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by

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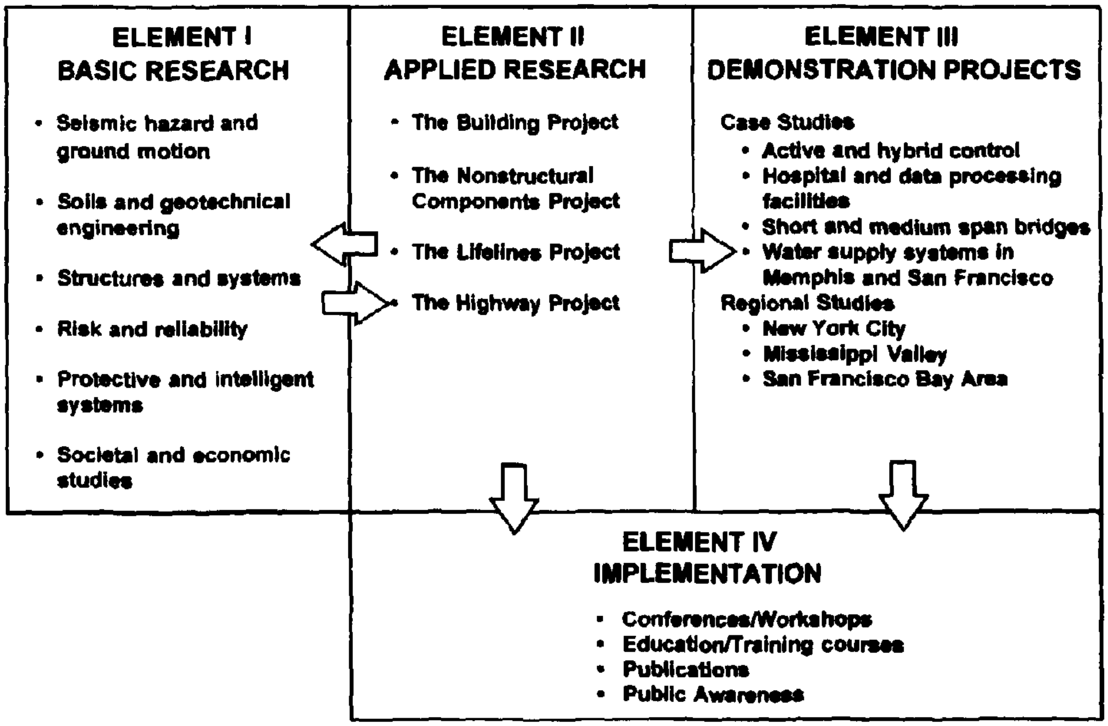
PREFACE

The National Center for Earthquake Engineering Research (NCEER) was established to expand and disseminate knowledge about earthquakes, improve earthquake-resistant design, and implement seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures in the eastern and central United States and lifelines throughout the country that are found in zones of low, moderate, and high seismicity.

NCEER's research and implementation plan in years six through ten (1991-1996) comprises four interlocked elements, as shown in the figure below. Element I, Basic Research, is carried out to support projects in the Applied Research area. Element II, Applied Research, is the major focus of work for years six through ten. Element III, Demonstration Projects, have been planned to support Applied Research projects, and will be either case studies or regional studies. Element IV, Implementation, will result from activity in the four Applied Research projects, and from Demonstration Projects.



Research in the **Building Project** focuses on the evaluation and retrofit of buildings in regions of moderate seismicity. Emphasis is on lightly reinforced concrete buildings, steel semi-rigid frames, and masonry walls or infills. The research involves small- and medium-scale shake table tests and full-scale component tests at several institutions. In a parallel effort, analytical models and computer programs are being developed to aid in the prediction of the response of these buildings to various types of ground motion.

Two of the short-term products of the **Building Project** will be a monograph on the evaluation of lightly reinforced concrete buildings and a state-of-the-art report on unreinforced masonry.

The **protective and intelligent systems program** constitutes one of the important areas of research in the **Building Project**. Current tasks include the following:

1. Evaluate the performance of full-scale active bracing and active mass dampers already in place in terms of performance, power requirements, maintenance, reliability and cost.
2. Compare passive and active control strategies in terms of structural type, degree of effectiveness, cost and long-term reliability.
3. Perform fundamental studies of hybrid control.
4. Develop and test hybrid control systems.

The work presented in this report represents one part of the full-scale active control implementation project focusing on the development of more efficient control algorithms. Since peak response is closely related to structural safety, control algorithms which provide improved peak response reduction are desirable. A class of nonlinear control algorithms are presented in this report for this purpose. Extensive simulation and experimental results presented in this report show that the proposed nonlinear control laws can be more effective than traditional linear control laws in peak response reduction. The successful accomplishment of the experiments indicates that the implementation of nonlinear control laws in practice present no inherent difficulties and their design can be carried out following the same procedures as in the linear control case. Good agreement between analytical and experimental results makes it possible to extrapolate the nonlinear control results for potential full-scale structural applications.

ABSTRACT

Linear quadratic regulator has been used extensively in many control systems designed for structural control applications due to its stability and robustness. Recent results obtained from simulation, model experiments, and full-scale structural applications, however, show that it is difficult to employ linear feedback control laws to produce a significant peak response reduction when the peak response occurs during the first few cycles of the time history. In this report, a class of nonlinear control algorithms are proposed which can provide improved peak response control performance. Through extensive simulation studies and experimental verification in the laboratory using a model structure, it is shown that these nonlinear control laws can significantly improve peak response reduction under the same constraints imposed on the control resources as in the linear quadratic regulator case.

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SECTION 1

INTRODUCTION

In recent years, remarkable progress has been made in research and implementation of active structural control technology for structural protection against environmental loads. It is now at the stage where actual systems have been designed, fabricated and installed in full-scale structures (Soong, et al., 1991; Reinhorn, et al., 1993). In most of the operating systems, linear control laws based upon some quadratic performance criteria are being used since they are best understood and they provide stable and robust controlled performance for the structures.

An important consideration in structural control is to reduce the peak structural responses in order to prevent possible structural damage due to severe environmental loads. However, the results obtained from simulations, model experiments and full-scale structural applications show that it is difficult to employ quadratic performance criteria and linear feedback control laws to produce a significant peak response reduction when the peak response occurs during the first few cycles of the time history, which is usually the case under seismic ground excitations (Soong, 1990; Soong and Reinhorn, 1993). This is somewhat expected since the weighted sum of the vibration energy and control energy is minimized in linear quadratic control laws but this minimization does not guarantee minimization of he maximum response. How to suppress the initial large responses, therefore, becomes a problem of practical importance as active control technology becomes more common in civil engineering.

A more effective control performance criterion is clearly one related to the minimization of some function of the maximum response, which has been studies by several authors (Sarma and Kozin, 1971; Glover and Schweppe, 1971; Corless and Leitmann, 1981; Chernousko, 1982). Unfortunately, the existence of an implementable solution for this nonlinear optimal problem has not been clearly established at this time. Lee and Kozin (1985, 1986) investigated the bounded state control of linear structures based on an extension of the Lyapunov function method; however, in their procedure, the external input must be known completely at the beginning, which is not possible in, for example, the earthquake case. Chuang and Wang (1991) introduced an additional state constraint, the oscillation amplitude, into the linear quadratic control law. By adjusting the weighting matrix at different response amplitudes, they derived a bounded state control approach based on the linear control law. This procedure, however, is available only in the scalar case and it also requires some knowledge of the input.

Alternatively, a class of nonlinear control laws based on the minimization of higher-order performance criteria was developed mainly for control of mechanical and electrical systems (Rekasins, 1964; Bass and Webber, 1966; Speyer, 1976; Jacobson, 1977; Suhardjo et al., 1992). The theoretical basis for employing higher-order performance criteria is that minimizing the maximum response can be approximated by minimizing a performance function of this type. That is, a minimax criterion of the type

$$\min_{u} \max_{t} \; g[\mathbf{z}(t)] \tag{1.1}$$

where $\mathbf{z}(t)$ represents the state vector of the structure, $g[\mathbf{z}(t)]$ denotes a positive definite scalar function of $\mathbf{z}(t)$, and u is the control law to be chosen, can be approximated by the criterion

$$\min_{u} \int_{0}^{T} \{g[\mathbf{z}(t)]\}^{2m} dt \tag{1.2}$$

for large m, since (Taylor, 1958)

$$\lim_{m \to \infty} \left\{ \int_{0}^{T} |f(t)|^{2m} dt \right\}^{1/(2m)} = \sup_{t} |f(t)| \tag{1.3}$$

Generally, the integrand in Eq. (1.2) can be replaced by a finite (or infinite) sum of positive definite homogeneous multinomial forms of degree $2m$ $(m = 1, 2, \cdots)$.

Practical applications of these control laws have shown a good control efficiency from the viewpoint of peak response reduction. On the other hand, Bang-Bang control laws, based on minimizing the vibration energy subjected to maximum control force constraint, have also shown a good ability to suppress large responses (Bellman, et. al., 1956;

Wonham and Johnson, 1964; Bryson, 1985; Meirovitch, 1990). Recently, Indrawan and Higashihara (1993) introduced a Bang-Bang control law to the control of a single-degree-of-freedom structure with an active mass damper subjected to seismic loads. Simulation results show that, keeping the same maximum control force, the linear control law gives a maximum displacement of 1.99 *mm*, while the Bang-Bang control law gives a maximum displacement of 1.11 *mm*. Remarkable control efficiency can be achieved by using the proposed Bang-Bang control law. But unfortunately, as this paper stated, servo-hydraulic actuators, which are popular control force delivery devices, are not suitable for this kind of control laws due to high-speed switching of control forces. Therefore, some modifications are necessary for practical implementation of Bang-Bang control laws in civil engineering.

The work presented in this report is focused on the development of implementable nonlinear control laws which can provide improved peak response control performance under the same constraints imposed on the control force and other resources as in the linear control law case. First, five different nonlinear control laws, based on both higher-order performance criterion and Bang-Bang control theory, are proposed in Section 2. The maximum control force constraint is imposed on these nonlinear control laws for practical consideration. Then, in Section 3, extensive parametric studies are performed, especially to identify the regions of effectiveness for nonlinear parameters. The influence of the maximum control force constraint is evaluated. Based on the typical parameters selected in Section 3, a series of comprehensive control experiments are carried out in the laboratory using model structures with ground excitations supplied by a shaking table. Section 4 is devoted to the presentation of the experimental results. The effectiveness of the proposed nonlinear control laws in peak response reduction is demonstrated experimentally. Finally, good agreement between numerical simulations and experimental results leads to the conclusion, in Section 5, that implementation of the proposed nonlinear control laws does not bring inherent difficulties to achieving a real enhancement of structural control performances.

SECTION 2
CONTROL ALGORITHMS

2.1 Brief Review of Classical Linear Quadratic Regulator (LQR)

Consider a general linear building structure modelled by an n-degree-of-freedom lumped mass-spring-dashpot system. The matrix equation of motion of the structural system, subjected to a horizontal earthquake ground acceleration $\ddot{x}_0(t)$ can be written as

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{D}\mathbf{u}(t) + \mathbf{m}\ddot{x}_0(t) \tag{2.1}$$

where $\mathbf{x}(t) = [x_1, x_2, \cdot \cdot \cdot, x_n]^T$ is an n-dimensional vector of relative displacements, $\mathbf{u}(t)$ is a r-dimensional control force vector, $\mathbf{D}$ is an $n \times r$ matrix denoting the location of the controllers, $\mathbf{M}$ is an $n \times n$ diagonal matrix with jth diagonal element m_j, $\mathbf{m} = -[m_1, m_2, \cdot \cdot \cdot, m_n]^T$, and $\mathbf{C}$ and $\mathbf{K}$ are $n \times n$ tri-diagonal damping and stiffness matrices, respectively. In the above, the superscript T indicates vector or matrix transpose.

In the state-space representation, Eq. (2.1) becomes

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{w}\ddot{x}_0(t) \tag{2.2}$$

where

$$\mathbf{z}(t) = \begin{bmatrix} \mathbf{x}(t) \\ \dot{\mathbf{x}}(t) \end{bmatrix} \; ; \quad \mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix} \; ; \quad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{D} \end{bmatrix} \; ; \quad \mathbf{w} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{m} \end{bmatrix} \tag{2.3}$$

In classical linear quadratic regulator (LQR), the control force is linear in the state vector $\mathbf{z}(t)$ (Soong,1990), i. e.,

$$\mathbf{u}(t) = \mathbf{G}\mathbf{z}(t) = -\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z}(t) \tag{2.4}$$

in which the control gain matrix **G** is found by minimizing

$$J = \frac{1}{2}\int_0^{t_f}\left[\mathbf{z}^T(t)\,\mathbf{Q}\mathbf{z}(t) + \mathbf{u}^T(t)\,\mathbf{R}\mathbf{u}(t)\right]dt \qquad (2.5)$$

where **Q** is a $2n \times 2n$ positive semi-definite weighting matrix and **R** is a $r \times r$ positive definite weighting matrix. In Eq. (2.4), **P** is the Riccati matrix which can be obtained by solving the approximated time invariant Riccati matrix equation

$$\mathbf{PA} + \mathbf{A}^T\mathbf{P} - \mathbf{PBR}^{-1}\mathbf{B}^T\mathbf{P} + \mathbf{Q} = \mathbf{0} \qquad (2.6)$$

As seen from Eq. (2.5), the linear control law derived above, while effective in reducing the structural response in the time-averaged mean-square sense, may not be effective in reducing the peak response, particularly when the peak response occurs near the beginning of the excitation interval. Since peak response reduction is of practical importance in structural control, other forms of the control law may be more desirable. A natural candidate is a control law which is nonlinear in the state vector in order that the control force be more sensitive to larger response values.

2.2 Higher-Order Regulator Formulation

In order to have a performance index that is more sensitive to larger response values, higher-order terms of the response vector are introduced into the performance index as follows:

$$J = \frac{1}{2}\int_0^{t_f}\left[\mathbf{z}^T\mathbf{Q}\mathbf{z}\left(1 + \alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right) + \left(\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)\mathbf{z}^T\mathbf{PBR}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z}\left(1 + \alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right) + \mathbf{u}^T\mathbf{R}\mathbf{u}\right]dt \qquad (2.7)$$

in which **Q** and **R** are the same as in Eq. (2.5), α_1 is a nonlinear feedback weighting factor, and **P** is an unknown symmetric matrix. In minimizing this kind of a performance index, not only the total energy but also its higher order terms are minimized, which should lead to a more effective control law in terms of maximum response control.

Following the same procedure as in the linear quadratic regular case, one can first form the Hamiltonian as

$$\mathcal{H} = \frac{1}{2}\left[\mathbf{z}^T\mathbf{Q}\mathbf{z}\left(1+\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)+\left(\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)\mathbf{z}^T\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z}\left(1+\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)+\mathbf{u}^T\mathbf{R}\mathbf{u}\right] + \lambda^T\left[\mathbf{A}\mathbf{z}+\mathbf{B}\mathbf{u}+\mathbf{w}\ddot{x}_0-\dot{\mathbf{z}}\right] \tag{2.8}$$

The necessary conditions for optimal control are

$$\frac{\partial\mathcal{H}}{\partial\lambda} = \mathbf{0} \;;\quad \frac{\partial\mathcal{H}}{\partial\mathbf{u}} = \mathbf{0} \;;\quad \dot{\lambda}^T - \frac{\partial\mathcal{H}}{\partial\mathbf{z}} = \mathbf{0} \;;\quad \lambda^T(t_f) = \mathbf{0} \;; \tag{2.9}$$

By carrying out necessary partial derivatives of $\mathcal{H}$ with respect to $\mathbf{u}$ and $\mathbf{z}$, one obtains

$$\mathbf{u}(t) = -\mathbf{R}^{-1}\mathbf{B}^T\lambda(t) \;; \qquad 0 \le t \le t_f \tag{2.10}$$

$$\begin{aligned}\dot{\lambda}(t) = & -\mathbf{A}^T\lambda-\left(1+\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)\mathbf{Q}\mathbf{z}-\left(\alpha_1\mathbf{z}^T\mathbf{Q}\mathbf{z}\right)\mathbf{P}\mathbf{z} \\ & -\left(1+\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)\left(\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z} \\ & -\left(1+\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)\left(\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z}\right)\mathbf{P}\mathbf{z} \\ & -\left(\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)\left(\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z}\right)\mathbf{P}\mathbf{z}\end{aligned} \tag{2.11}$$

The set of Eqs. (2.2), (2.10) and (2.11) provides the optimal solution for $\mathbf{z}(t)$, $\mathbf{u}(t)$ and $\lambda(t)$. Once the form of $\lambda(t)$ is assumed according to a prescribed control strategy, the optimal control force can be derived.

