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INSTANTANEOUS OPTIMAL CONTROL WITH ACCELERATION AND VELOCITY FEEDBACK

by

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In the experimental demonstration of aseismic control systems, difficulties were encountered in the measurement of the displacement response of the structure. During earthquake ground motions, both the building and the ground are moving so that there is no absolute reference for the determination of the displacement response. An optimal control theory is proposed herein, which utilizes the measurements of acceleration and velocity responses rather than the displacement and velocity measurements. Such an optimal control law is developed based on the instantaneous optimal control theories, and it is evaluated and compared with other available optimal control laws. Numerical results indicate that the performance of the proposed optimal control law is as good as that of other optimal control laws currently available. However, the contribution of such an optimal control law to the practical implementation of active control systems for seismic hazard mitigations may be quite significant.

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PREFACE

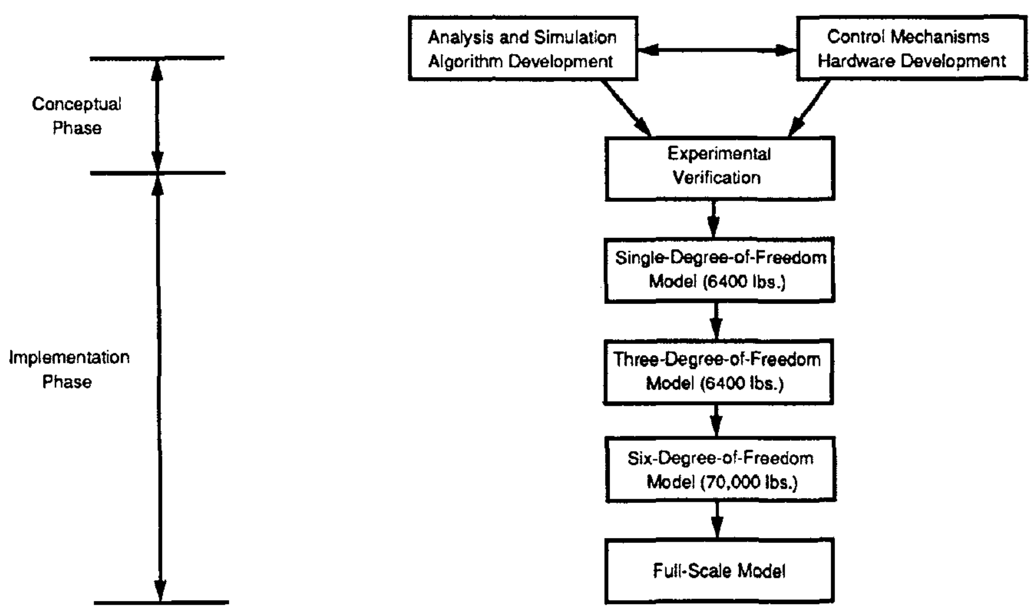
The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

This technical report pertains to Program 2, Secondary and Protective Systems, and more specifically, to protective systems. Protective Systems are devices or systems which, when incorporated into a structure, help to improve the structure's ability to withstand seismic or other environmental loads. These systems can be passive, such as base isolators or viscoelastic dampers; or active, such as active tendons or active mass dampers; or combined passive-active systems.

In the area of active systems, research has progressed from the conceptual phase to the implementation phase with emphasis on experimental verification. As the accompanying figure shows, the experimental verification process began with a small single-degree-of-freedom structure model, moving to larger and more complex models, and finally, to full-scale models.



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At NCEER, research and development of active control technology have reached the stage of full-scale implementation. In this report, the authors consider one of the practical issues in control algorithm design. Since displacement measurements are not easily accessible due to a lack of an absolute reference, a control law involving only velocity and acceleration measurements is developed. Simulation results show that the performance of the proposed control law compares favorably with those of other available optimal control laws.

ABSTRACT

In the experimental demonstration of aseismic control systems, difficulties were encountered in the measurement of the displacement response of the structure. During earthquake ground motions, both the building and the ground are moving so that there is no absolute reference for the determination of the displacement response. An optimal control theory is proposed herein, which utilizes the measurements of acceleration and velocity responses rather than the displacement and velocity measurements. Such an optimal control law is developed based on the instantaneous optimal control theories, and it is evaluated and compared with other available optimal control laws. Numerical results indicate that the performance of the proposed optimal control law is as good as that of other optimal control laws currently available. However, the contribution of such an optimal control law to the practical implementation of active control systems for seismic hazard mitigations may be quite significant.

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INTRODUCTION

Recent experimental demonstrations for the application of aseismic control systems to scaled building structures [e.g., 1-7] indicate some difficulties involved in the measurement of floor displacements. The main reason is that during earthquake ground motions, both the building and the ground are moving so that there is no absolute reference for the determination of the floor displacement. This is particularly critical for practical implementations of active control systems to full-scale buildings for earthquake hazard mitigations. Laboratory experiments [1-7] further indicate that the floor displacement response obtained by numerically integrating the velocity measurement differs significantly from the actual floor displacement due to (i) noise pollutions and (ii) error accumulations resulting from numerical integrations.

Unfortunately, available optimal control theories [e.g., 8-10, 12-18] require measurements of displacement and velocity responses of the building structure. Although the instantaneous optimal open-loop control law proposed by Yang, et al. [9-10] does not require the measurements of the state vector of the structure, it is more vulnerable to a system time delay [11,17] and system uncertainties [11,16]. Since the measurements of acceleration and velocity of the structural response are much easier without involving an absolute reference, it is highly desirable to use acceleration and velocity sensors rather than displacement sensors.

The purpose of this paper is to present an optimal control law utilizing the acceleration measurements rather than the displacement measurements. This optimal control law is developed based on the instantaneous optimal control theories developed by Yang, et al. [9-10, 12-13]. For a building structure subjected to an earthquake, the performance of the proposed optimal control law is evaluated and demonstrated by comparing numerically with other available optimal control laws using both deterministic and stochastic earthquake excitations.

