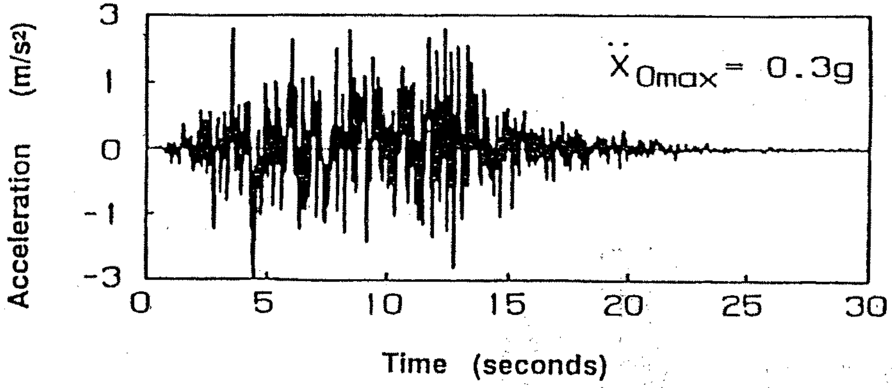


Figure 3 A Simulated Earthquake Ground Acceleration

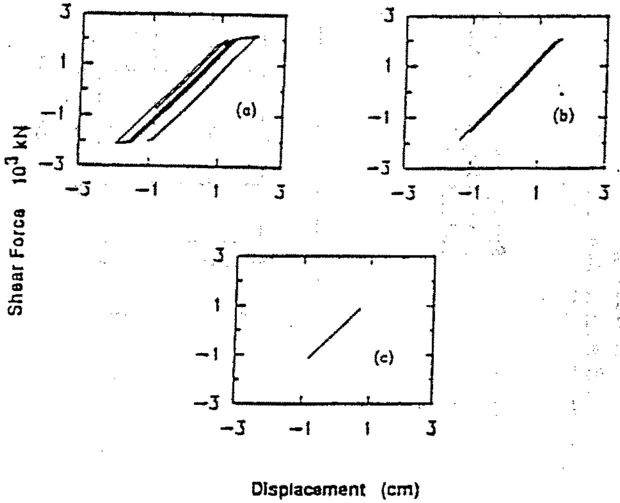


Figure 6 Hysteresis Loop of Shear Force in Top Story Unit; (a)Without Control; (b) With Base Sliding System; (c)Dynamic Linearization Method; (d) Direct Output Feedback

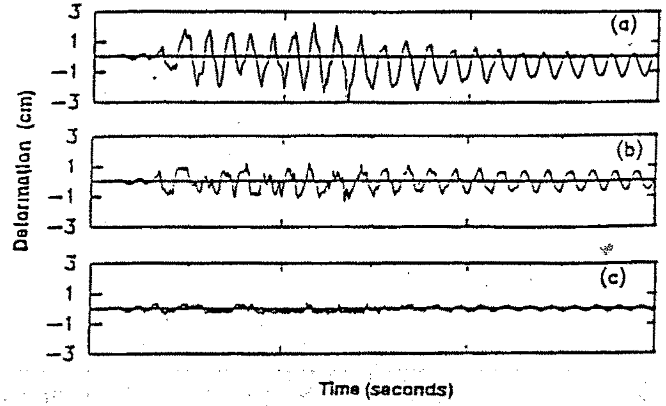


Figure 4 Deformation of First Story of Building; (a) Without Control; (b) With Base Sliding System; (c) Dynamic Linearization Method

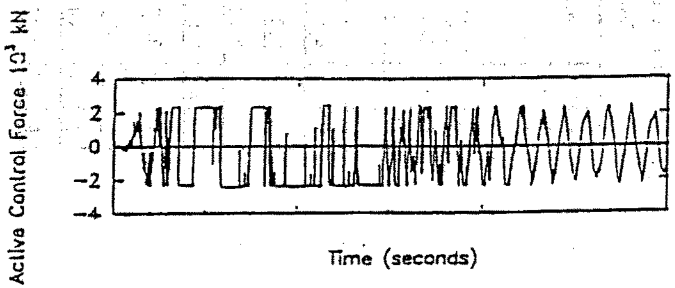


Figure 5 Required Active Control Force: Dynamic Linearization Method