In view of the non-quadratic terms in the performance index, a nonlinear feedback control law appears to be appropriate. Hence, let $\lambda(t)$ be of the form

$$\lambda(t) = \left(1+\alpha_1\mathbf{z}^T\mathbf{P}\mathbf{z}\right)\mathbf{P}\mathbf{z} \tag{2.12}$$

where $\mathbf{P}$ is a $2n \times 2n$ matrix to be determined. Taking the derivative of $\lambda(t)$ with respect to time t, one has

$$\dot{\lambda}(t) = \left[\left(1+\alpha_1 \mathbf{z}^T\mathbf{P}\mathbf{z}\right)\mathbf{P} + 2\alpha_1 \mathbf{P}\mathbf{z}\mathbf{z}^T\mathbf{P}\right]\dot{\mathbf{z}} \tag{2.13}$$

Substituting Eq. (2.12) into Eq. (2.10), the control law is found to be

$$\mathbf{u}(t) = -\left(1+\alpha_1 \mathbf{z}^T\mathbf{P}\mathbf{z}\right)\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z} \tag{2.14}$$

If the input is neglected, Eq. (2.2) becomes

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z} - \left(1+\alpha_1 \mathbf{z}^T\mathbf{P}\mathbf{z}\right)\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z} \tag{2.15}$$

Substituting Eq. (2.15) into Eq. (2.13), the derivative of $\lambda(t)$ is

$$\begin{aligned}\dot{\lambda}(t) = {} & \left(1+\alpha_1 \mathbf{z}^T\mathbf{P}\mathbf{z}\right)\mathbf{P}\mathbf{A}\mathbf{z} - \left(1+\alpha_1 \mathbf{z}^T\mathbf{P}\mathbf{z}\right)^2\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z} + \\ & \left[\alpha_1 \mathbf{z}^T\left(\mathbf{P}\mathbf{A}+\mathbf{A}^T\mathbf{P}\right)\mathbf{z}\right]\mathbf{P}\mathbf{z} - 2\left(1+\alpha_1 \mathbf{z}^T\mathbf{P}\mathbf{z}\right)\left(\alpha_1 \mathbf{z}^T\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}\mathbf{z}\right)\mathbf{P}\mathbf{z}\end{aligned} \tag{2.16}$$

Equating the right-hand sides of Eqs. (2.11) and (2.16) leads to

$$\begin{aligned}& \left(1+\alpha_1 \mathbf{z}^T\mathbf{P}\mathbf{z}\right)\left(\mathbf{P}\mathbf{A}+\mathbf{A}^T\mathbf{P}-\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}+\mathbf{Q}\right)\mathbf{z} - \\ & \quad \left[\alpha_1 \mathbf{z}^T\left(\mathbf{P}\mathbf{A}+\mathbf{A}^T\mathbf{P}-\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}+\mathbf{Q}\right)\mathbf{z}\right]\mathbf{P}\mathbf{z} = \mathbf{0}\end{aligned} \tag{2.17}$$

which holds if and only if the following equation is satisfied:

$$\mathbf{P}\mathbf{A}+\mathbf{A}^T\mathbf{P}-\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}+\mathbf{Q} = \mathbf{0} \tag{2.18}$$

This is seen to be the standard matrix Riccati equation. There are many solution algorithms which can be used to determine the Riccati matrix $\mathbf{P}$. Finally, the substitution of $\mathbf{P}$ into Eq. (2.14) produces the desired control law. Obviously, for small response $\mathbf{z}(t)$ or small weighting factor α_1, $\mathbf{u}(t)$ reduces to Eq. (2.4), which is the standard linear control law based on the quadratic performance criterion. In this report, we call Eq. (2.14) *Nonlinear Control Algorithm 1.*

2.3 Power Series Feedback Control Law

It is noted that in Eq. (2.14) the nonlinear term is of the third order of $\mathbf{z}(t)$. A natural extension is to include higher-order terms of $\mathbf{z}(t)$ in the form

$$\mathbf{u}(t) = \mathbf{G}\mathbf{z}(t) + \frac{\alpha_2^2}{3!}\mathbf{G}\mathbf{z}^3(t) + \frac{\alpha_2^4}{5!}\mathbf{G}\mathbf{z}^5(t) + \cdots = \frac{1}{\alpha_2}\mathbf{G}\ \mathrm{sh}(\alpha_2\mathbf{z}) \qquad (2.19)$$

in which

$$\mathbf{z}^i(t) = \left[z_1^i(t), z_2^i(t), \cdots, z_n^i(t)\right]^T \qquad (2.20)$$

α_2 is also a nonlinear feedback weighting factor and $\mathrm{sh}(x)$ is the hyperbolic sine function. Equation (2.19) is called *Nonlinear Control Algorithm 2* here.

2.4 Polynomial Velocity Feedback Control Law

In Eq. (2.14) the feedback control force includes both displacement feedback and velocity feedback. Generally, velocity feedback dominates the control force. Therefore, another two nonlinear velocity feedback control laws, enhanced by a quadratic term in velocity or displacement, are proposed specially for single-degree-of-freedom (SDOF) systems. They are

$$u(t) = g_{\dot{x}}\dot{x}(t) + \left[\alpha_3\dot{x}^2(t)\right]g_{\dot{x}}\dot{x}(t) \qquad (2.21)$$

$$u(t) = g_{\dot{x}}\dot{x}(t) + \left[\alpha_4 x^2(t)\right]g_{\dot{x}}\dot{x}(t) \qquad (2.22)$$

where $g_{\dot{x}}$ is an element of control gain vector $\mathbf{g} = [g_x, g_{\dot{x}}]$. In turn, Eq. (2.21) and Eq.

(2.22) are called *Nonlinear Control Algorithms 3 and 4*, respectively.

2.5 Inverse Order Feedback Control Law

All of the control laws presented above provide the control forces which are directly proportional to some powers of the response $\mathbf{z}(t)$. In practical applications, however, due to necessary control force limitations, a control force constraint is usually imposed on the nonlinear control laws, which is difficult to deal with theoretically. In view of this requirement, a control law which is inversely proportional to some powers of the response is suggested below.

First consider a SDOF system. If performance index takes the form

$$J = \frac{1}{2} \int_{0}^{t_f} \left[\mathbf{z}^T(t) \mathbf{Q} \mathbf{z}(t) \right] dt \tag{2.23}$$

and subjected to the maximum control force constraint

$$\max |\mathrm{u}(t)| \le \mathrm{u}_b \tag{2.24}$$

then from Bang-Bang control theory, we know that the optimal control force is

$$\mathrm{u}(t) = -\mathrm{u}_b \mathrm{sgn} \left[\mathbf{B}^T \lambda(t) \right] \tag{2.25}$$

in which $\lambda(t)$ is the co-state vector and $\mathrm{sgn}[x]$ denotes the signum function. When velocity feedback is dominant in the control force, we can approximate $\mathrm{u}(t)$ as

$$\mathrm{u}(t) = -\mathrm{u}_b \mathrm{sgn}\left[\dot{x}(t) \right] = \mathrm{u}_b \frac{\dot{x}(t)}{|\dot{x}(t)|} \tag{2.26}$$

In the linear control case, the maximum control force is approximately

$$\max |\mathrm{u}(t)| = g_{\dot{x}} (\dot{x})^{L}_{max} \tag{2.27}$$

where $(\dot{x})^L_{max}$ is the absolute maximum of relative velocity during $[0, t_f]$ under linear control. In the nonlinear control case, when keeping the same maximum control force as in the linear control, Eq. (2.26) becomes

$$\mathrm{u}(t) = g_{\dot{x}} \frac{\dot{x}(t)}{|\dot{x}(t)|} (\dot{x})^L_{max} = \gamma(t) g_{\dot{x}} \dot{x}(t) \tag{2.28}$$

where

$$\gamma(t) = \frac{(\dot{x})^L_{max}}{|\dot{x}(t)|} ; \qquad 1.0 \le \gamma(t) \le \gamma_{max} \tag{2.29}$$

represents a time-variant amplification factor which is an inverse function of the velocity response and is bounded by γ_{max} in order to prevent $\gamma(t)$ from becoming unbounded as $\dot{x}(t)$ approaches zero.

For a MDOF system, the control force vector corresponding to Eq. (2.28) takes the form

$$\mathbf{u}(t) = \mathbf{G}_x \mathbf{x}(t) + \gamma(t) \mathbf{G}_{\dot{x}} \dot{\mathbf{x}}(t) \tag{2.30}$$

and the top floor response is chosen to form $\gamma(t)$, i.e.,

$$\gamma(t) = \alpha_5 \frac{(\dot{x}_n)^L_{max}}{|\dot{x}_n(t)|} ; \qquad 1.0 \le \gamma(t) \le \gamma_{max} \tag{2.31}$$

where subscript n represents the top floor and α_5 is a nonlinear weighting factor. Finally, Eq. (2.30) is called *Nonlinear Control Algorithm 5.*

To sum up, all five nonlinear control algorithms proposed in this report are listed in Table 2-1.

2.6 Maximum Control Force Constraint

The possibility of reaching the maximum limit in the control force requirement is a desirable condition in order to enhance the control effectiveness. However, the demand on the control force for the nonlinear control laws presented above depends on the frequency content of the forcing term and on the amplitude of the external excitation. This direct dependency on the amplitude of the external excitation is not a desirable characteristic in designing active devices. Indeed, difficulties in determining the control force requirement related to stochastic behavior of the external excitation are increased by the nonlinearity of the controller. Moreover, similar reasons do not permit one to easily conduct comparative studies between the performance of nonlinear algorithms and the classical LQR. Therefore, a maximum control force constraint, exactly the same as Eq. (2.24) in the nonlinear control algorithm 5, is added to the nonlinear control algorithms 1 to 4. Thus, in order to evaluate the performance of the nonlinear algorithms, a reference level of performance for the system will be determined by a specified level of performance of the linear control algorithm (LQR). This performance level determines the peak value of the linear control force which is then taken as the bounded control force u_b for the nonlinear algorithms.

Table 2-1. Nonlinear Control Algorithms

Algorithms	Formulae
LQR	$\mathbf{u}(t) = \mathbf{G}\mathbf{z}(t) = -\mathbf{R}^{-1}\mathbf{B}^{T}\mathbf{P}\mathbf{z}(t)$
Nonlinear 1	$\mathbf{u}(t) = -\left(1 + \alpha_1 \mathbf{z}^{T}\mathbf{P}\mathbf{z}\right)\mathbf{R}^{-1}\mathbf{B}^{T}\mathbf{P}\mathbf{z}$
Nonlinear 2	$\mathbf{u}(t) = \mathbf{G}\mathbf{z}(t) + \frac{\alpha_2^2}{3!}\mathbf{G}\mathbf{z}^3(t) + \frac{\alpha_2^4}{5!}\mathbf{G}\mathbf{z}^5(t) + \cdot\ \cdot\ \cdot$
Nonlinear 3	$u(t) = g_x \dot{x}(t) + \left[\alpha_3 \dot{x}^2(t)\right] g_{\dot{x}} \dot{x}(t)$
Nonlinear 4	$u(t) = g_x \dot{x}(t) + \left[\alpha_4 x^2(t)\right] g_{\dot{x}} \dot{x}(t)$
Nonlinear 5	$\mathbf{u}(t) = \mathbf{G}_x \mathbf{x}(t) + \gamma(t)\,\mathbf{G}_{\dot{x}} \dot{\mathbf{x}}(t)$

SECTION 3

PARAMETRIC STUDIES

3.1 Introduction

The nonlinear control laws proposed in Section 2 are extensively investigated in this section by numerical simulation. Numerical calculations are necessary in the design process of control systems to determine the parameter values or control gains for obtaining an optimal feedback. In the expressions of these nonlinear control algorithms, two groups of parameters are unknown. The first one is related to the linear part of the feedback and the second one concerns the nonlinear part. The determination of the linear gains can be carried out by solving the optimal problem characterized by the Riccati equation (Eq. (2.6)). Optimal formulation using the linear quadratic functional permits one to regulate the level of control activity by an appropriate choice of weighting matrices $\mathbf{Q}$ and $\mathbf{R}$. The influence of the choice of matrices $\mathbf{Q}$ and $\mathbf{R}$ on the control performance is analyzed for two structural systems. Correspondingly, in the nonlinear feedback part, the emphasis of parametric studies is placed on the weighting coefficient α. The introduction of this parameter in the nonlinear expression permits one to regulate the relative importance between the linear and the nonlinear terms. A correct choice of α has been found to be important for enhancing control performance. Thus, the study of the influence of parameter on the structural response is carried out first. Finally, through extensive parametric studies, the design parameter values for experimental verification are suggested.

3.2 Controlled Structural Systems and Earthquake Inputs

The effectiveness of the nonlinear control techniques for peak response reduction is evaluated using two different structural systems. The first controlled structure is a one-story steel frame with a set of active tendon control devices, which can be idealized as a single-degree-of-freedom (SDOF) control system. The second one is a three-story steel frame with the same active tendon control devices as in the SDOF system. A schematic sketch of this system is shown in Fig. 3-1. Actually, if the top tow floors of the three-story frame are braced rigidly, the MDOF system becomes a SDOF system. Later in the experimental phase, this technique will be utilized to build the model structures. The dynamic parameter values of the structural system are given in Table 3-1, which are chosen to correspond to the ones estimated from an identification process of the experimental set-up that will be presented in the next section.

As typical earthquake records, the N-S component of the 1940 El Centro acceleration record and the N21E component of the 1957 Taft earthquake record are chosen as the base excitations due to dependency of the nonlinear control laws on the frequency content of the external input. But the intensities of these records are scaled down appropriately in order to prevent the structure from exceeding the elastic limit in the uncontrolled case and to have a comparable level of excitations. The two base acceleration time histories are shown in Fig. 3-2.

The parametric studies are performed for different structural systems, under different earthquake inputs, and by using different control algorithms. Table 3-2 summarizes all parametric study cases in this investigation.

3.3 Weighting Matrices Q and R

Under the quadratic performance criterion expressed by Eq. (2.5), the feedback control law is designed such that integral J is minimized. Generally, in terms of minimizing vibratory energy and control energy, weighting matrix **Q** can be chosen as

$$\mathbf{Q}_1 = \begin{bmatrix} \mathbf{K} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \quad or \quad \mathbf{Q}_2 = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{M} \end{bmatrix} \quad or \quad \mathbf{Q}_3 = \begin{bmatrix} \mathbf{K} & \mathbf{0} \\ \mathbf{0} & \mathbf{M} \end{bmatrix} \tag{3.1}$$

and since only one controller is used in this investigation weighting matrix **R** is a scalar which takes the form

$$R = 4\beta k_c \tag{3.2}$$

In Eqs. (3.1) and (3.2), **K** and **M** are the structural stiffness and mass matrices, respectively; k_c is the tendon stiffness; and β is a non-dimensional parameter which determines the relative importance of control effectiveness (response reduction) and economy (control force requirement). The results from previous research (Wu and Soong, 1994) have shown that choice of weighting matrix **Q** among $\mathbf{Q}_1$, $\mathbf{Q}_2$ or $\mathbf{Q}_3$ would lead to almost the same control efficiency if the corresponding weighting coefficient β is chosen properly. Therefore, the parametric study in terms of weighting matrices **Q** and **R** is focused on the evaluation of effectiveness of the control actions for different choices of the parameter β. The weighting matrix **Q** is simply taken as $\mathbf{Q} = \mathbf{Q}_1$.

At the beginning of the parametric study, it is useful to introduce a definition for the reduction factor which will be used as a measure of control efficiency. it is defined by

$$R_e = \frac{\max|V_u| - \max|V_c|}{\max|V_u|} \tag{3.3}$$

where V represents a general response quantity such as relative displacement, relative velocity or absolute acceleration, and subscripts u and c denote the uncontrolled and controlled cases, respectively.

First, consider the SDOF system. Figure 3-3 shows the numerical simulation results representing the maximum relative displacement reduction, maximum absolute acceleration reduction and maximum required control force for different β values under the 1/3-scaled N-S El Centro acceleration input. It is clearly illustrated that, as the value of β decreases, the control force increases, leading to an increase in response reduction. Therefore, the selection of the level of control activity by choosing an optimal value of β depends on the capacity of the employed control device. Initially, a value of $\beta = 32$ is chosen as a reference for the next nonlinear control analysis, and the corresponding maximum control force is 0.92 *kN*.

For the three-story frame controlled by one active device, the maximum response reductions at the top-floor are drawn in Fig. 3-4 under the 1/4-scaled El Centro earthquake input, and the exact peak values are listed in Table 3-3 under the 1/2-scaled Taft earthquake input. The response reduction trend by varying the parameter β is similar to the previous SDOF system case. But note that, in the case of the scaled El Centro excitation, a value of β smaller than 32 produces a decreasing rate of acceleration reduction. Thus, the aforementioned value of β may be suitable for the next nonlinear control analysis in consideration of a better force reduction performance. Correspondingly, the maximum control forces are 0.984 *kN* and 1.194 *kN* for El Centro and Taft earthquake excitations, respectively.

3.4 Weighting Coefficient α

Keeping the same β value and observing maximum control force limitation as in the linear control case, an extensive parametric study about coefficient α has been carried out as summarized in Table 3-2. The results are given in terms of peak response reduction, response time history and accumulated energy time history.