SECTION 2
FORMULATION

Consider a shear-beam type building structure implemented by an active control system, such as an active mass damper or an active tendon system as shown in Fig. 2-1. The structure is idealized by an n degrees of freedom linear system and subjected to a one-dimensional earthquake ground acceleration $\ddot{X}_0(t)$. The matrix equation of motion can be expressed as

$$\dot{\underline{Z}}(t) = \underline{A}\ \underline{Z}(t) + \underline{B}\ \underline{U}(t) + \underline{W}_1\ \ddot{X}_0(t) \qquad (2.1)$$

in which an under bar denotes a vector or matrix. In Eq. (2.1), $\underline{Z}(t)$ = a 2n state vector, $\underline{U}(t)$ = a r-dimensional control vector, $\underline{A}$ = a (2nx2n) system matrix, representing the structural characteristics of the building, $\underline{B}$ = a (2nxr) location matrix specifying the location of r controllers and $\underline{W}_1$ is an appropriate 2n vector denoting the effect of the earthquake ground acceleration $\ddot{X}_0(t)$. The state vector $\underline{Z}(t)$ consists of the displacement vector $\underline{Y}(t)$ and velocity vector $\dot{\underline{Y}}(t)$, all relative to the ground, as

$$\underline{Z}(t) = \begin{bmatrix} \underline{Y}(t) \\ \hdashline \dot{\underline{Y}}(t) \end{bmatrix} \qquad (2.2)$$

with the initial condition $\underline{Z}(0) = 0$.

Following the concept of instantaneous optimal control proposed by Yang, et al. [8-9], we define a time-dependent quadratic performance index

$$J^*(t) = \dot{\underline{Z}}'(t)\ \underline{Q}^*\ \dot{\underline{Z}}(t) + \underline{U}'(t)\ \underline{R}\ \underline{U}(t) \qquad (2.3)$$

in which a prime denotes the transpose of a vector or matrix. In Eq. (2.3),

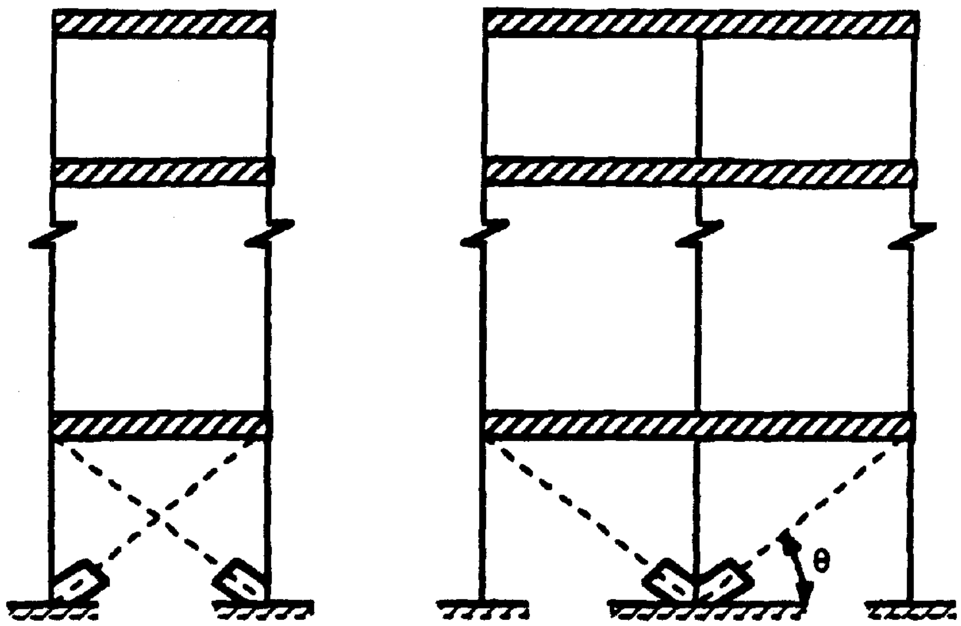

Figure 2-1: Structural Model With An Active Tendon Control System: (a) Single Bay; (b) Two Bays.

$\underline{Q}^*$ is a (2nx2n) positive semi-definite weighting matrix and $\underline{R}$ is a (rxr) positive definite weighting matrix.

In order to minimize the performance index given by Eq. (2.3), the state vector, $\underline{Z}(t)$, in the equation of motion, Eq. (2.1), will be expressed in terms of the finite difference as follows

$$\underline{Z}(t) = \underline{Z}(t-\Delta t) + \Delta t \; \dot{\underline{Z}}(t-\Delta t) \tag{2.4}$$

Substituting Eq. (2.4) into Eq. (2.1), one obtains the equation of motion in the following form

$$\dot{\underline{Z}}(t) = \underline{A} \; \underline{Z}(t-\Delta t) + \underline{A} \; \Delta t \; \dot{\underline{Z}}(t-\Delta t) + \underline{B} \; \underline{U}(t) + \underline{W}_1 \; \ddot{X}_0(t) \tag{2.5}$$

The Hamiltonian H(t) is obtained from Eqs. (2.3) and (2.5) as

$$H(t) = \dot{\underline{Z}}'(t) \; \underline{Q}^* \; \dot{\underline{Z}}(t) + \underline{U}'(t) \; \underline{R} \; \underline{U}(t) + \underline{\lambda}' \Big[\dot{\underline{Z}}(t) - \underline{A} \; \underline{Z}(t-\Delta t) - \underline{A} \; \dot{\underline{Z}}(t-\Delta t) \; \Delta t - \underline{B} \; \underline{U}(t) - \underline{W}_1 \; \ddot{X}_0(t) \Big] \tag{2.6}$$

where $\underline{\lambda}$ is a Lagrangian multiplier vector.

The necessary conditions for the minimization of the performance index $J^*(t)$ subjected to the constraint given by Eq. (2.5) are as follows

$$\frac{\partial H(t)}{\partial \dot{\underline{Z}}} = 0, \qquad \frac{\partial H(t)}{\partial \underline{U}} = 0, \qquad \frac{\partial H(t)}{\partial \underline{\lambda}} = 0 \tag{2.7}$$

The optimal control vector $\underline{U}(t)$ can be obtained by substituting Eq. (2.6) into Eq. (2.7). Depending on the way the control vector is regulated, one obtains optimal closed-loop control (feedback), optimal open-loop control (feedforward) and optimal closed-open-loop control (feedforward and feedback) as presented in the Appendix. It is mentioned, however, that the performance of the three optimal control laws derived in the Appendix is identical. For simplicity, the optimal closed-loop control vector $\underline{U}(t)$ is given in the following [see the Appendix]

$$\underline{U}(t) = -\underline{R}^{-1}\underline{B}'\underline{Q}^{*}\underline{\dot{Z}}(t) \tag{2.8}$$

Thus, the control vector $\underline{U}(t)$ depends on the feedback vector, $\underline{\dot{Z}}(t)$, that consists of the velocity and acceleration responses,

$$\underline{\dot{Z}}(t) = \begin{bmatrix} \underline{\dot{Y}}(t) \\ \hdashline \underline{\ddot{Y}}(t) \end{bmatrix} \tag{2.9}$$

Consequently, the measurement of the displacement response $\underline{Y}(t)$ is replaced by the measurement of the acceleration response $\underline{\ddot{Y}}(t)$.