3.4.1 Peak Response Reductions

The nonlinear differential equations governing the closed-loop systems are numerically solved in the time domain using the Adams-Moulton method and the high-order Runge-Kutta integration scheme. The peak responses are evaluated for a wide range of values of parameter α and using different nonlinear control laws. Figure 3-5 shows the peak response reductions at the top-floor of the three-story frame obtained from nonlinear control algorithm 1 (Case 4) under the 1/4 El Centro earthquake excitation. Table 3-4 gives the results using the same nonlinear control law under the 1/2 Taft earthquake input. It can be clearly seen that, as the value of α increases, the peak response reduction of relative displacement increases significantly under the same maximum control force limitation as in the linear control case. For example, as seen from Fig. 3-5, the reduction under linear control is 37% and 53% under nonlinear control at $\alpha_1 = 0.032$. These results indicate that the proposed nonlinear control law is more suitable than a linear one since it can produce a larger peak response reduction under the same control force requirement. For acceleration response reduction, the improvement by using the nonlinear control law is within 5% range compared with the linear control case, and as the value of α_1 increases the peak response reduction becomes even worse. Thus, a decision of using $\alpha_1 = 0.016$ is made for nonlinear control algorithm 1 based on a proper trade off between structural safety and occupant comfort.

Similar results were obtained by employing other nonlinear control laws (Wu, et al., 1994, Gattulli 1994). These results show that all nonlinear control laws presented in the previous section yield a better control performance than LQR control in term of reducing the peak response. Generally, reductions for the relative displacement are 10% - 15% over that in the linear control case. For reduction of the peak absolute acceleration, nonlinear control algorithm 5 is better than the others. According to the trade off between structural safety and occupant comfort, an optimal value of α is chosen for each nonlinear control algorithm as listed in Table 3-5.

3.4.2 Response Time Histories

Using the optimal values chosen for parameters β and α, response time histories can be calculated directly by using numerical integration method in the time domain. A set of typical response time histories for uncontrolled, linear controlled and nonlinear controlled cases are shown in Fig. 3-6, showing the top floor responses of the three-story frame under the 1/4-scaled El Centro earthquake excitation, and the nonlinear control is Case 4. These time histories illustrate that not only the peak values but the overall responses are also reduced by employing the proposed nonlinear control law. Also as expected, the maximum control force applied in the nonlinear control case is kept at the same value as in the linear control case.

3.4.3 Accumulated Energy Time Histories

Energy formulations have been developed to evaluate the performance of structural systems (Zahrah and Hall, 1982; Uang and Bertero,1988). The evaluation of energy dissipation capacity of control devices is one way of studying a wide range of behavior characteristics concerning the considerable number of different passive and active devices installed in structures throughout the world. On this basis, comparative studies can be performed among different innovative technologies.

For a MDOF controlled system, the equation of motion is given in Eq. (2.1). This can be considered as a force equilibrium equation, each term representing a force that will do work during the dynamic event. Thus, an energy equilibrium equation can be derived, giving

$$E_K + E_D + E_S = E_u + E_I \tag{3.4}$$

where E_K is the kinetic energy, E_D is the viscously damped energy, E_S is the strain energy, E_u is the control force energy and E_I is the input energy. The expressions of these energy terms are

$$E_K = \frac{1}{2}\dot{\mathbf{X}}^T\mathbf{M}\dot{\mathbf{X}} \tag{3.5}$$

$$E_D = \int \dot{\mathbf{X}}^T\mathbf{C}\dot{\mathbf{X}}dt \tag{3.6}$$

$$E_S = \frac{1}{2}\mathbf{X}^T\mathbf{K}\mathbf{X} \tag{3.7}$$

$$E_u = \int \mathbf{u}^T\mathbf{D}^T d\mathbf{X} \tag{3.8}$$

$$E_I = \int \ddot{x}_0\mathbf{m}^T d\mathbf{X} \tag{3.9}$$

It can be seen that each energy term is a function of time and has positive values. Figures 3-7, 3-8 and 3-9 show the accumulated energy time histories for, respectively, the uncontrolled, linear controlled and nonlinear controlled cases. First, from Fig. 3-7, it is noted that, in the uncontrolled case, a significant portion of the energy input to the structure is dissipated by inherent damping. Evidently, the consumption of this quantity of energy may force the structure into the nonlinear range of material behavior accompanied by excessive response and consequently structural damage. On the other hand, the introduction of the active control system consumes a large portion of the input energy, which is clearly demonstrated in Fig. 3-8 for the case of linear control. Furthermore, it can be observed from Fig. 3-9 that, if the active control action follows the nonlinear control law, only a small portion of the total input energy is dissipated by inherent damping, while the active control energy is dominant. Since structural damping does not change with installation of the control system, the decrease in viscous damping energy in the controlled case indicates that a remarkable reduction in the structural response is achieved by applying an active control force.

Table 3-1. Parameter Values of Structural Systems

Parameters	Values	
	SDOF	MDOF
Mass matrix **M** (*kg*)	2943	$\begin{bmatrix} 981 & 0 & 0 \\ 0 & 981 & 0 \\ 0 & 0 & 981 \end{bmatrix}$
Natural frequency **f** (*Hz*)	4.10	$\begin{bmatrix} 2.37 & 7.45 & 12.30 \end{bmatrix}^T$
Damping factor ξ (%)	2.62	$\begin{bmatrix} 1.00 & 0.53 & 0.55 \end{bmatrix}^T$
Modal matrix Φ	1.0	$\begin{bmatrix} 0.0897 & 0.2859 & 0.2979 \\ 0.2365 & 0.2143 & -0.2769 \\ 0.3385 & -0.2255 & 0.1146 \end{bmatrix}$
Tendon stiffness k_c (*kN/m*)	385.3	411.55
Tendon angle θ (*deg.*)	36	36

Table 3-2. Summary of Parametric Studies

Systems	Earthquakes	Cases & Algorithms	Parameters	Results
SDOF	El Centro (1/3)	LQR	**Q, R**	Peak Value, Time History, Accumulated Energy
		Case 1: Nonlinear 2	α_2	
		Case 2: Nonlinear 3	α_3	
		Case 3: Nonlinear 4	α_4	
MDOF	El Centro (1/4) Taft (1/2)	LQR	**Q, R**	
		Case 4: Nonlinear 1	α_1	
		Case 5: Nonlinear 2	α_2	
		Case 6: Nonlinear 5	α_5	

Table 3-3. Maximum Response of Three-Story Frame with LQR Control

(1/2 Scaled TAFT Earthquake Input)

Control Algorithms	Floor No.	Relative Displacement		Absolute Acceleration		Control Force (kN)
		Values (cm)	Reduction (%)	Values (g)	Reduction (%)	
Uncontrolled	1	0.353		0.235		0.000
	2	0.912		0.283		
	3	1.420		0.430		
Linear Control $\beta = 256$	1	0.292	17.13	0.199	15.42	0.372
	2	0.823	9.750	0.245	13.44	
	3	1.271	10.52	0.376	12.61	
Linear Control $\beta = 128$	1	0.274	22.39	0.177	24.58	0.572
	2	0.783	14.09	0.233	17.57	
	3	1.204	15.21	0.347	19.31	
Linear Control $\beta = 64$	1	0.251	28.87	0.171	30.44	0.862
	2	0.722	20.78	0.202	28.72	
	3	1.108	21.97	0.317	26.29	
Linear Control $\beta = 32$	1	0.226	35.93	0.147	37.15	1.194
	2	0.646	29.11	0.181	36.17	
	3	0.992	30.13	0.284	33.83	
Linear Control $\beta = 16$	1	0.195	44.71	0.143	41.75	1.561
	2	0.564	38.19	0.154	45.54	
	3	0.864	39.18	0.246	42.76	
Linear Control $\beta = 8$	1	0.163	53.78	0.121	48.32	1.935
	2	0.473	48.16	0.136	51.87	
	3	0.726	48.84	0.207	51.84	

Table 3-4. Maximum Response for Nonlinear Control Algorithm 1

(1/2 Scaled TAFT Earthquake Input)

Control Algorithms	Floor No.	Relative Displacement		Absolute Acceleration		Control Force (kN)
		Values (cm)	Reduction (%)	Values (g)	Reduction (%)	
Uncontrolled	1	0.353		0.235		
	2	0.912		0.283		
	3	1.420		0.430		
Linear Control $\beta = 32$	1	0.226	35.93	0.147	37.15	1.194
	2	0.646	29.11	0.181	36.17	
	3	0.992	30.13	0.284	33.83	
Nonlinear 1 $\beta = 32$ $\alpha_1 = 0.004$	1	0.201	43.06	0.157	33.19	1.194
	2	0.598	34.43	0.193	31.80	
	3	0.928	34.65	0.283	34.19	
Nonlinear 1 $\beta = 32$ $\alpha_1 = 0.008$	1	0.192	45.61	0.187	20.43	1.194
	2	0.569	37.61	0.202	28.62	
	3	0.892	37.18	0.287	33.26	
Nonlinear 1 $\beta = 32$ $\alpha_1 = 0.016$	1	0.179	49.29	0.212	9.787	1.194
	2	0.538	41.01	0.207	26.86	
	3	0.844	40.56	0.287	33.26	
Nonlinear 1 $\beta = 32$ $\alpha_1 = 0.032$	1	0.177	49.86	0.225	4.255	1.194
	2	0.505	44.63	0.211	25.44	
	3	0.790	44.37	0.281	34.65	
Nonlinear 1 $\beta = 32$ $\alpha_1 = 0.064$	1	0.176	50.14	0.243	-3.40	1.194
	2	0.472	48.25	0.224	20.85	
	3	0.739	47.96	0.279	35.12	

Table 3-5. Optimal Value for Nonlinear Control Laws

Systems	Cases & Algorithms	Parameters	Max. Force (kN)
	LQR	$\beta = 32$	0.920
SDOF	Case 1: Nonlinear 2	$\alpha_2 = 0.6$	(El Centro)
	Case 2: Nonlinear 3	$\alpha_3 = 0.06$	
	Case 3: Nonlinear 4	$\alpha_4 = 120$	
	LQR	$\beta = 32$	0.984
MDOF	Case 4: Nonlinear 1	$\alpha_1 = 0.016$	(El Centro)
	Case 5: Nonlinear 2	$\alpha_2 = 1.2$	1.194
	Case 6: Nonlinear 5	$\alpha_5 = 0.8$	(Taft)

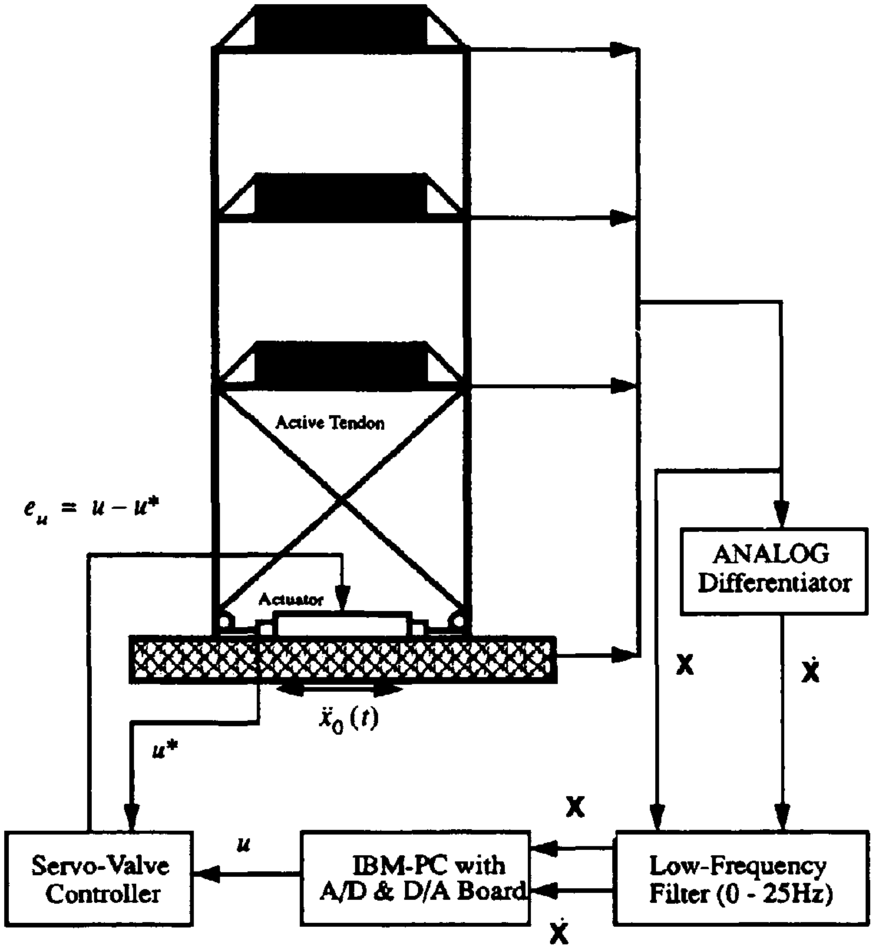
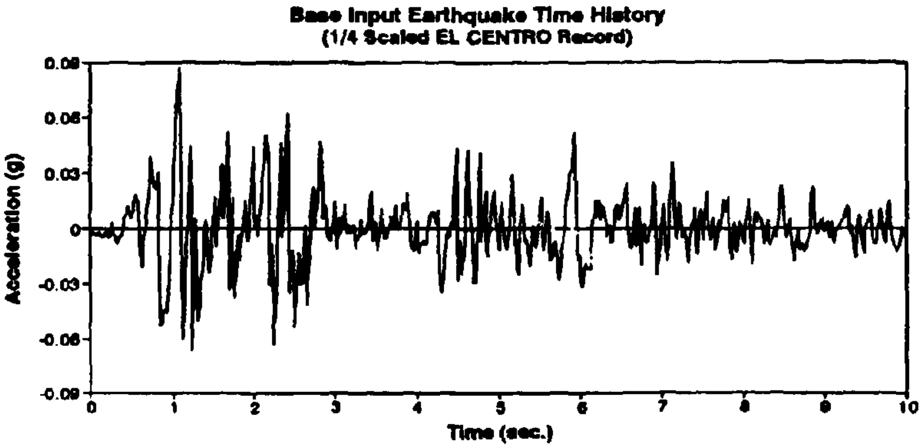


Fig. 3-1. Structural System and Control System



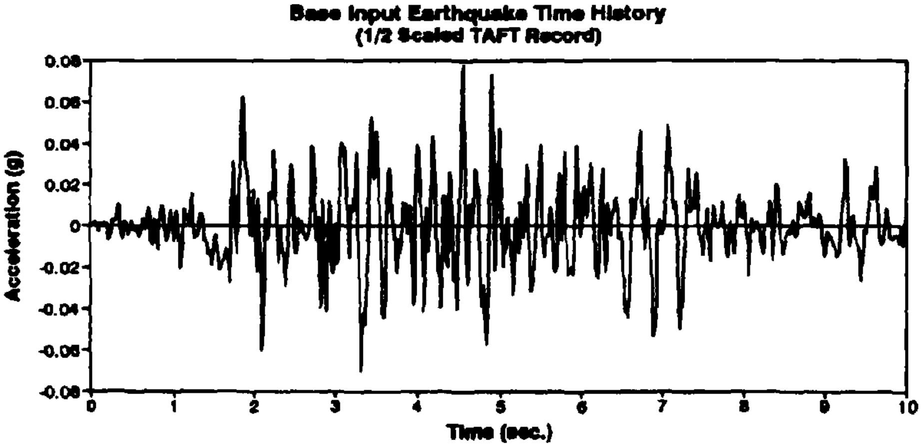


Fig. 3-2. Base Input Earthquake Time Histories

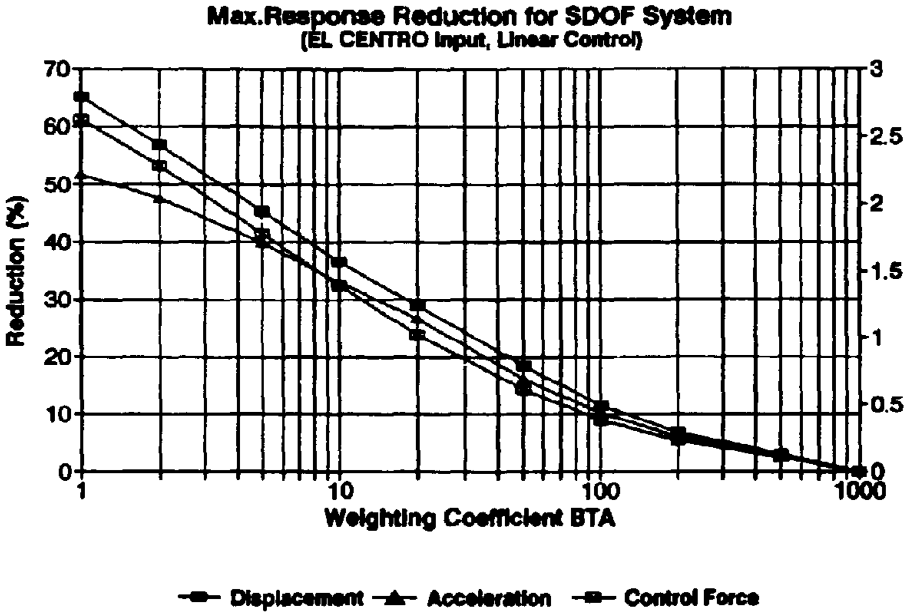


Fig. 3-3. Maximum Response Reduction of SDOF System with LQR Control

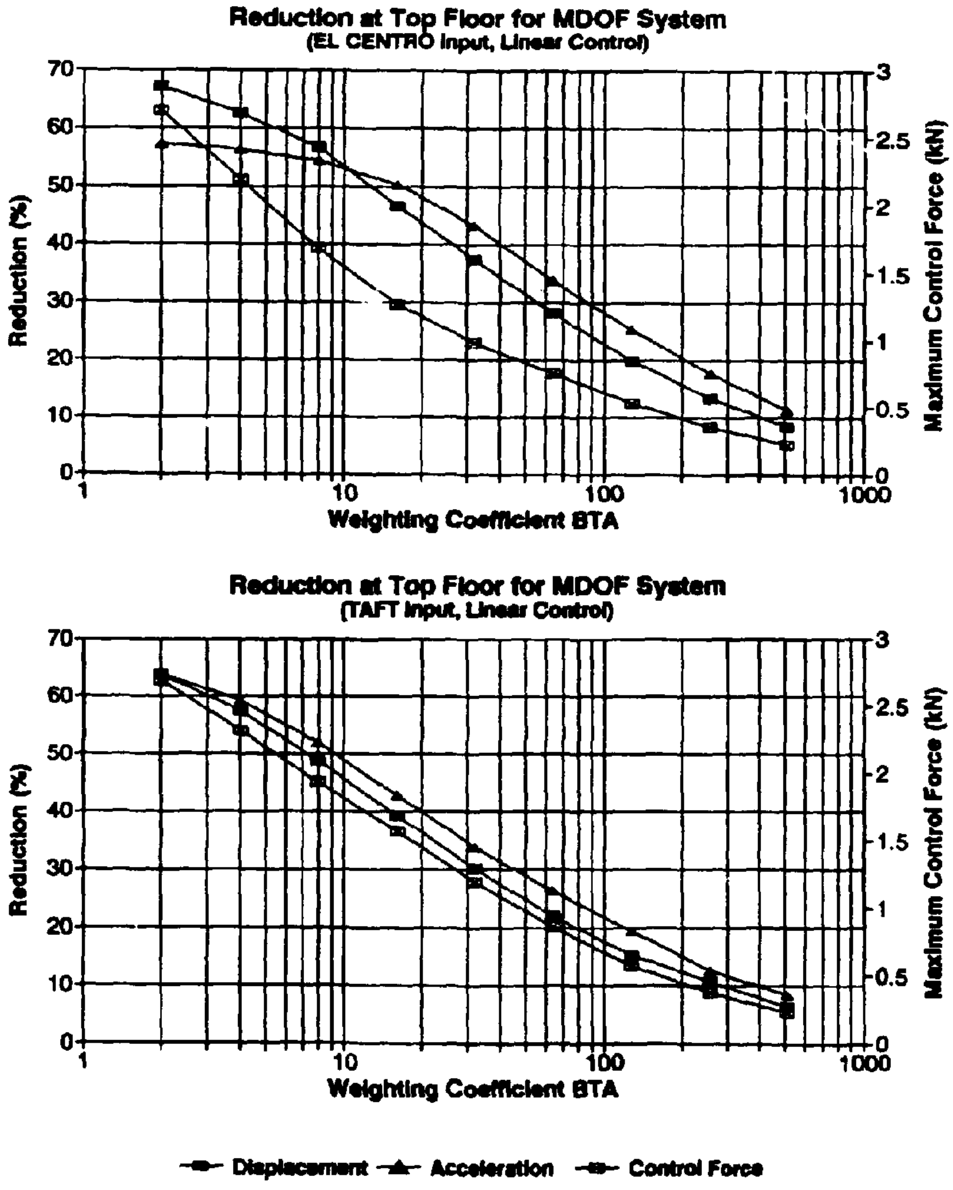
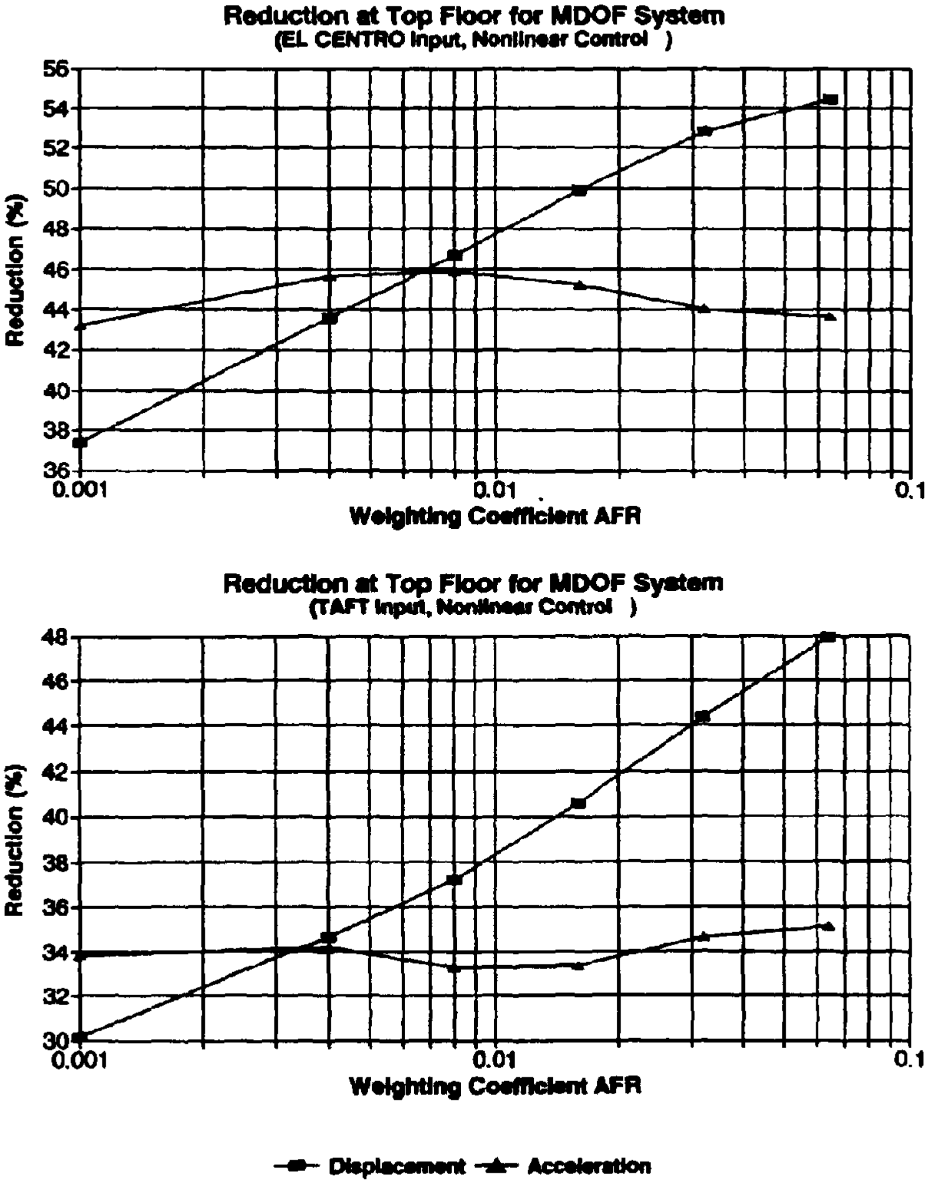


Fig. 3-4. Maximum Response Reduction of MDOF System with LQR Control



Reduction at Top Floor for MDOF System
(EL CENTRO Input, Nonlinear Control)

Reduction at Top Floor for MDOF System
(TAFT Input, Nonlinear Control)