It is mentioned that the implication of minimizing the performance index, $J^{*}(t)$, given by Eq. (2.3) is that the quadratic function, involving the velocity response, acceleration response and control forces, is minimized at every time instant t for all $0 \le t \le t_f$, where t_f is longer than the duration of the earthquake. Although the displacement response $\underline{Y}(t)$ does not appear in the performance index $J^{*}(t)$, Eq. (2.3), it is expected that a minimization of $J^{*}(t)$ will also reduce $\underline{Y}(t)$.

Based on the instantaneous optimal closed-loop control law proposed in Refs. 9 and 10, the optimal control vector is given by

$$\underline{U}(t) = - \frac{\Delta t}{2} \underline{R}^{-1} \underline{B}' \underline{Q} \underline{Z}(t) \tag{2.10}$$

in which $\underline{Q}$ is a (2nx2n) positive semi-definite weighting matrix.

The optimal control vector $\underline{U}(t)$ based on the linear quadratic optimal control law is as follows [e.g.,8,14]

$$\underline{U}(t) = - \frac{1}{2} \underline{R}^{-1} \underline{B}' \underline{P} \underline{Z}(t) \tag{2.11}$$

where $\underline{P}$ is a (2nx2n) Riccati matrix.

Finally, the matrix equation of motion for a structure implemented by an active control system is obtained by substituting Eq. (2.8) into Eq. (2.1) as

$$\left(\underline{I} + \underline{B} \underline{R}^{-1} \underline{B}' \underline{Q}^{*} \right) \dot{\underline{Z}}(t) = \underline{A} \underline{Z}(t) + \underline{W}_1 X_0(t) \tag{2.12}$$

in which I is a (2n x 2n) identity matrix.

Further, substitution of Eq. (2.10) or (2.11) into Eq. (2.1) leads to the following matrix equation of motion

$$\dot{\underline{Z}}(t) = (\underline{A} + \underline{B} \underline{G}) \underline{Z}(t) + \underline{W}_1 X_0(t) \tag{2.13}$$

in which $\underline{G} = -0.5 \underline{R}^{-1} \underline{B}' \underline{P}$ for linear quadratic optimal control and $\underline{G} = -0.5 \Delta t \underline{R}' \underline{B} \underline{Q}$ for instantaneous optimal control.

In what follows, the performance of the three optimal control laws given by Eqs. (2.8), (2.10) and (2.11) will be compared using a 6-story full-scale building implemented by an active tendon control system, Fig. 2-1(b), and subjected to earthquake ground accelerations.

SECTION 3

STOCHASTIC EARTHQUAKE RESPONSE

The controlled structural response can be solved numerically using Eq. (2.12) or (2.13), if the time history of an earthquake ground acceleration $\ddot{X}_0(t)$ is given. The earthquake ground acceleration $\ddot{X}_0(t)$, however, varies from occurrence to occurrence and it can be characterized more appropriately by a random process. Hence, the performance of the new optimal control law will be evaluated not only using an earthquake sample time history, such as the El Centro earthquake, but also considering $\ddot{X}_0(t)$ as a random process.

The earthquake ground acceleration, $\ddot{X}_0(t)$, is modeled as a filtered shot noise. In other words, $\ddot{X}_0(t)$ is the outpout of a filter due to a shot noise exicitation,

$$\ddot{X}_g(t) = \psi(t)\ \eta(t) \tag{3.1}$$

in which $\psi(t)$ is a deterministic non-negative envelope function, and $\eta(t)$ is a stationary white noise with zero mean and a power spectral density S^2. Various types of envelope functions $\psi(t)$ have been used in the literature. A particular envelope function given in the following will be used: $\psi(t) = 0$ for $t < 0$, $\psi(t) = (t/t_1)^2$ for $0 \le t \le t_1$, $\psi(t) = 1$ for $t_1 \le t \le t_2$ and $\psi(t) = \exp[-c(t-t_2)]$ for $t > t_2$, where t_1, t_2 and c are parameters which should be selected appropriately to reflect the shape and the duration of the earthquake ground acceleration.

The frequency response function of the filter, denoted by $H_f(\omega)$, is given by

$$H_f(\omega) = \frac{1 + 2\zeta_g(\omega/\omega_g)\,\underline{i}}{\left[1 - (\omega/\omega_g)^2\right] + 2\zeta_g(\omega/\omega_g)\,\underline{i}} \tag{3.2}$$

in which $\underline{i} = (-1)^{1/2}$ and ζ_g and ω_g are parameters depending on the characteristics of the earthquake at a particular location.

Since the earthquake ground acceleration $\ddot{X}_0(t)$ has a zero mean, the mean values of the response state vector $\underline{Z}(t)$ and the active control vector $\underline{U}(t)$ are zero. The mean square values of $\underline{Z}(t)$ and $\underline{U}(t)$ are identical to the variances $\underline{\sigma}_z^2(t)$ and $\underline{\sigma}_u^2(t)$, respectively.

Let $\underline{H}_z(\omega)$ and $\underline{H}_u(\omega)$ be the frequency response vectors of $\underline{Z}(t)$ and $\underline{U}(t)$ due to a unit steady state ground acceleration, i.e., $\ddot{X}_0(t) = \exp[\underline{i}\omega t]$, $\underline{Z}(t) = \underline{H}_z(\omega)$ $\exp[\underline{i}\omega t]$ and $\underline{U}(t) = \underline{H}_u(\omega)\exp[\underline{i}\omega t]$. The frequency response vectors, $\underline{H}_z(\omega)$ and $\underline{H}_u(\omega)$, for a controlled structure can be obtained easily from Eq. (2.12) or (2.13).

The impulse response vectors, $\underline{h}_z^*(t)$ and $\underline{h}_u^*(t)$, of $\underline{Z}(t)$ and $\underline{U}(t)$, respectively, due to the shot noise input $\ddot{X}_g(t) = \delta(t)$ are related to the frequency response vectors through the Fourier transform pair

$$\underline{h}_z^*(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H_f(\omega)\,\underline{H}_z(\omega)\,e^{\underline{i}\omega t}\,d\omega \quad ; \quad \underline{h}_u^*(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H_f(\omega)\underline{H}_u(\omega)\,e^{\underline{i}\omega t}\,d\omega \tag{3.3}$$

in which $H_f(\omega)$ is given by Eq. (3.2)

The mean square response of the state vector $\underline{Z}(t)$ can be obtained easily as follows [e.g., 9].