Fig. 3-5. Maximum Response Reduction of MDOF System with Nonlinear Control 1

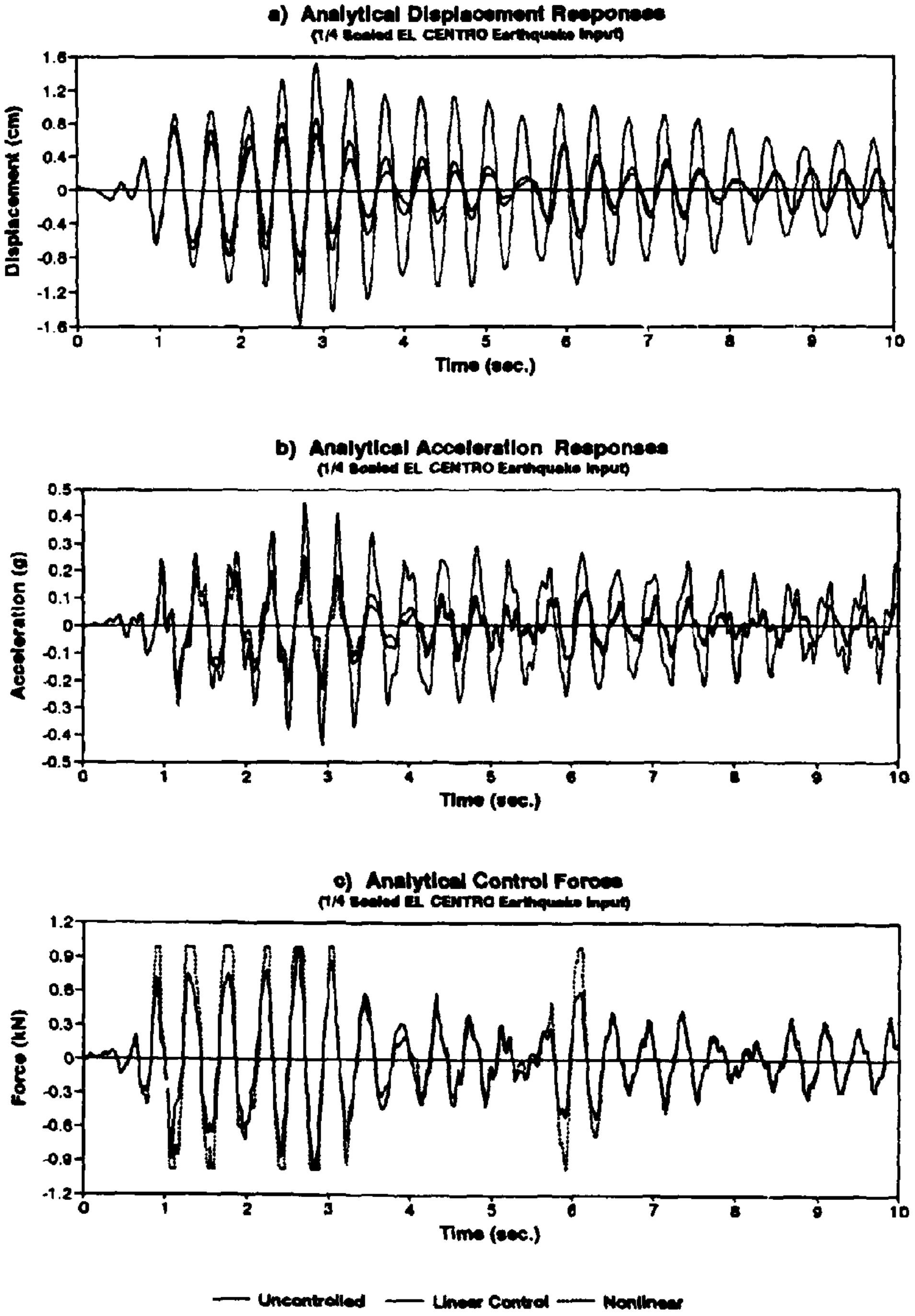


Fig. 3-6. Response Time Histories of MDOF System with Nonlinear Control 1

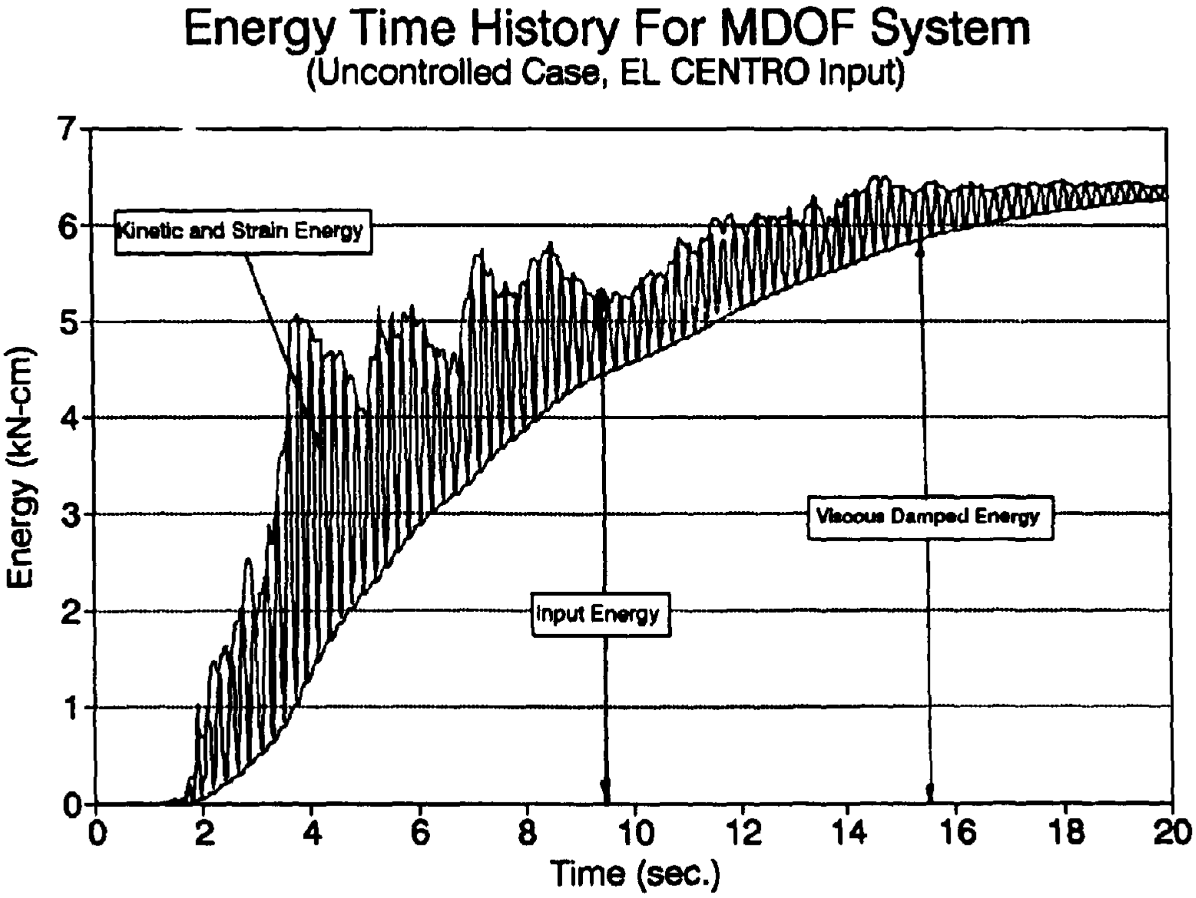


Fig. 3-7. Accumulated Energy Time Histories of MDOF System without Control

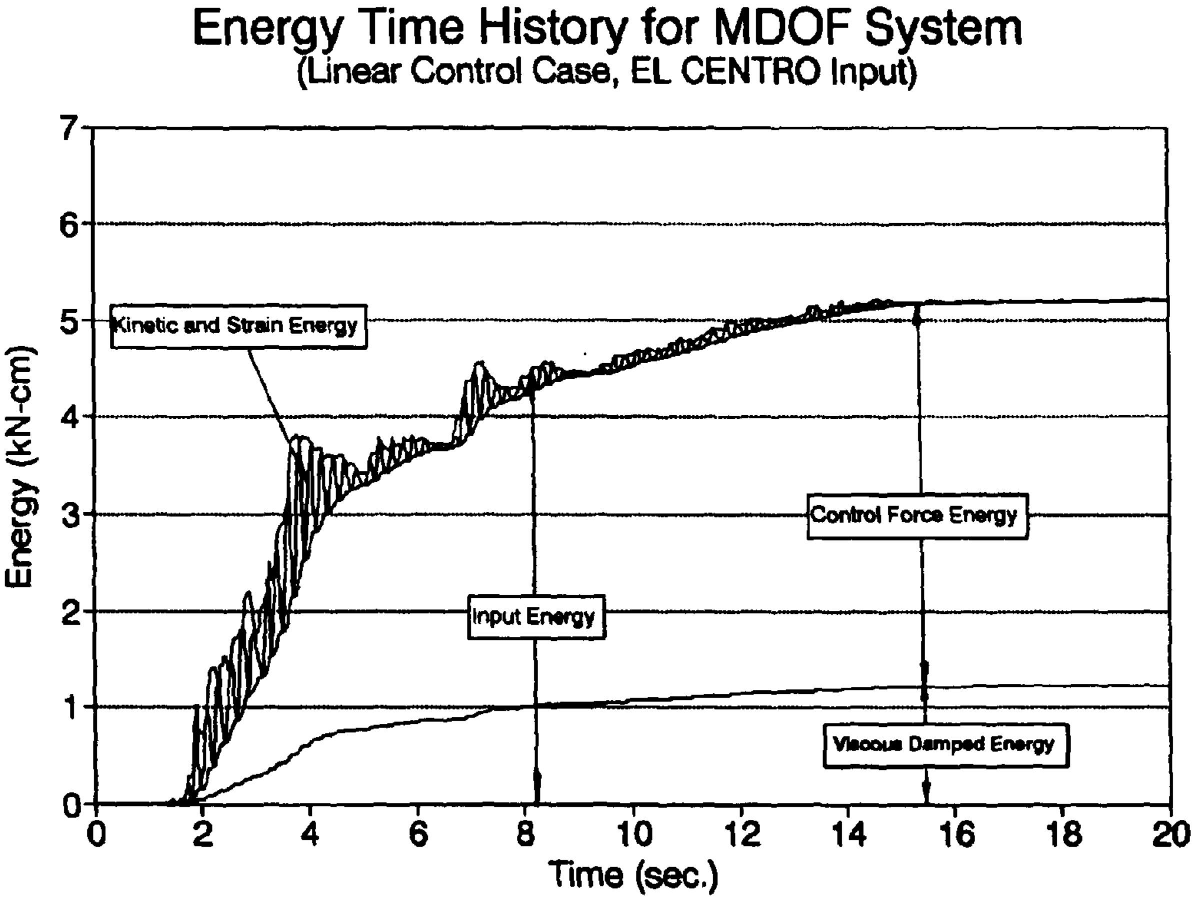


Fig. 3-8. Accumulated Energy Time Histories of MDOF System with Linear Control

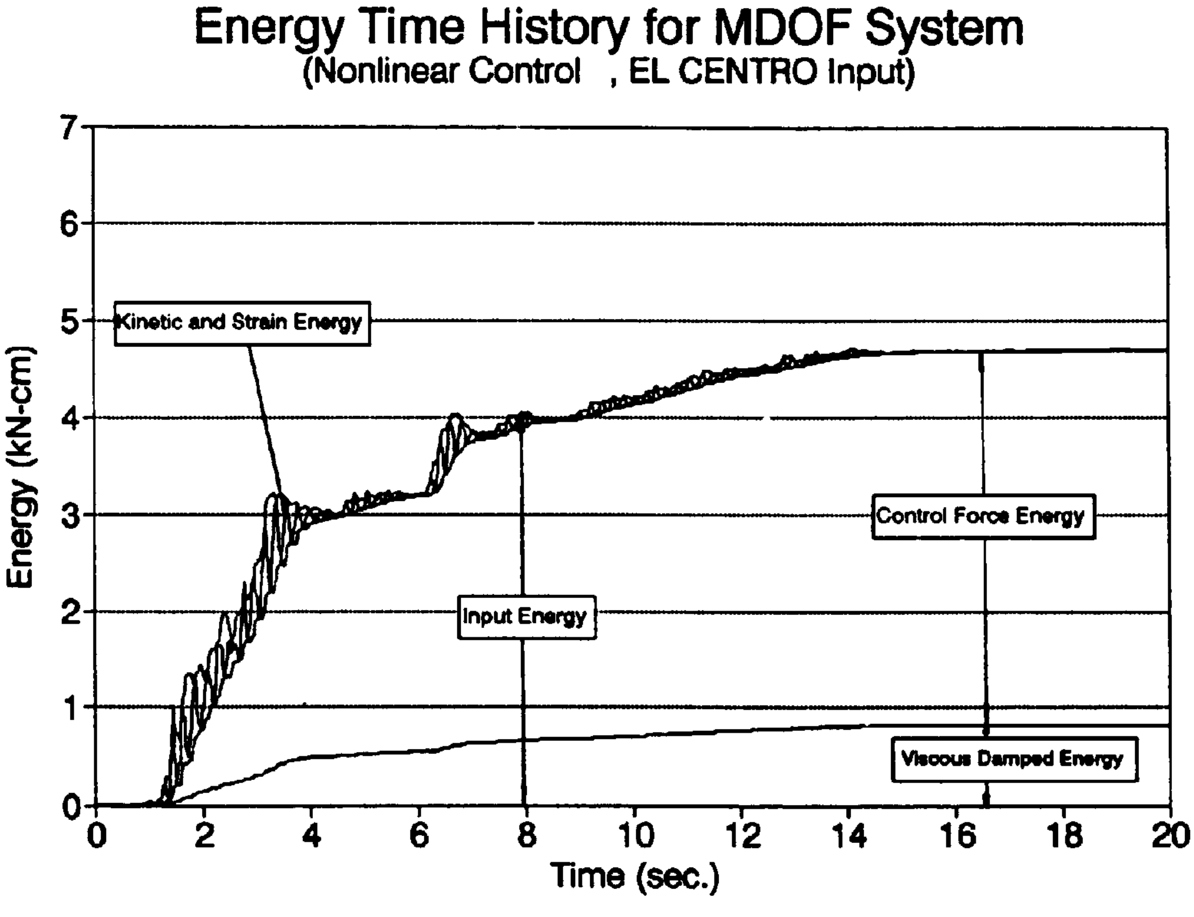


Fig. 3-9. Accumulated Energy Time Histories of MDOF System with Nonlinear Control

SECTION 4

EXPERIMENTAL VERIFICATION

4.1 Experimental Setup and Model Structure

In order to evaluate implementability of the nonlinear control algorithms, an experimental investigation was carried out on a 1/3-scale model structure in the laboratory. The model structure was a three-story frame modeling a shear building by the method of artificial mass simulation. As stated in the previous section, as the first step, the top two floors of the model structure were rigidly braced so that the structure would behave as a SDOF system. Then, at the second step, the rigid braces on the top two floors were removed so that a MDOF structural system could be simulated by this model. Figure 4-1 shows its configuration in the laboratory. The model structure was bolted to a rigid foundation which in turn was bolted to the center of the shaking table which supplied the desired base excitation.

The control force was supplied by a servo-controlled hydraulic actuator through a system of tendons attached to the first floor of the model structure. The tendons were pretensioned to about 2.2 *kN*, a value larger than the maximum designed control force so as to insure tension at all times.

For the SDOF system, the state variable measurements were made by means of strain gage bridges installed on one of the columns. The signal from one strain gage bridge was used as the measured relative displacement. The signal was further passed through an analog differentiator to yield measured relative velocity. For the MDOF system, the state variable measurements were made by means of displacement transducers (Temposonic-TM) installed on each floor and on the base. The measured relative displacements were obtained from the differences between the measured absolute displacements and the base displacement. The transducer signals were further passed through the analog differentiators to yield the measured relative velocities. The measured displacements and velocities were low-frequency filtered to eliminate the high-frequency noise. The base acceleration and absolute accelerations of the masses were directly measured by accelerometers installed at the base and on each floor slab. The Control force was obtained from the measured displacements of actuator piston or from the load cells installed on each tendon. These measurements also provided information for control operations and for performance evaluation of the system. A block diagram showing the measurement system and the control procedure is given in Fig.3-1. More details of this experimental setup can be found in Chung et. al.(1989).

4.2 System Identification

A good model of a real structural system is essential for the success of vibration mitigation using a control system. Thus, a reliable identification of the structural parameters was required. The identification of the experimental structural model was based on the assumption that the model response was in the linear range under control actions. The parameters of the linear analytical model were identified based on measurements of the frequency domain response of the structural model. Another important factor to be considered in order to reach final success of the performance of the control system is the time delay that will always occur when the designed control force is applied to the structure.

4.2.1 Parameters of Model Structure

In frequency domain, the absolute acceleration transfer function of the jth degree-of-freedom contributed by the kth mode is

$$(\mathbf{H}_{jk}(i\omega))_a = \frac{-\Gamma_k\left(2i\xi_k\omega_k\omega + \omega_k^2\right)}{\omega_k^2 - \omega + 2i\xi_k\omega_k\omega} \cdot \varphi_{jk} \tag{4.1}$$

in which, ω_k and ξ_k are, respectively, the natural frequency and damping factor; $\Gamma_k = \phi_k^T\mathbf{m}$, where $\mathbf{m}$ is a vector of lumped masses; and ϕ_k is the kth modal vector, i.e., the kth column of modal shape matrix Φ which was orthogonally normalized such that

$\Phi^T \mathbf{M} \Phi = \mathbf{I}$. The peak value of the jth acceleration transfer function is a superposition of all modes, i.e.,

$$(\mathbf{H}_j(i\omega))_a = \sum_{k=1}^{n} (\mathbf{H}_{jk}(i\omega))_a \tag{4.2}$$

However, for small damping and well separated modes, the kth peak of the jth transfer function will be assumed equal to $(\mathbf{H}_{jk}(i\omega))_a$ by neglecting the contribution of other modes. The assumption of lightly damped structure permits considering the peaks of the transfer function occur precisely at $\omega = \omega_k$, $k = 1, 2, \cdot \cdot \cdot$, with its amplitude determined by

$$|(\mathbf{H}_{jk}(i\omega))_a| = \frac{\Gamma_k \sqrt{1+4\xi_k^2}}{2\xi_k} \cdot \varphi_{jk} \tag{4.3}$$

From Eq. (4.3), it is shown that the kth peak value of the jth transfer function is proportional to the jth component of the kth modal shape. Therefore, by measuring the absolute acceleration transfer function at each degree-of-freedom, the modal shapes can be determined from the ratios of the peak values at the frequency corresponding to each mode of vibration. The frequency corresponding to the kth peak value of the acceleration response function is the natural frequency of the kth mode. Moreover, the damping factor of each mode can be estimated by solving Eq. (4.3).

The identification tests of the model structure were carried out on the shaking table. The banded (0 - 20Hz) white noise was used as the input excitation. For the SDOF system, the absolute acceleration transfer function is shown in Fig.4-2 and the identification results are listed in Table 3-1. For the MDOF system. the absolute acceleration transfer function is shown in Fig.4-3 and the identification results are also listed in Table 3-1.

4.2.2 Evaluation of Time Delay

In the performance of an active control system, the time delay is unavoidable. The time delays generated by the differentiator, low-frequency filter, on-line computations and execution of the control force must be considered. The necessity of compensation for time delay has been discussed by Chung et. al.(1989) and Reinhorn et. al.(1989).

Time delay can be determined from the phase lag measured between the input and the respective output signal for each component of the control system. In the identification test for evaluating time delay, the banded (0 - 20Hz) white noise was used as input. The phase lag angle for each control system component was determined from the real and imaginary parts of the frequency transfer function of the input and output signals. Thus, time delay is determined for each component of system using

$$T_d = \frac{1}{360} \cdot \frac{\theta^{\circ}}{f} \tag{4.4}$$

where T_d is the time delay, θ° is the phase lag in degrees and f is the frequency in Hz.

A set of the experimental results obtained is shown in Fig.4-4. The time delay was 4 milliseconds for the differentiator, 20 milliseconds for the low-frequency filter, $6 \sim 8$ milliseconds for the on-line computation, and 7 milliseconds for the generation of the control force. Therefore, the total delay time that the control force lagged behind the state variables was $33 \sim 35$ milliseconds for displacements and $37 \sim 39$ milliseconds for velocities.

For the experiment on the structural model, the phase shift method was found to be effective for time delay compensation. Details regarding the derivation of the phase shift method can be found in Reinhorn et. al.(1989).

4.3 Experiment Verification

4.3.1 Peak Response Reductions

Peak Response under Optimal β and α Values. In the previous section, the optimal β and α values listed in Table 3-5 were suggested from extensive parametric studies. The first part of the experiment was to verify the control performance provided by the proposed nonlinear control laws based on these optimal control parameters. Corresponding to simulation cases, maximum responses of the SDOF system with and without control actions are listed in Table 4-1, and Tables 4-2 and 4-3 give the results at the top-floor of the MDOF system, respectively, under El Centro and Taft Earthquake excitations. From these tables, the following observations can be made. First, experimental results show that, relative to the linear control case, all five nonlinear control laws provide better control performance in terms of reducing peak response. For the example in Table 4-3, the relative displacement reduction is 38% by employing the linear control law, while by using nonlinear control algorithm 5, the reduction reaches 54%. For absolute acceleration, the reduction under linear control is 34% and 42% under nonlinear control. Second, comparisons of experimental and analytical results indicate good agreement, and the errors are generally within 10%. Third, reductions from experiments are somewhat larger than those from simulations. The major reason is that the hydraulic actuator was not able to generate the required control forces precisely, and in general a small part of control force overshoot would occur at the peak of control actions.

Peak Response under Different β Values. Apart from the experimental verification based on the optimal β and α values, a group of linear control experiments were also carried out as the second part of the experiment. The purpose of doing this group of tests was to verify suitability and reliability of the hydraulic active control system. Figures 4-5 and 4-6 illustrate the top-floor response reduction from both experiment and simulation under El Centro and Taft Earthquake excitations, respectively. It can be seen that good agreement is achieved within a broad range of β values. Generally, an increase in the control force, which implies a decrease in β values, the peak response reduction increases. But one may specially note from Fig. 4-5(b) that a control force smaller than 1.2 *kN*, corresponding to $\beta = 32$, will produce a decreasing ratio of acceleration reduction. The experiment verified that the optimal β value should be chosen as $\beta = 32$.

Peak Response under Different α Values. Similar to the previous tests for different β values, the third part of the experiment was focused on nonlinear control algorithms, specially on different α values. All five nonlinear algorithms were verified based the optimal β value but varying α values. Typically, the results obtained from the MDOF system by using nonlinear algorithms 1 and 5 are shown in Figs. 4-7 and 4-8, respectively. First, for nonlinear algorithm 1, Fig. 4-7(a) indicates that, keeping the same maximum control force, as α-value increases, the peak response reduction of relative displacement increases monotonously, which implies that the heavier the weighting of nonlinear feedback in the control actions, the larger the reduction. But from Fig. 4-7(b), one may note that the reduction of absolute acceleration decreases remarkably after α-value exceeds 0.016. Thus it is reasonable to choose the optimal α value as 0.016. Second, for nonlinear algorithm 5, the similar trend can be observed from Fig. 4-8, and the optimal α value may be selected as 0.8. Moreover, extensive experimental verifications were also performed for SDOF system, for other nonlinear algorithms and for a broad range of α values. Generally speaking, all five nonlinear control algorithms are effective in terms of reducing peak response within a broad range of α values. The reduction of relative displacement is better than that of absolute acceleration, and the reduction as obtained from the experiments is better than that from simulation. Different nonlinear algorithms lead to different optimal α values and it is possible to find these optimal values from simulation analysis.

4.3.2 Response Time Histories

As shown in Fig. 3-1, for each story of the model structure, we can measure the relative displacement and absolute acceleration. Furthermore, through the analog differentiaor, the relative velocity can be obtained from the measured relative displacement. On the other hand, using the recorded acceleration on the base of the model structure as the simulation input, we can calculate responses for the same model structure under the same excitation as in the experiment. Conclusions may be drawn from comparisons between experimental and analytical results.

First, Fig. 4-9 shows the experimental response time histories and control force time histories for uncontrolled, linear control and nonlinear control cases. These are only the top floor response of the MDOF model structure under 1/4-scaled El Centro earthquake excitation, and the nonlinear control is Case 4. From this typical set of time histories, it can be seen that not only the peak response but the overall response is also reduced by employing suggested nonlinear control law. As expected, the peak response during the initial period is suppressed properly. For other nonlinear control laws, similar trend can be observed, for example, as shown in Figs. 4-10 and 4-11 for Case 5 and Case 6, respectively.

Second, the comparison between experimental and analytical time histories are illustrated in Figs. 4-12, 4-13 and 4-14, respectively, for Case 4, Case 5, and Case 6. Good agreement between the two groups of time histories can be observed. Small overshoots of peak control forces in the experimental results are due to inherent mechanical limitations of the hydraulic actuator.