$$\underline{\sigma}_z^2(t) = \int_{-\infty}^{\infty} |\underline{M}_z(t,\omega)|^2 \; S^2 \; d\omega \tag{3.4}$$

in which $|\underline{M}_z(t,\omega)|^2$ is a vector whose jth element is equal to the square of the absolute value of the jth element of $\underline{M}_z(t,\omega)$ given by Eq. (3.5),

$$\underline{M}_z(t,\omega) = \int_0^t \underline{h}_z^*(\tau)\psi(t-\tau) \; e^{-\underline{i}\omega\tau} \; d\tau \tag{3.5}$$

In a similar manner, the mean square vector of the active control force can be obtained as

$$\underline{\sigma}_u^2(t) = \int_{-\infty}^{\infty} |\underline{M}_u(t,\omega)|^2 \; S^2 \; d\omega \tag{3.6}$$

in which

$$\underline{M}_u(t,\omega) = \int_0^t \underline{h}_u^*(\tau)\psi(t-\tau) \; e^{-\underline{i}\omega\tau} \; d\tau \tag{3.7}$$

The numerical computation of the non-stationary root mean square vectors, $\underline{\sigma}_z(t)$ and $\underline{\sigma}_u(t)$, of $\underline{Z}(t)$ and $\underline{U}(t)$ can be carried out very efficiently by repeated applications of the Fast Fourier Transform (FFT) in the following manner: (i) The impulse response vectors $\underline{h}_z^*(t)$ and $\underline{h}_u^*(t)$ due to $\ddot{X}_g(t) = \delta(t)$ are computed from the corresponding frequency response vectors $H_f(\omega)$ $\underline{H}_z(\omega)$ and $H_f(\omega)\underline{H}_u(\omega)$ using the FFT technique, Eq. (3.3); (ii) $\underline{M}_z(t,\omega)$ and $\underline{M}_u(t,\omega)$ are computed from Eqs. (3.5) and (3.7) again using the FFT technique; and (iii) The root mean square vectors $\underline{\sigma}_z(t)$ and $\underline{\sigma}_u(t)$ are evaluated by numerically integrating Eqs. (3.4) and (3.6) and taking the square root.

SECTION 4
NUMERICAL DEMONSTRATION

The performance of the proposed optimal control law will be demonstrated using two examples; one with the El Centro earthquake ground excitation and the other with a stochastic earthquake ground acceleration. The controlled structural response and the required active control force will be compared with those obtained using both the linear quadratic optimal control law and the instantaneous optimal control law.

A six-story full-scale building has been constructed recently in Japan by Takenaka Company in order to conduct field demonstrations of an active tendon control system and an active mass damper. The properties of the building have been provided by NCEER as follows. The (6x6) mass matrix is a diagonal matrix with each diagonal element being equal to 571.4 slugs. The (6x6) stiffness matrix K and damping matrix C are given in the following

$$\underline{K} = \begin{bmatrix} 325.56 & -159.41 & 39.14 & -6.28 & 0.92 & -0.08 \\ -159.38 & 195.81 & -111.51 & 25.32 & -3.57 & 0.41 \\ 39.14 & -111.50 & 149.94 & -82.93 & 16.34 & -1.71 \\ -6.23 & 25.31 & -82.92 & 113.13 & -59.44 & 8.68 \\ 0.94 & -3.59 & 16.35 & -59.44 & 80.65 & -34.66 \\ -0.04 & 0.39 & -1.70 & 8.67 & -34.66 & 27.33 \end{bmatrix} 10^4 \text{ lb/in.}$$

$$\underline{C} = \begin{bmatrix} 822.97 & -257.50 & 21.63 & -6.43 & -1.02 & -1.01 \\ -257.45 & 572.34 & -231.38 & 8.18 & -8.04 & -3.29 \\ 21.65 & -231.37 & 498.08 & -201.29 & -0.31 & -9.43 \\ -6.33 & 8.18 & -201.27 & 432.21 & -171.18 & -9.70 \\ -0.96 & -8.07 & -0.31 & -171.18 & 367.47 & -141.15 \\ -0.91 & 3.31 & -9.41 & -9.72 & -141.15 & 205.76 \end{bmatrix} \text{ lb.sec./in.}$$

With the mass, stiffness and damping matrices above, the natural frequencies of the building are computed as 0.943, 2.765, 4.876, 7.279, 10.114 and 14.423 Hz. The damping ratio for each vibrational mode is 1%. This six-story building has two bays and an active tendon controller is installed on the first floor as shown in Fig. 2-1(b) where the angle of inclination θ for tendons is 51.5 degrees.

The El Centro earthquake ground acceleration scaled by a factor of 32% is shown in Fig. 4-1. This 32% El Centro earthquake is considered as the input excitation. Without any control system, the maximum interstory deformation $x_i^*(i = 1,2,\ldots,6)$ of each story unit, the maximum total acceleration of each floor $\ddot{y}_i^*$ (i = 1,2,...,6) and the maximum relative displacement y_6^* of the top floor with respect to the ground are shown in Column A of Table 4-I.

With the active tendon control system, the controlled building response and the required active control force depend on the particular control law. In the present example with only one tendon controller, the $\underline{R}$ matrix consists of one element, denoted by R. For demonstrative purposes, R = 1 is used. For linear quadratic optimal control, the (12x12) weighting matrix $\underline{Q}$ is considered as a diagonal matrix in which every diagonal element is identical to q. The Riccati matrix $\underline{P}$ is computed for $q = 3 \times 10^7$ and 2×10^9, respectively. Then, the maximum structural response quantities and the maximum active control force U_{max} are computed and shown in Column B of Table 4-I.

With the application of the instantaneous optimal control law, the weighting matrix $0.5\Delta t\underline{Q}$ is partitioned as follows

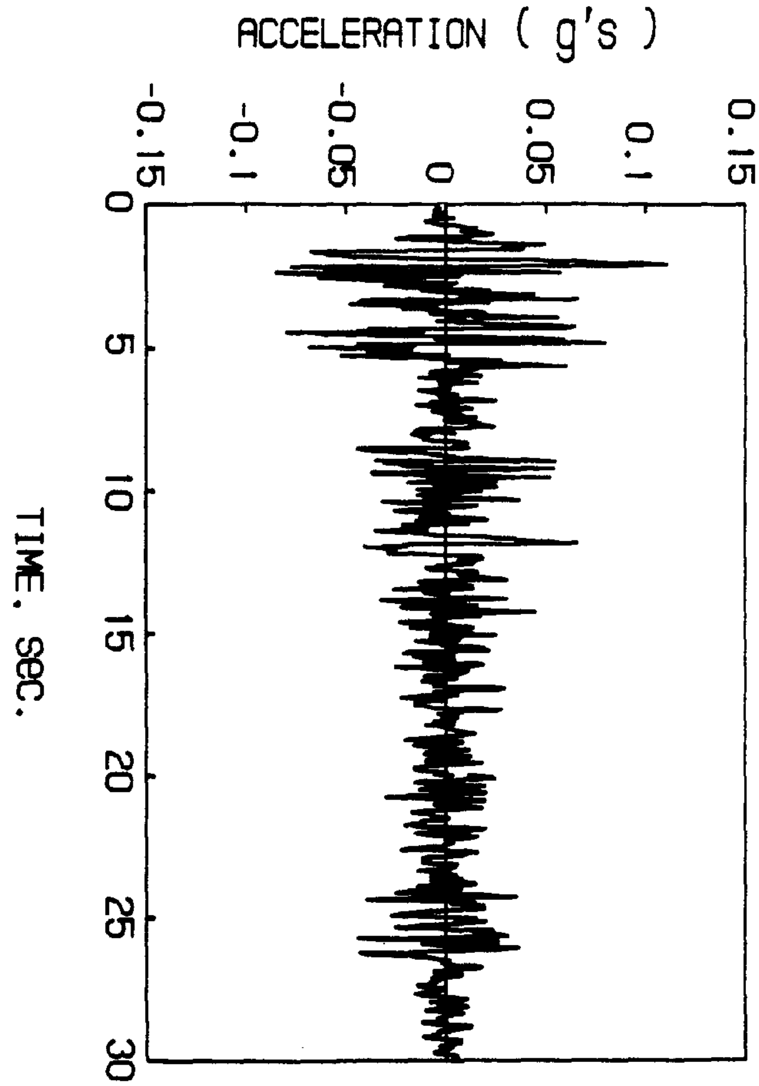

Figure 4-1: 32% El Centro Earthquake Ground Acceleration.

TABLE 4-I: MAXIMUM RESPONSE QUANTITIES OF BUILDING: (A) WITHOUT CONTROL; (B) CLASSICAL OPTIMAL LINEAR CONTROL, EQ.(2.11); (C) INSTANTANEOUS OPTIMAL CONTROL, EQ.(2.10); AND (D) INSTANTANEOUS OPTIMAL CONTROL WITH FEEDBACK $\dot{\underset{\sim}{Z}}(t)$, EQ.(2.8)

STORY	(A) NO CONTROL $y_6^* = 7.99$ cm		(B) $q = 3x10^7$ $U_{max} = 659$ kN $y_6^* = 5.57$ cm		(C) $\alpha = 1.15x10^5$ $U_{max} = 687.8$ kN $y_6^* = 5.29$ cm		(D) $\alpha = 2.8x10^3$ $U_{max} = 650.8$ kN $y_6^* = 5.53$ cm	
	x_i^* (cm)	$\ddot{Y}_i^*$ (cm/s^2)	x_i^* (cm)	$\ddot{Y}_i^*$ (cm/s^2)	x_i^* (cm)	$\ddot{Y}_i^*$ (cm/s^2)	x_i^* (cm)	$\ddot{Y}_i^*$ (cm/s^2)
1	0.734	120.4	0.488	113.3	0.518	107.9	0.530	123.4
2	1.453	234.5	1.024	147.6	1.011	143.5	1.036	111.7
3	1.615	283.7	1.153	203.2	1.125	197.8	1.165	157.4
4	1.753	284.5	1.171	205.7	1.148	191.5	1.143	149.8
5	1.651	331.7	1.090	203.7	1.067	199.8	0.991	193.8
6	1.135	361.2	0.790	261.9	0.784	259.0	0.718	234.6

STORY	(A) NO CONTROL $y_6^* = 7.99$ cm		(B) $q = 2x10^9$ $U_{max} = 2236$ kN $y_6^* = 2.29$ cm		(C) $\alpha = 10^6$ $U_{max} = 2129$ kN $y_6^* = 2.41$ cm		(D) $\alpha = 2x10^4$ $U_{max} = 1931$ kN $y_6^* = 2.79$ cm	
	x_i^* (cm)	$\ddot{Y}_i^*$ (cm/s^2)	x_i^* (cm)	$\ddot{Y}_i^*$ (cm/s^2)	x_i^* (cm)	$\ddot{Y}_i^*$ (cm/s^2)	x_i^* (cm)	$\ddot{Y}_i^*$ (cm/s^2)
1	0.734	120.4	0.518	256.8	0.490	260.8	0.383	185.1
2	1.453	234.5	0.488	142.0	0.513	153.3	0.591	155.4
3	1.615	283.7	0.508	158.2	0.530	157.7	0.772	172.4
4	1.753	284.5	0.635	163.8	0.629	165.3	0.723	227.5
5	1.651	331.7	0.749	154.9	0.731	152.6	0.706	198.8
6	1.135	361.2	0.648	233.9	0.637	230.8	0.670	252.2

X_i^* = MAXIMUM DEFORMATION OF iTH STORY UNIT

$\ddot{Y}_i$ = MAXIMUM TOTAL ACCELERATION OF iTH FLOOR

y_6 = RELATIVE DISPLACEMENT OF TOP FLOOR WITH RESPECT TO THE GROUND

U_{max} = MAXIMUM CONTROL FORCE

$$\frac{\Delta t}{2}\, \underline{Q} = \alpha \left[\begin{array}{c|c} \underline{0} & \underline{0} \\ \hline \underline{Q}_{21} & \underline{Q}_{22} \end{array} \right] \tag{4.1}$$

in which α is a constant, and $\underline{Q}_{21}$ and $\underline{Q}_{22}$ are (6x6) matrices. Since only one controller is installed on the first floor, the i-jth element of $\underline{Q}_{21}$ and $\underline{Q}_{22}$, denoted by $Q_{21}(i,j)$ and $Q_{22}(i.j)$, respectively, can be chosen to be zero for i = 2,3,...6. For illustrative purpose, the following values are assigned to elements of $Q_{21}(1,j)$ and $Q_{22}(1,j)$: $Q_{21}(1,j)$ = [1660, -1080, 24.1, 73.1, -11.4, 15.1], $Q_{22}(1,j)$ = [43.5, 29.4, 7.8, 7.8, 8.0, 7.2].

The maximum building response quantities and the required maximum active control force are shown in Column C of Table 1 for $\alpha = 1.15 \times 10^5$ and 10^6, respectively.