Table 4-1. Maximum Response Verification for SDOF System

(1/3 Scaled EL-CENTRO Earthquake Input)

Control Algorithms	Relative Displacement				Absolute Acceleration				Max. Control Force (kN)	
	Values (cm)		Reduction (%)		Values (g)		Reduction (%)			
	Simu.	Exp.	Simu.	Exp.	Simu.	Exp.	Simu.	Exp.	Simu.	Exp.
Uncontrolled	0.501	0.522			0.341	0.350				
Linear Control $\beta = 32$	0.388	0.403	22.55	22.80	0.274	0.279	19.65	20.29	0.85	0.92
Case 1 $\alpha_2 = 0.6$	0.357	0.334	28.74	36.02	0.255	0.261	25.22	25.43	0.85	1.09
Case 2 $\alpha_3 = 0.06$	0.371	0.353	25.95	32.38	0.263	0.269	22.87	23.14	0.85	1.09
Case 3 $\alpha_4 = 120$	0.357	0.339	28.74	35.06	0.267	0.256	21.70	26.86	0.85	0.96

Table 4-2. Top Floor Maximum Response Verification for MDOF System

(1/4 Scaled EL-CENTRO Earthquake Input)

Control Algorithms	Relative Displacement				Absolute Acceleration				Max. Control Force (kN)	
	Values (cm)		Reduction (%)		Values (g)		Reduction (%)			
	Simu.	Exp.	Simu.	Exp.	Simu.	Exp.	Simu.	Exp.	Simu.	Exp.
Uncontrolled	1.578	1.664			0.450	0.449				
Linear Control $\beta = 32$	0.988	0.999	37.37	39.96	0.256	0.251	43.20	44.10	0.984	1.125
Case 4 $\alpha_1 = 0.016$	0.790	0.782	49.94	53.03	0.246	0.255	45.33	43.21	0.984	1.171
Case 5 $\alpha_2 = 1.2$	0.779	0.788	50.60	52.64	0.267	0.265	40.67	40.98	0.984	1.229
Case 6 $\alpha_5 = 0.8$	0.866	0.850	45.12	48.92	0.240	0.232	46.66	48.33	1.255	1.388

Table 4-3. Top Floor Maximum Response Verification for MDOF System
(1/2 Scaled TAFT Earthquake Input)

Control Algorithms	Relative Displacement				Absolute Acceleration				Max. Control Force (kN)	
	Values (cm)		Reduction (%)		Values (g)		Reduction (%)			
	Simu.	Exp.	Simu.	Exp.	Simu.	Exp.	Simu.	Exp.	Simu.	Exp.
Uncontrolled	1.420	1.569			0.430	0.414				
Linear Control $\beta = 32$	0.992	0.967	30.13	38.37	0.284	0.273	33.83	34.06	1.194	1.175
Case 4 $\alpha_1 = 0.016$	0.844	0.796	40.56	49.27	0.287	0.262	33.26	36.71	1.194	1.209
Case 5 $\alpha_2 = 1.2$	0.804	0.780	43.38	50.29	0.284	0.278	33.95	32.85	1.194	1.238
Case 6 $\alpha_5 = 0.8$	0.838	0.726	40.99	53.73	0.246	0.239	42.79	42.27	1.232	1.363

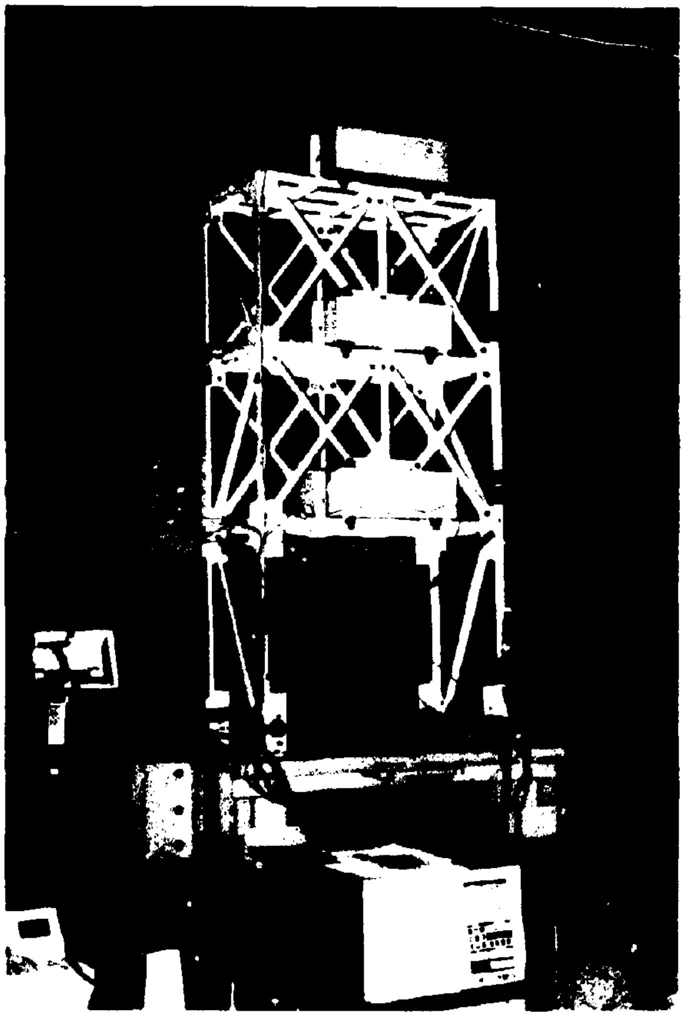


Fig. 4-1. View of the Model Structure

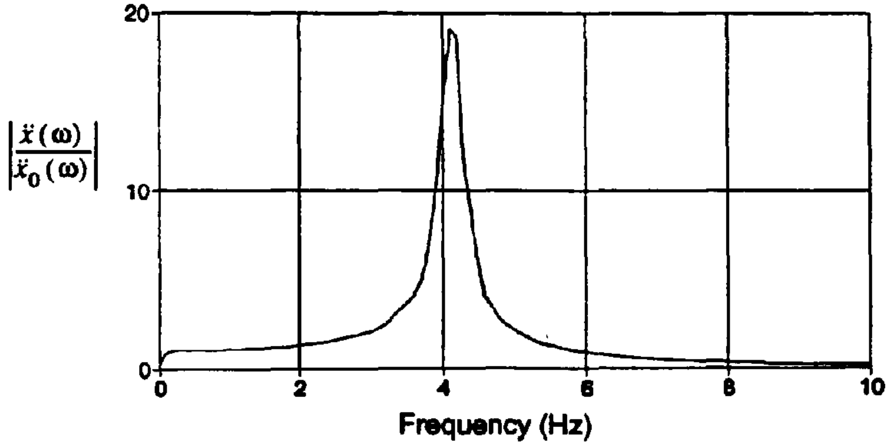


Fig. 4-2. Absolute Acceleration Transfer Function for SDOF System

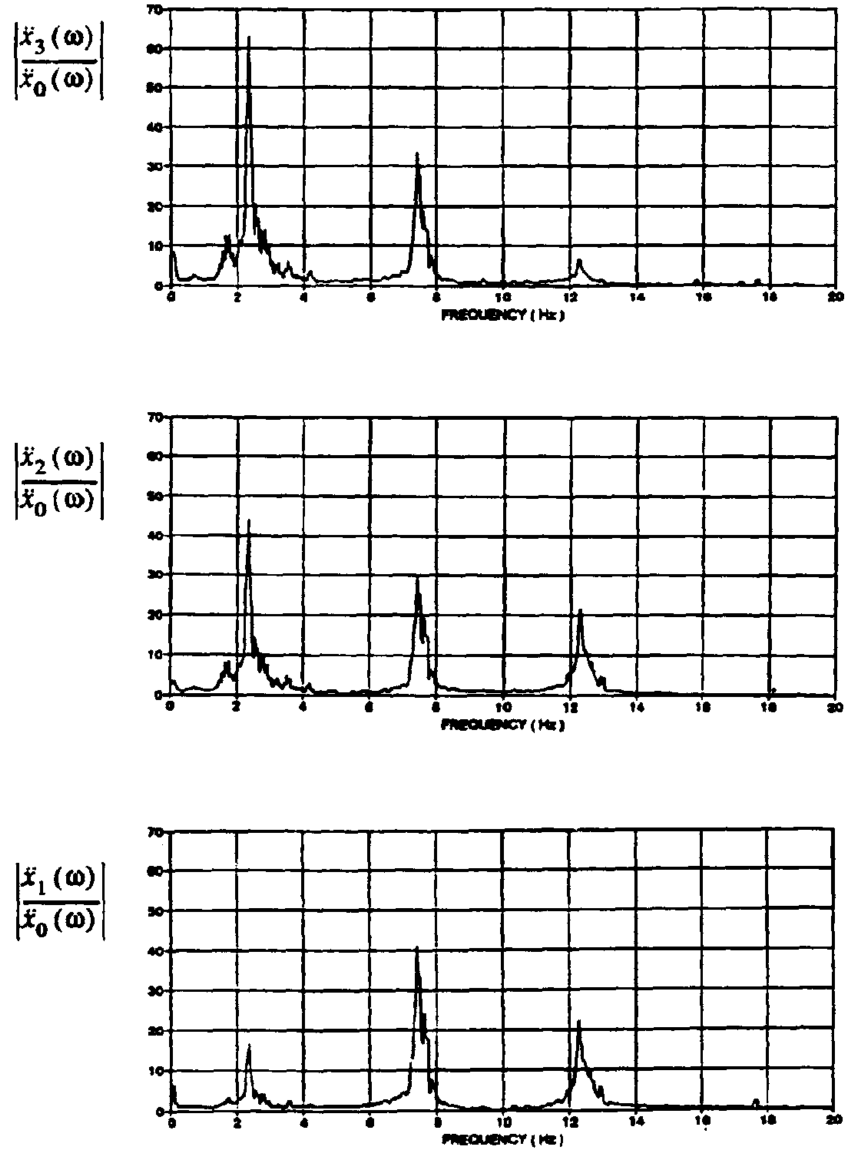
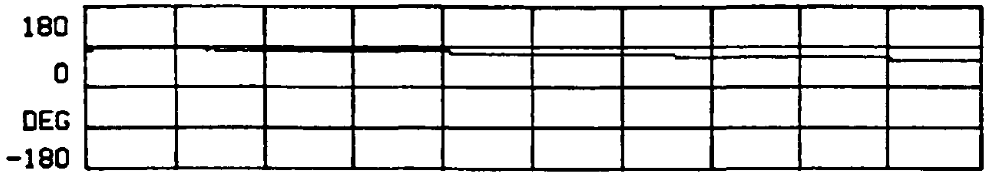
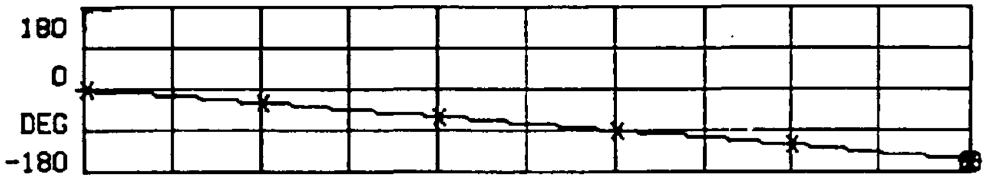


Fig. 4-3. Absolute Acceleration Transfer Function for MDOF System

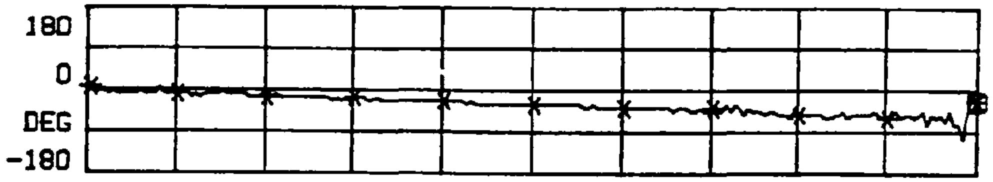
a). For Analog Differentiator $t_d = 4$ *msec*



b). For Low-Frequency Filter $t_d = 20$ *msec*



c). Computation Time $t_d = 8$ *msec*



d). Actuator Delay $t_d = 7$ *msec*

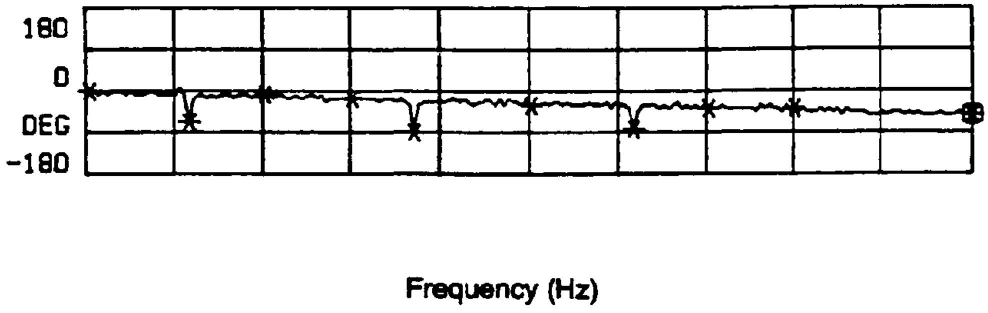
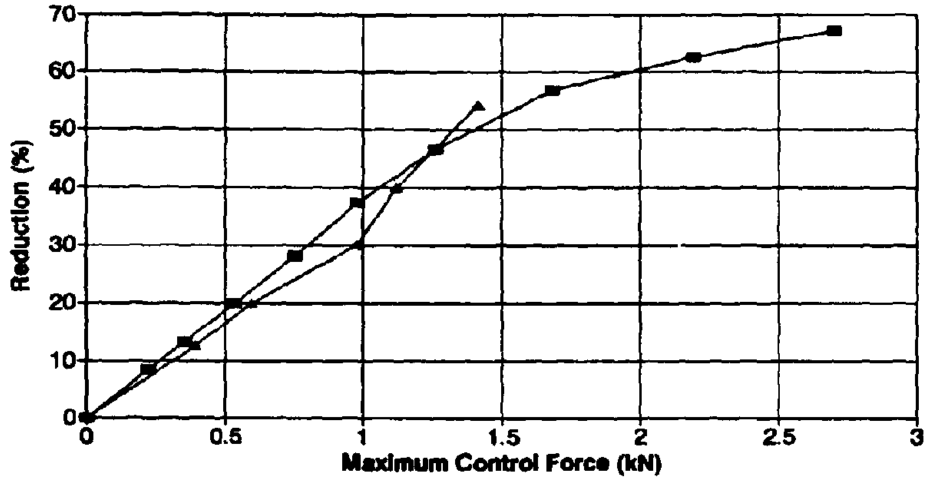


Fig. 4-4. Evaluation of Time Delay from Slope of Phase Lag

a) Comparison of Displacement Reduction
(EL CENTRO input, Linear Control)



b) Comparison of Acceleration Reduction
(EL CENTRO input, Linear Control)

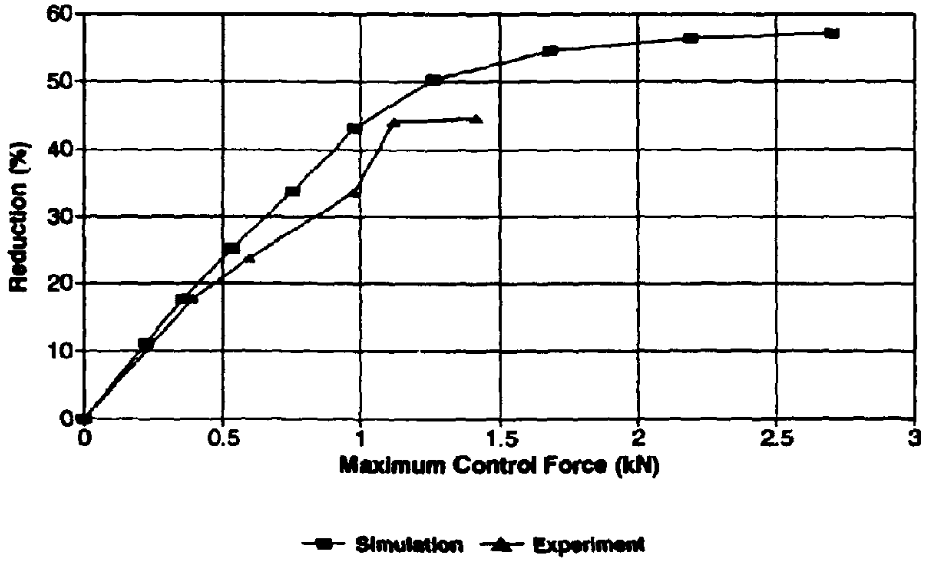


Fig. 4-5. Top-Floor Maximum Response Reduction (Linear Control, El Centro)