For the proposed optimal control law, the weighting matrix $\underline{Q}^*$ is partitioned similar to Eq. (4.1) as

$$\underline{Q}^* = \alpha \left[\begin{array}{c|c} \underline{0} & \underline{0} \\ \hline \underline{Q}^*_{21} & \underline{Q}^*_{22} \end{array} \right] \tag{4.2}$$

in which α is a constant, and $\underline{Q}^*_{21}$ and $\underline{Q}^*_{22}$ are (6x6) matrices. Again, the i-jth element of $\underline{Q}^*_{21}$ and $\underline{Q}^*_{22}$, denoted by $Q^*_{21}(i,j)$ and $Q^*_{22}(i,j)$, respectively, can be chosen to be zero for i = 2,3,...,6. For illustrative purpose, $Q^*_{21}(1,j)$ and $Q^*_{22}(1,j)$ are given as follows: $Q^*_{21}(1,j)$ = [3612, 2485, 170, 82.5, 36.8, 24.5], $Q^*_{22}(1,j)$ = [101.7, 71.1, 20.4, 20.3, 19.1, 18.1].

The maximum building response quantities, i.e., x^*_i, $\ddot{y}^*_i$ (i = 1,2...,6), y^*_6 and the required maximum control force U_{max} are presented in

Column D of Table 4-I for $\alpha = 2.8 \times 10^3$ and 2×10^4, respectively.

Table 4-I provides a clear comparison for the performance among different optimal control laws, because the required maximum control force is approximately the same. The following observations are made from Table 4-I: (i) The active tendon control system is quite effective in reducing the building response quantities, whereas, the required active control force is well within the practical limit, and (ii) The difference in the performance is minimal for the three optimal control laws investigated.

We next consider that the earthquake ground acceleration $\ddot{X}_0(t)$ is a nonstationary random process with zero mean as described previously. For illustrative purpose, the parameters appearing in the envelope function, the filter and the power spectral density S^2 of the white noise are chosen as follows: $t_1 = 3$ sec., $t_2 = 13$ sec., $c = 0.26$ sec.$^{-1}$, $\zeta_g = 0.65$, $\omega_g = 18.85$ rad./sec., and $S^2 = 10.824$ cm^2/sec^2.

Time dependent root mean squares of the response vector, $\underset{\sim}{\sigma}_z(t)$, and the control force, $\sigma_u(t)$, were computed using the three different optimal control laws described previously. The weighting matrices $\underset{\sim}{Q}$ and $\underset{\sim}{R}$ are identical to those used in the previous case. Within 30 seconds of the earthquake episode, the maximum root mean square values of the relative displacement of the first floor and the top floor with respect to the ground, denoted by $\bar{\sigma}_1$ and $\bar{\sigma}_6$, respectively, are presented in Table 4-II. Also presented in Table 4-II are the corresponding maximum root mean square of the required active control force, denoted by $\bar{\sigma}_u$. As observed from Table 4-II, the difference in the performance for each optimal control law is minimal.

TABLE 4-II: MAXIMUM ROOT MEAN SQUARE OF STRUCTURAL RESPONSE AND CONTROL FORCE: (A) WITHOUT CONTROL; (B) CLASSICAL OPTIMAL LINEAR CONTROL, EQ.(2.11); (C) INSTANTANEOUS OPTIMAL CONTROL, EQ.(2.10); AND (D) INSTANTANEOUS OPTIMAL CONTROL WITH FEEDBACK $\dot{\underline{Z}}(t)$, EQ.(2.8)

	(A) WITHOUT CONTROL	(B) $q=3x10^7$	(C) $\alpha=1.15x10^5$	(D) $\alpha=2.8x10^3$
$\bar{\sigma}_1$ (cm)	0.136	0.077	0.082	0.080
$\bar{\sigma}_6$ (cm)	1.405	0.756	0.760	0.780
$\bar{\sigma}_u$ (kN)	0	473.3	490.6	481.5

	(A) WITHOUT CONTROL	(B) $q=2x10^9$	(C) $\alpha=10^6$	(D) $\alpha=2x10^4$
$\bar{\sigma}_1$ (cm)	0.136	0.074	0.069	0.050
$\bar{\sigma}_6$ (cm)	1.405	0.358	0.363	0.381
$\bar{\sigma}_u$ (kN)	0	1348.9	1283.2	1227.1

$\bar{\sigma}_1$ = MAXIMUM RMS OF 1ST FLOOR RELATIVE DISPLACEMENT

$\bar{\sigma}_6$ = MAXIMUM RMS OF TOP FLOOR RELATIVE DISPLACEMENT

$\bar{\sigma}_u$ = MAXIMUM RMS OF CONTROL FORCE

Using the proposed optimal control law, the time dependent root mean square values of the relative displacement of the top floor with respect to the ground, denoted by $\sigma_6(t)$, are plotted in Fig. 4-2. In Fig. 4-2, Curve 0 is the response without control, whereas Curves 1 and 2 are the responses with active tendon control using $\alpha = 2.8 \times 10^3$ and 2×10^4, respectively, see Table 4-II. The time dependent root mean squares of the required active control force, $\sigma_u(t)$, are presented in Fig. 4-3 as Curves 1 and 2. Curve 1 in Fig. 4-3 is the required active control force for $\alpha = 2.8 \times 10^3$, corresponding to the case for Curve 1 of Fig. 4-2, whereas Curve 2 in Fig. 4-3 corresponds to the case for Curve 2 of Fig. 4-2, $\alpha = 2 \times 10^4$. Finally, the results for the time dependent root mean squares of the response and the active control force using the other two optimal control laws are very close to those shown in Figs. 4-2 and 4-3, and hence they are not presented.

It is observed from Figs. 4-2 and 4-3 and Table 4-II that, under stochastic earthquake ground excitations, (i) the proposed optimal control law with velocity and acceleration feedbacks performs very well, and (ii) the difference in the performance is minimal for the three optimal control laws investigated.

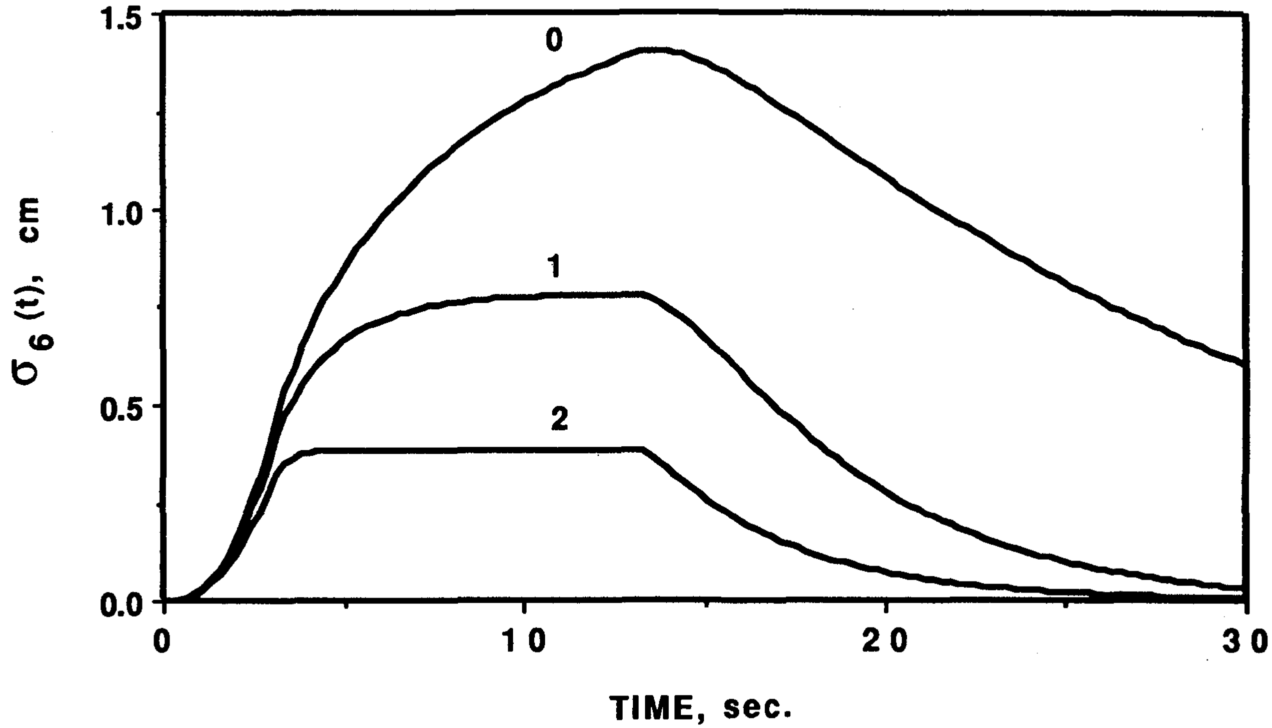

Figure 4-2: Root-Mean-Square of Top Floor Relative Displacement With Respect To The Ground: Curve 0 (Without Control); Curve 1 ($\alpha = 2.8 \times 10^3$); Curve 2 ($\alpha = 2 \times 10^4$).

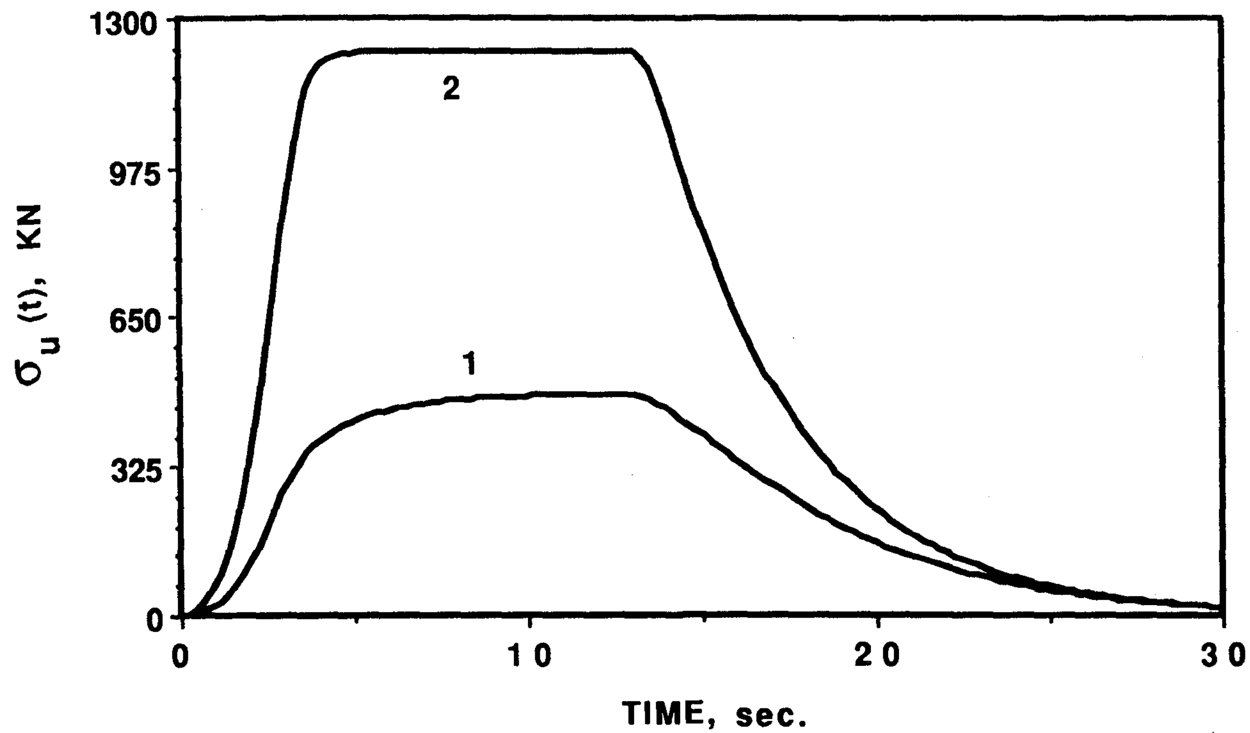

Figure 4-3: Root-Mean-Square of Active Control Force; Curve 1 (α = 2.8 x 10^3); Curve 2 (α = 2 x 10^4).

SECTION 5

CONCLUSION

For practical implementations of an active control system to building structures for seismic hazard mitigations, it is important to avoid the measurement of the displacement response. A new intantaneous optimal control law is proposed, which requires the measurements of the acceleration and velocity responses rather than the displacement and velocity responses. The performance of such an optimal control law has been investigated, evaluated, and compared with other optimal control laws using both deterministic and stochastic earthquake excitations. It is demonstrated that the performance of the proposed optimal control law is as good as other optimal control laws currently available. The contribution of such an optimal control law to practical implementations of an active control system for earthquake hazard mitigation can be significant.