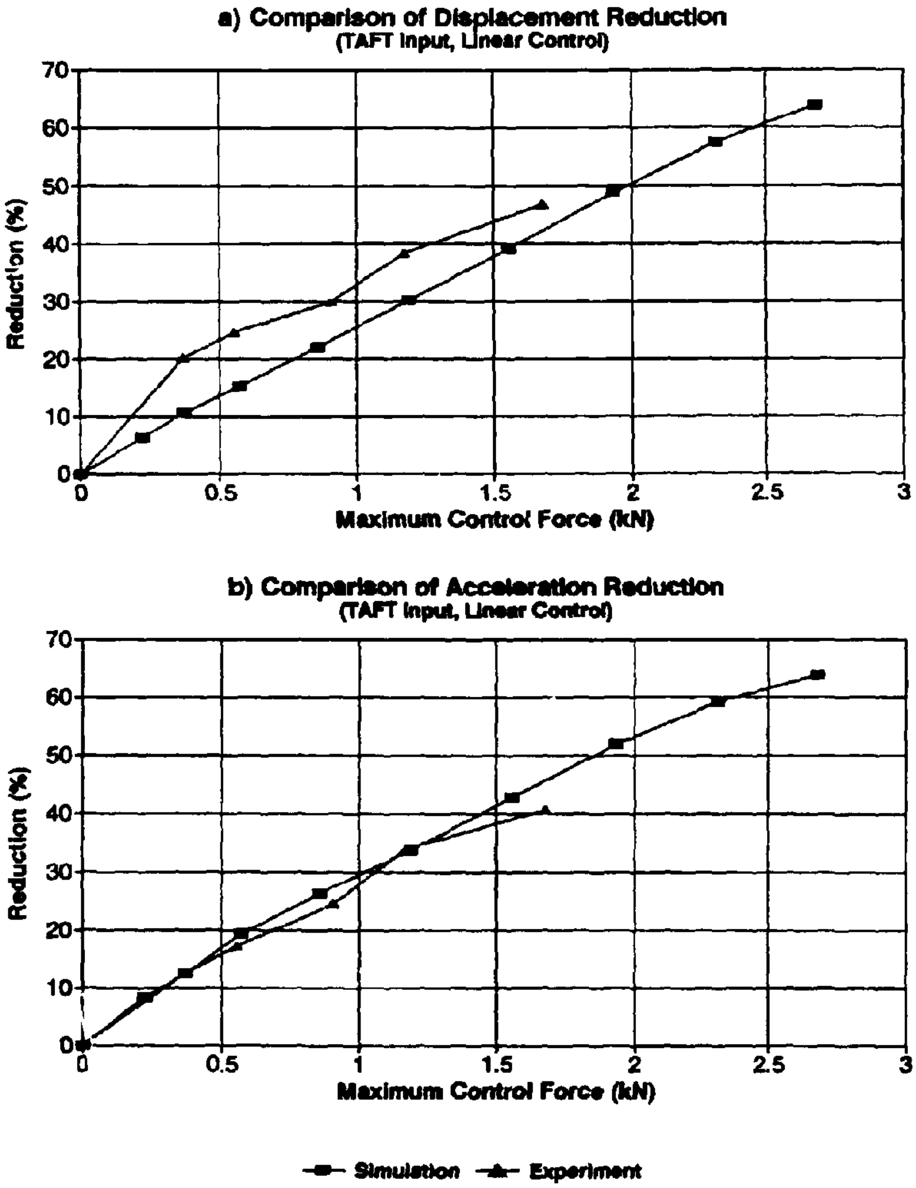


Fig. 4-6. Top-Floor Maximum Response Reduction (Linear Control, Taft)

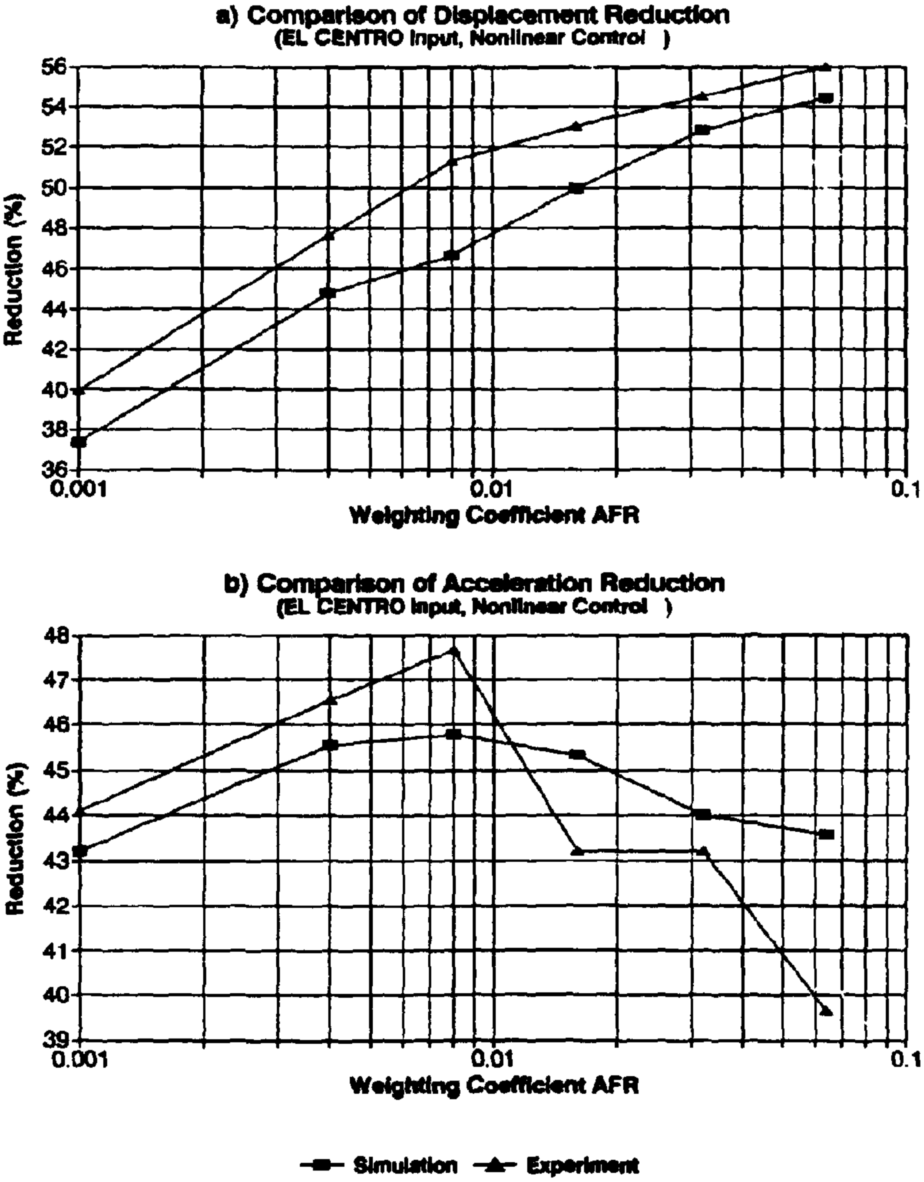


Fig. 4-7. Top-Floor Maximum Response Reduction (Nonlinear 1, El Centro)

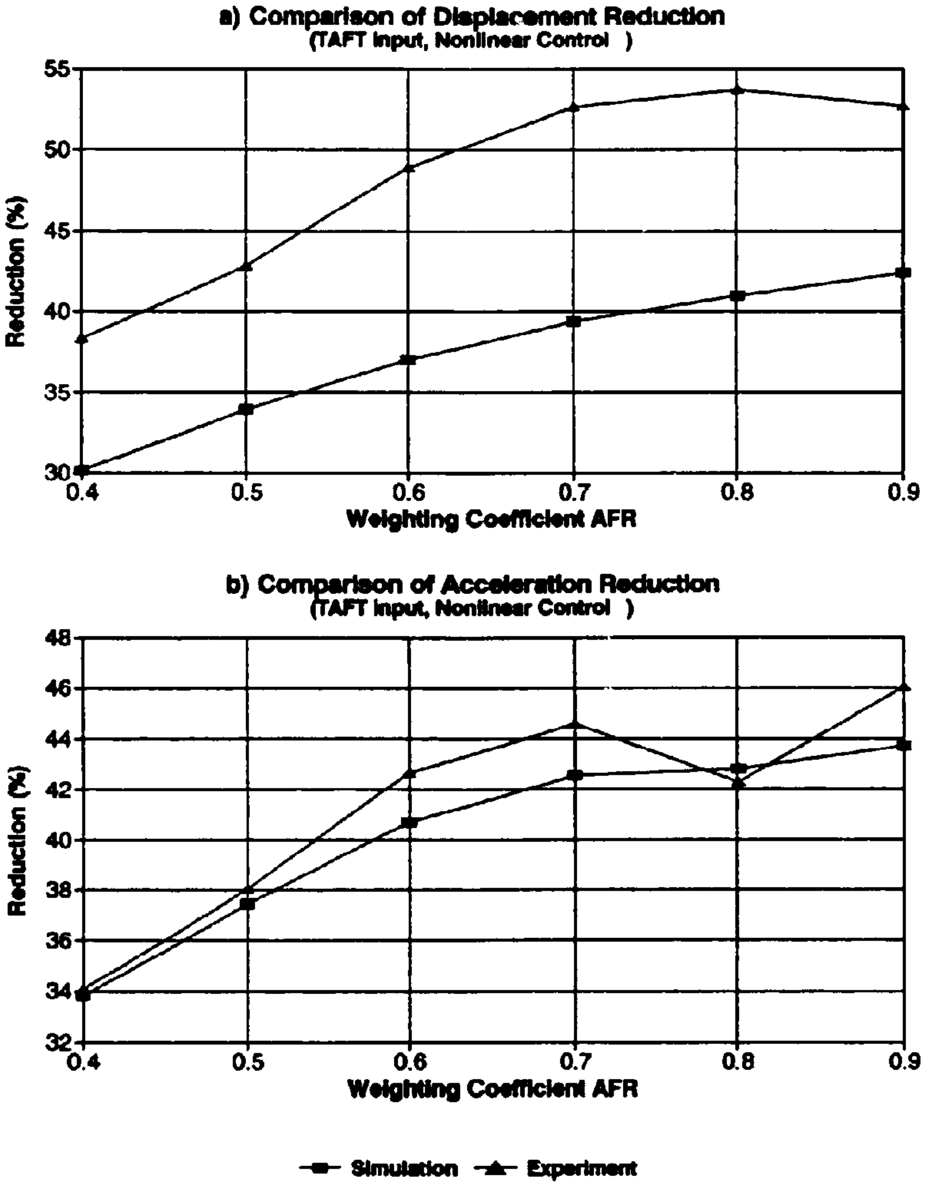


Fig. 4-8. Top-Floor Maximum Response Reduction (Nonlinear 5, Taft)

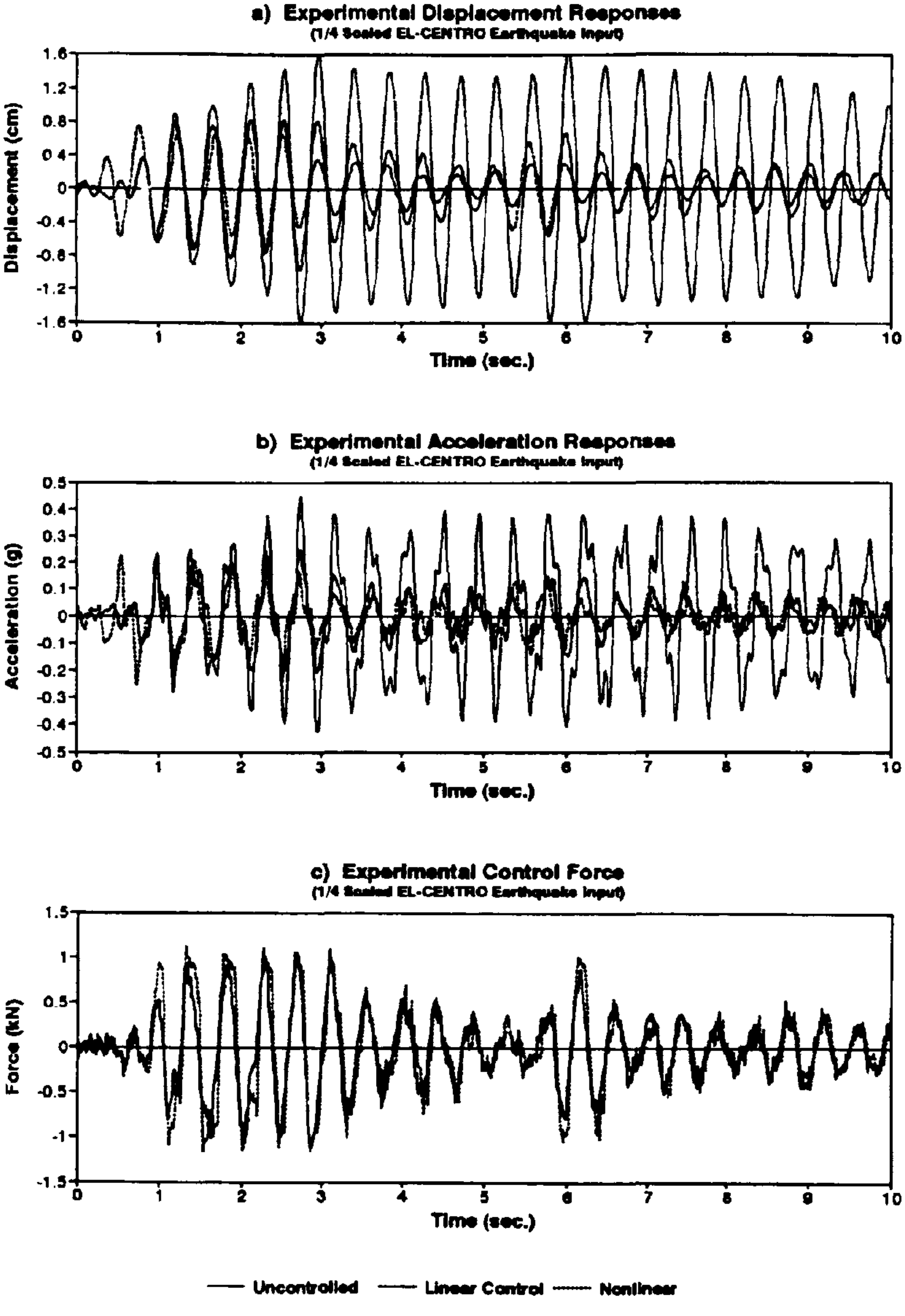
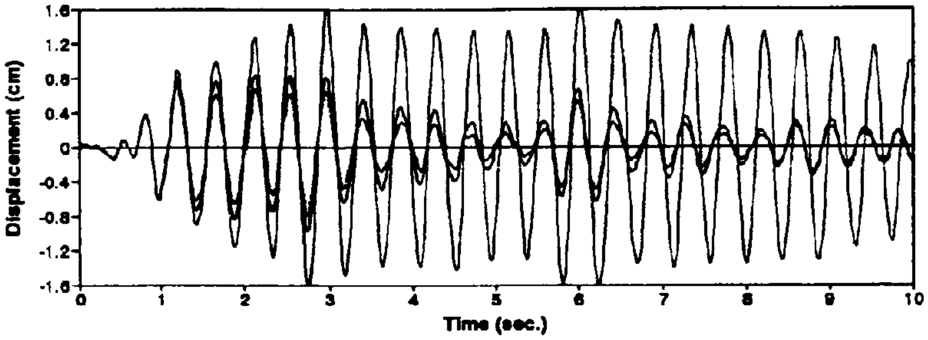
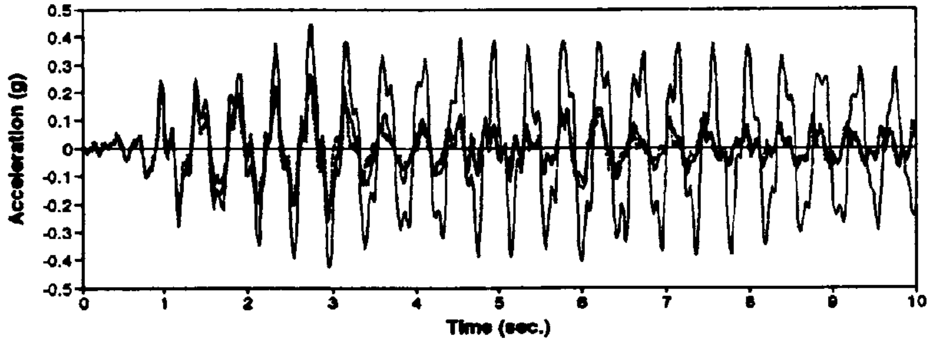


Fig. 4-9. Experimental Time Histories of MDOF System (Nonlinear 1, El Centro)