SECTION 6

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APPENDIX:
OPTIMAL CONTROL LAWS

Substituting the Hamiltonian H(t) given by Eq. (2.6) into Eq. (2.7), one obtains the necessary conditions for minimizing the performance index $J^*(t)$ as follows

$$2\,\underline{Q}^*\;\dot{\underline{Z}}(t) + \underline{\lambda}(t) = 0 \tag{A-1}$$

$$2\,\underline{R}\;\underline{U}(t) - \underline{B}'\;\underline{\lambda}(t) = 0 \tag{A-2}$$

$$\dot{\underline{Z}}(t) = \underline{A}\;\underline{Z}(t-\Delta t) + \underline{A}\;\dot{\underline{Z}}(t-\Delta t)\;\Delta t + \underline{B}\;\underline{U}(t) + \underline{W}_1\;\ddot{X}_0(t) \tag{A-3}$$

(i) Optimal Closed-Loop Control (Feedback Control)

It follows from Eq. (A-2) that the optimal control vector $\underline{U}(t)$ is proportional to the Lagrangian multiplier vector $\underline{\lambda}(t)$, i.e.,

$$\underline{U}(t) = \frac{1}{2}\;\underline{R}^{-1}\;\underline{B}'\;\underline{\lambda}(t) \tag{A-4}$$

Let the control vector $\underline{U}(t)$ be regulated by the velocity state vector $\dot{\underline{Z}}(t)$ alone, i.e.,

$$\underline{\lambda}(t) = \underline{\Lambda}\;\dot{\underline{Z}}(t) \tag{A-5}$$

Then, substitution of Eq. (A-5) into Eq. (A-1) yields

$$\left(2\,\underline{Q}^* + \underline{\Lambda}\right)\dot{\underline{Z}}(t) = 0 \tag{A-6}$$

from which the unknown matrix $\underline{\Lambda}$ is obtained, for $\dot{\underline{Z}}(t) \neq 0$,

$$\underline{\Lambda} = -\,2\,\underline{Q}^* \tag{A-7}$$

The optimal control vector $\underline{U}(t)$ is obtained by substituting Eq. (A-7) into Eq. (A-5) and then into Eq. (A-4) as

$$\underline{U}(t) = - \underline{R}^{-1} \underline{B}' \underline{Q}^{*} \underline{\dot{Z}}(t) \tag{A-8}$$

(ii) Optimal Open-Loop Control (Feedforward Control)

Let the control vector $\underline{U}(t)$ be regulated by the measured earthquake excitation $\ddot{X}_0(t)$. Substituting Eq. (A-3) into Eq. (A-1), one eliminates $\underline{\dot{Z}}(t)$ as follows

$$\underline{\lambda}(t) = -2 \underline{Q}^{*} \left[\underline{A} \underline{Z}(t-\Delta t) + \underline{A} \underline{\dot{Z}}(t-\Delta t) \Delta t + \underline{B} \underline{U}(t) + \underline{W}_1 \underline{\ddot{X}}_0(t) \right] \tag{A-9}$$

Further substitution of Eq. (A-9) into Eq. (A-4) yields the optimal control vector $\underline{U}(t)$ as

$$\underline{U}(t) = - (\underline{R} + \underline{B}' \underline{Q}^{*} \underline{B})^{-1} (\underline{B}' \underline{Q}^{*}) \left[\underline{A} \underline{Z}(t-\Delta t) + \underline{A} \underline{\dot{Z}}(t-\Delta t) \Delta t + \underline{W}_1 \ddot{X}_0(t) \right] \tag{A-10}$$

Thus, the optimal control vector is regulated by the measured external excitation $\ddot{X}_0(t)$

(iii) Optimal Closed-Open-Loop Control (Feedback and Feedforward Control)

Suppose the optimal control vector is regulated by both the feedback velocity state vector $\underline{\dot{Z}}(t)$ and the external excitation $\ddot{X}_0(t)$, i.e.,

$$\underline{\lambda}(t) = \underline{\tilde{\Lambda}} \underline{\dot{Z}}(t) + \underline{\tilde{q}}(t) \tag{A-11}$$

It follows from Eq. (A-4) that

$$\underline{U}(t) = \frac{1}{2} \underline{R}^{-1} \underline{B}' \left[\underline{\tilde{\Lambda}} \underline{\dot{Z}}(t) + \underline{\tilde{q}}(t) \right] \tag{A-12}$$

Now, the term 2 $\underline{Q}^*\ \dot{\underline{Z}}(t)$ appearing in Eq. (A-1) is separated into two terms such that $\underline{Q}^*\ \dot{\underline{Z}}(t) + \underline{Q}^*\ \dot{\underline{Z}}(t) + \underline{\lambda}(t) = 0$. Then, only the $\dot{\underline{Z}}(t)$ in the second term is replaced by Eq. (A-3), and $\underline{\lambda}(t)$ and $\underline{U}(t)$ are replaced by Eqs. (A-11) and (A-12), respectively; with the result

$$\left(\underline{Q}^* + \frac{1}{2}\,\underline{Q}^*\,\underline{B}\,\underline{R}^{-1}\,\underline{B}'\,\underline{\tilde{\Lambda}} + \underline{\tilde{\Lambda}} \right) \dot{\underline{Z}}(t) + \left(\underline{I} + \frac{1}{2}\,\underline{Q}^*\,\underline{B}\,\underline{R}^{-1}\,\underline{B}' \right) \underline{\tilde{q}}(t)$$

$$+\ \underline{Q}^* \left[\underline{A}\ \underline{Z}(t-\Delta t) + \underline{A}\ \dot{\underline{Z}}(t-\Delta t)\ \Delta t + \underline{W}_1\ \ddot{X}_0(t) \right] = 0 \tag{A-13}$$

It follows from Eq. (A-13) that

$$\left[\underline{Q}^* + \left(\underline{I} + \frac{1}{2}\,\underline{Q}^*\,\underline{B}\,\underline{R}^{-1}\,\underline{B}' \right) \underline{\tilde{\Lambda}} \right] \dot{\underline{Z}}(t) = 0 \tag{A-14}$$

$$\left(\underline{I} + \frac{1}{2}\,\underline{Q}^*\,\underline{B}\,\underline{R}^{-1}\,\underline{B}' \right) \underline{\tilde{q}}(t)$$

$$+\ \underline{Q}^* \left[\underline{A}\ \underline{Z}(t-\Delta t) + \underline{A}\ \dot{\underline{Z}}(t-\Delta t)\ \Delta t + \underline{W}_1\ \ddot{X}_0(t) \right] = 0 \tag{A-15}$$

Thus, the unknown matrix $\underline{\tilde{\Lambda}}$ and the unknown vector $\underline{\tilde{q}}(t)$ are obtained from Eqs. (A-14) and (A-15) as follows

$$\underline{\tilde{\Lambda}} = -\left(\underline{I} + \frac{1}{2}\,\underline{Q}^*\,\underline{B}\,\underline{R}^{-1}\,\underline{B}' \right)^{-1} \underline{Q}^* \tag{A-16}$$

$$\underline{\tilde{q}}(t) = \underline{\tilde{\Lambda}} \left[\underline{A}\ \underline{Z}(t-\Delta t) + \underline{A}\ \dot{\underline{Z}}(t-\Delta t)\ \Delta t + \underline{W}_1\ \ddot{X}_0(t) \right] \tag{A-17}$$

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