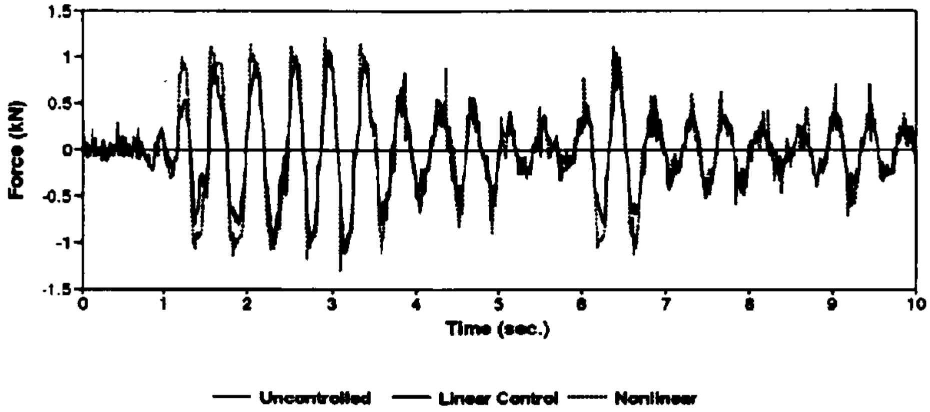
a) Experimental Displacement Responses

(1/4 Scaled EL-CENTRO Earthquake Input)



b) Experimental Acceleration Responses

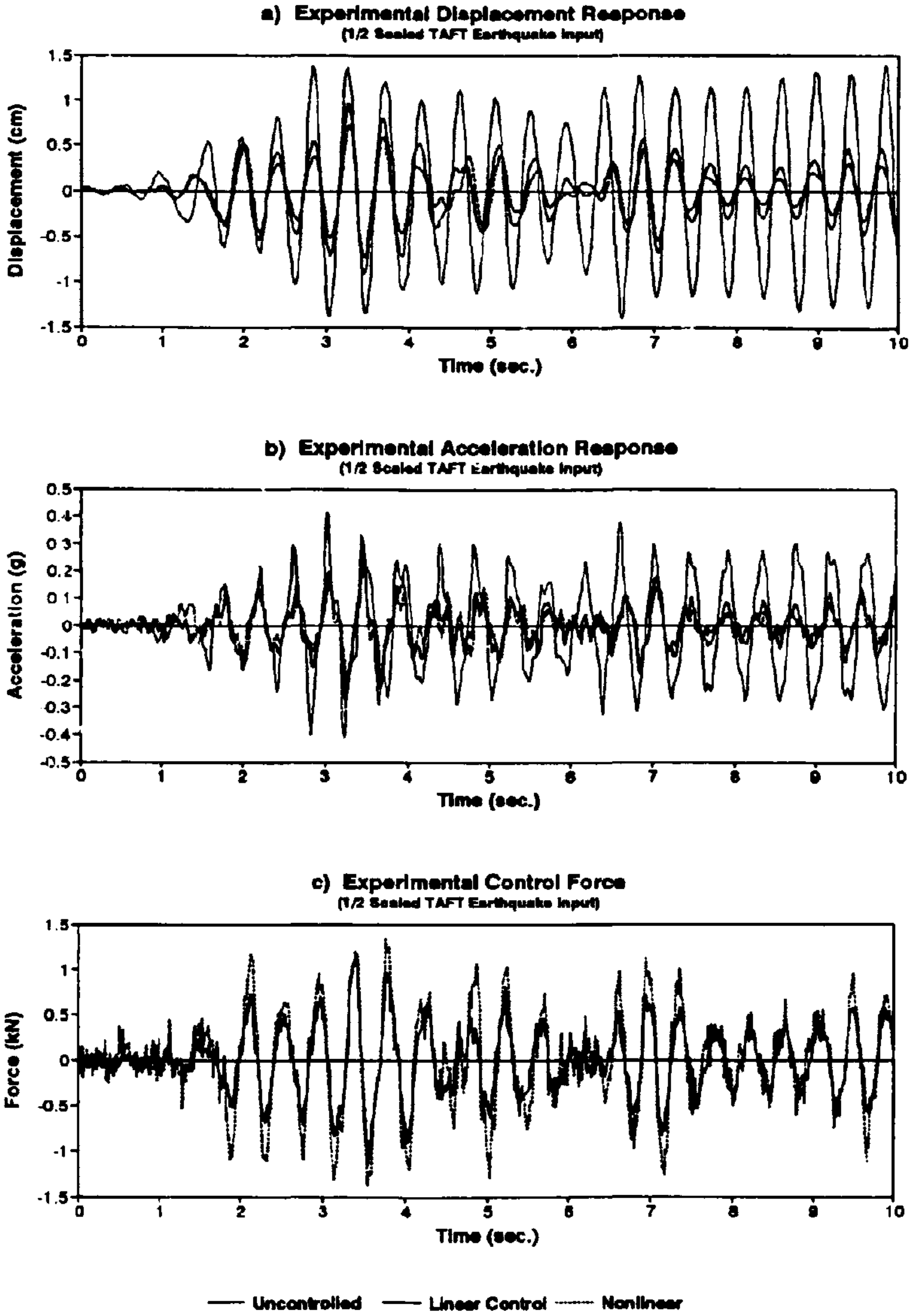
(1/4 Scaled EL-CENTRO Earthquake Input)



c) Experimental Control Force

(1/4 Scaled EL-CENTRO Earthquake Input)

Fig. 4-10. Experimental Time Histories of MDOF System (Nonlinear 2, El Centro)



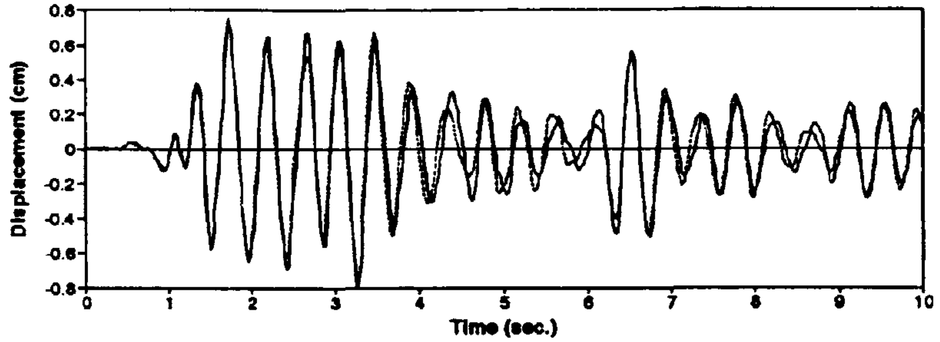
a) Experimental Displacement Response
(1/2 Scaled TAFT Earthquake Input)

b) Experimental Acceleration Response
(1/2 Scaled TAFT Earthquake Input)

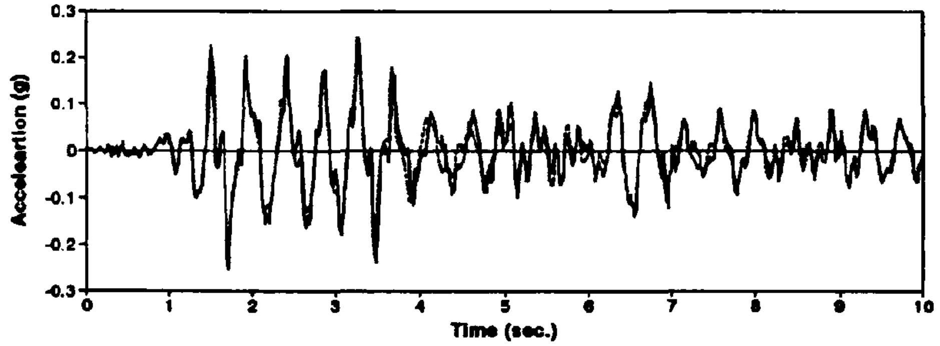
c) Experimental Control Force
(1/2 Scaled TAFT Earthquake Input)

Fig. 4-11. Experimental Time Histories of MDOF System (Nonlinear 5, Taft)

a) Comparison of Displacement Response
(EL-CENTRO Earthquake, Nonlinear)



b) Comparison of Acceleration Response
(EL-CENTRO Earthquake, Nonlinear)



c) Comparison of Control Force
(EL-CENTRO Earthquake, Nonlinear)

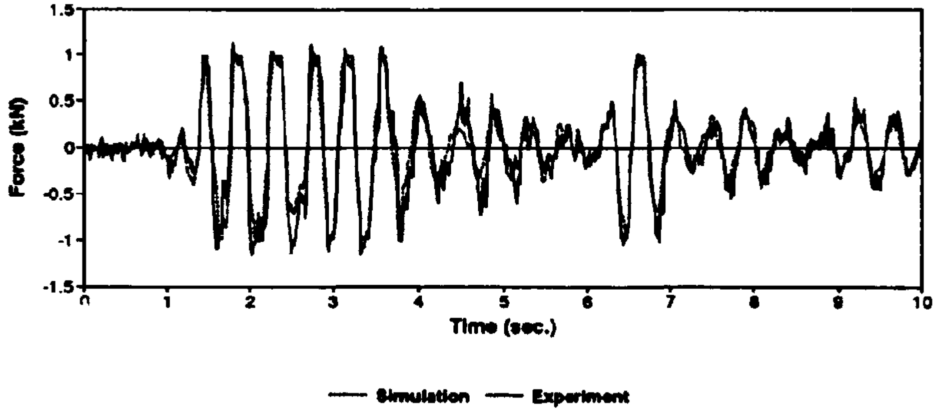
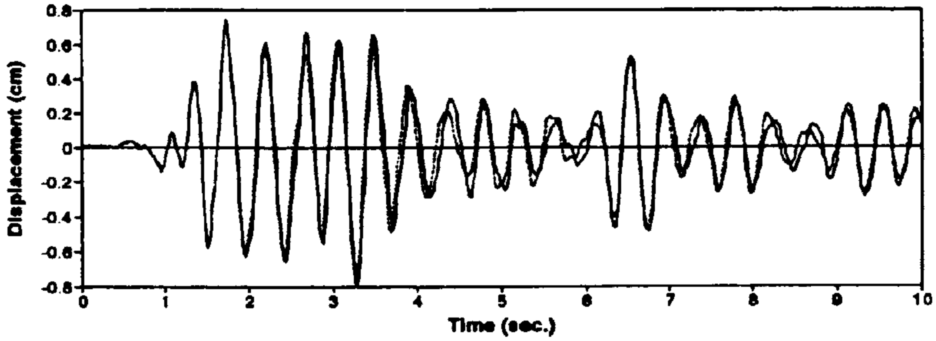
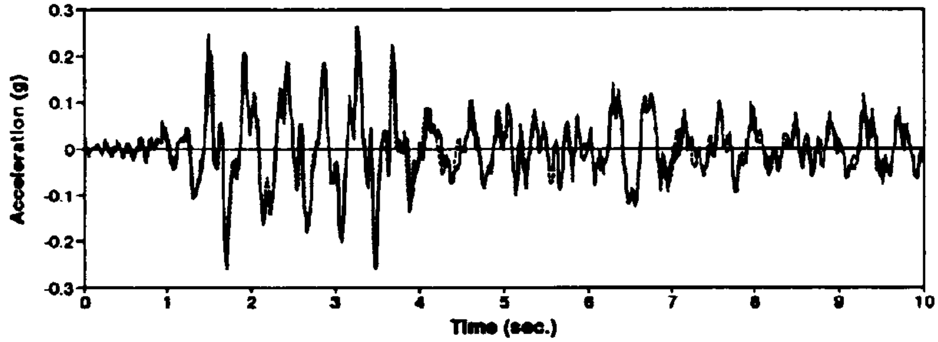


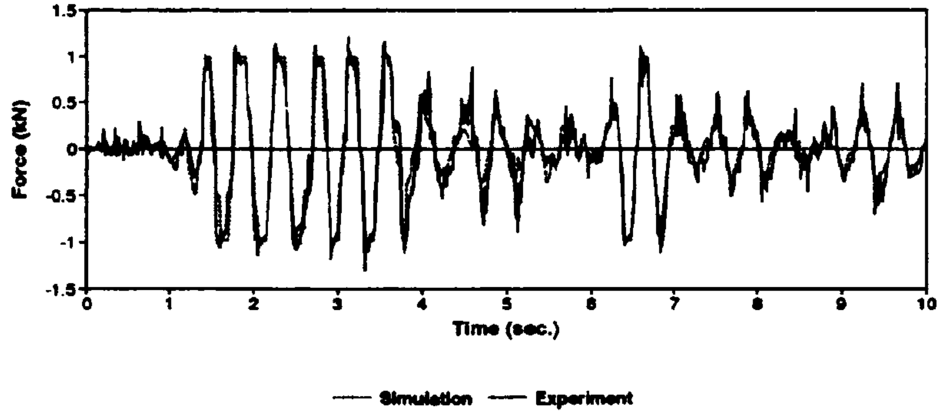
Fig. 4-12. Comparison of Response Time Histories (Nonlinear 1, El Centro)



a) Comparison of Displacement Response
(EL-CENTRO Earthquake, Nonlinear)



b) Comparison of Acceleration Response
(EL-CENTRO Earthquake, Nonlinear)

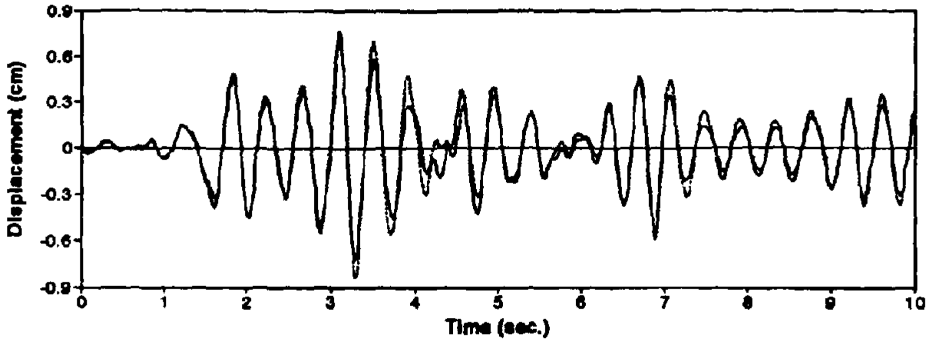


c) Comparison of Control Force
(EL-CENTRO Earthquake, Nonlinear)

Fig. 4-13. Comparison of Response Time Histories (Nonlinear 2, El Centro)

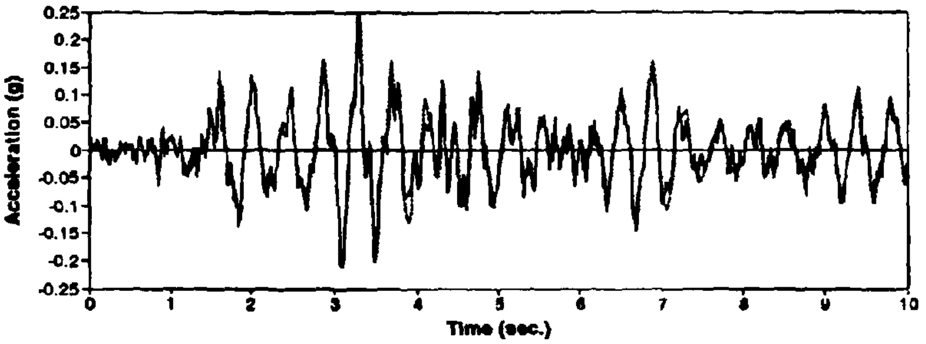
a) Comparison of Displacement Response

(TAFT Earthquake, Nonlinear)



b) Comparison of Acceleration Response

(TAFT Earthquake, Nonlinear)



c) Comparison of Control Force

(TAFT Earthquake, Nonlinear)

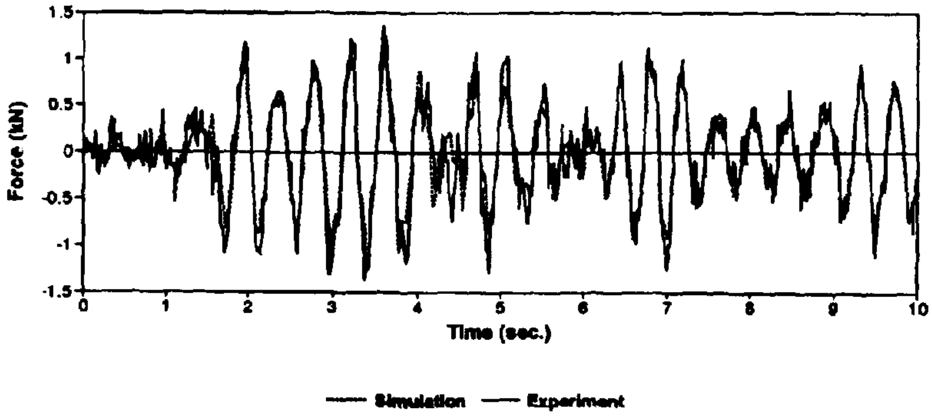


Fig. 4-14. Comparison of Response Time Histories (Nonlinear 5, Taft)

SECTION 5

CONCLUDING REMARKS

In civil engineering structural applications, peak response control is of practical importance due to its close relation with safety. The work presented in this report is focused on the development of implementable nonlinear control laws which can provide improved peak response control performance under the same constraints imposed on the control force and other resources as in the linear control law case. Five different nonlinear control laws have been proposed. The first algorithm is derived based on a higher-order performance criterion and optimal control strategy, and the last algorithm is developed from modifications of Bang-Bang control theory. Other three algorithms come from the simplifications of the first algorithm.

Extensive parametric studies have been performed for each of the proposed nonlinear control algorithms. Based on the control performance, such as peak response reduction, response time history or accumulated energy, the regions of effectiveness for nonlinear control parameters are identified, and the optimal values of these parameters are determined. Simulation results indicate that all five nonlinear control algorithms are effective in terms of improving peak response reduction. In general, the relative displacement reduction is about 10% - 15% over that in the linear control case, and the reduction of absolute acceleration is somewhat smaller than that of the relative displacement.

In order to verify the feasibility of developed nonlinear control laws, a series of comprehensive control experiments have been carried out in the laboratory using a model structure with ground excitations supplied by a shaking table. The successful accomplishment of experiments indicates that the implementation of nonlinear control laws is feasible and presents no inherent difficulties. Their designs can be carried out following an iterative procedure based on the linear control gains. Good agreement between experimental and analytical results makes it possible to extrapolate these nonlinear control results for potential full-scale structural applications. Nonlinear control laws such as those suggested herein can provide an effective means for enhancing structural control effectiveness.

SECTION 6

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