ASIAN JOURNAL OF CIVIL ENGINEERING (BUILDING AND HOUSING) VOL. 10, NO. 1(2009)
PAGES 57-78

HYBRID PREVIEW CONTROL OF STRUCTURES UNDER EARTHQUAKE EXCITATIONS

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Abstract

Passive, active and hybrid vibration control of structures during earthquakes were studied. Particular attention was given to hybrid preview control strategy for protection of structures against earthquakes. A three-story building under fixed-base condition and with laminated rubber bearing base isolation system subject to the El Centro 1940 earthquake were analyzed. The cases that an active control system with and without preview was present were studied in details. The corresponding structural responses with passive, active and hybrid vibration control systems were evaluated. Accelerations and displacements responses for active systems with and without preview sensors for fixed-base and base-isolated structures were computed and the results were compared with those for the unprotected building. It was shown that properly designed passive, active and hybrid control systems could effectively reduce the acceleration transmitted to structures during a major earthquake. It was also shown that the inclusion of the preview sensors in the active control strategy improved the system performance considerably. The hybrid use of the laminated rubber bearing isolation system with the active control strategies could provide significant improvement of the protection of buildings during seismic events.

Keywords: Passive control; active control; hybrid control; seismic isolation; earthquake resisting design; structural protection

1. Introduction

Last three decade has witnessed an increasing interest in the use of passive and active vibration control mechanisms for earthquake resisting design of structures. Use of passive base isolation techniques reduces the earthquake vibration energy entering the structure from the ground. The laminated rubber bearing (LRB) is the most commonly used passive base isolation system, which has been implemented in numerous buildings around the globe. The

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active vibration control strategy, on the other hand, senses the structural vibrations and uses actuators to actively reduce the vibration structural elements. The more recently proposed hybrid approach combines the base isolation system with an active mechanism for optimal vibration suppression. It is now well known that the passive and active devices have considerable potential in preventing earthquake damages to structures and their internal equipment. Here the study is focused on the performance analysis of preview hybrid control strategy. In this approach a combination of LRB and optimal active control with preview sensors is used.

Use of base isolation and passive energy dissipation devices has attracted considerable attention for earthquake resisting design of buildings and bridges. Kelly [1,2] and Skinner et al. [3] provided extensive reviews of the base isolation methodology and its historical developments. Numerous digital simulations (Mostaghel and Khodaverdian [4], Su et al. [5,6] and Fan et al. [7-9]) and shaking table experiments (Kelly [10,11]) have shown that the peak acceleration and deflection of structures are drastically reduced by using properly designed base isolation and energy dissipation mechanisms.

Use of active control methodologies for vibration suppression of structures during earthquakes is relatively more recent. Abdel-Rohman and Leipholz [12,13], Soong and co-workers [14-16], Masri et al. [17], Yang and Giannopoulos [18-20], Meirovitch [21,22], and Reinhorn et al. [23] provided significant contributions to the field of active structural control. A model-independent active vibration absorber (AVA) controller for vibration suppression of flexible space structures and buildings during earthquakes was proposed by Lee-Glauser et al. [24,25]. Housner et al. [26] provided a state-of-the-art review of structural control for earthquake applications. Masri et al. [27], Dyke et al. [28] and Spencer et al. [29] studied the potential usage of electro- and magnetorheological devices for structural control applications. Multi-objective optimal structural control was described by Johnson et al. [30]. Yamada and Kobori [31] discussed the linear quadratic regulator for structural control applications. Dyke et al. [32] and Suhardjo et al. [33] analyzed acceleration feedback control and feedback-feedforward control of structures. Spencer et al. [34] reported advances in active tendon and active mass drive systems. Mei et al. [35] described model predictive control for seismic applications.

For practical application, the conventional feedback active control has a major limitation in that the servo-control system must react very quickly to suppress disturbances that already have been encountered by the structure. As the strong ground motion in most earthquakes occurs after a few seconds, the actuation system should be designed to react extremely fast, which may not be always practical. Bener [36] noted the advantage of having some preparation time and suggested the use of preview control in connection with the vehicle suspension systems. In this preview control approach information concerning the disturbance becomes available to the controller before it is encountered the structure. The optimal preview control law consists of a combination of feed back and feed forward control algorithms. The feed back part is the same as that of traditional linear quadratic (LQ) regulator control algorithm and the feed forward part results from preview input of the ground excitation. Recent advances in computer hardware, and sensor and actuator technology as well as reduction in their costs, have made the usage of active preview control systems more attractive. Successful application of preview active control of vehicle suspension systems have already been reported by Tomizuka [37-39], Hac [40], Hac and Youn [41,42], and Marzbanrad et al. [43-45]. These studies showed that preview information about the excitation for only a fraction of second is sufficient to significantly improve the controller performance.

Recently, application of preview control for seismic protection of buildings was reported by Marzbanrad et al [46]. In practice sensors could be placed around the building to provide preview information about the earthquake ground acceleration. With the knowledge of incoming seismic excitations and an appropriate active control law, the actuators could react before the excitations arrive. Marzbanrad et al. [46] showed that the active system with and without preview could provide significant protection for the structures against earthquake. They treated a fixed-base structure and used an optimal active control strategy with preview. It was also assumed that the actuators apply forces to different floors of the building.

In this paper, the performance of hybrid preview control strategy for a generic three-story structure is studied and the results are compared with those for the base-isolated and fixed-base structure with and without active control mechanisms. The optimal control theory is used, and it is assumed that the control force is only exerted to the first floor of the building. (In the work of [46] the control actuators were assumed to be present in all three floors of the building.) Responses of the unprotected building and the structure with a laminated rubber bearing base-isolation system to El Centro 1940 earthquake excitation are evaluated for comparison. In addition, active vibration control systems with and without preview sensors are designed for the fixed-base and the hybrid structures. Peak absolute acceleration responses of fixed-base and base-isolated structures for optimal control and optimal preview control systems are evaluated and the results are compared with each other and with those of the unprotected building. A range of natural period for the building is considered and the response spectra curves for different cases are also computed. The result shows that using a properly designed optimal preview control system and/or an appropriate LRB base-isolation system can effectively reduce the peak floor accelerations of the structure. The hybrid combination of base isolation and active preview control, however, leads to the maximum protection of buildings against earthquake. Comparison of the control forces for active and active and preview control shows that the required control force significantly reduces for the base-isolated structure.

2. Governing Equations

A generic three-story building for fixed-base and base-isolated structure as shown schematically in Figure 1 is used in this study. In this section, the governing equations of motion of a (hybrid) base-isolated structure with and without an active control system are presented. Assuming an elastic structure and a linear model for the laminated rubber bearing, the equations of motion are given as,

$$m_1(\ddot{z}_1 + \ddot{s} + \ddot{x}_g) = -k_1 z_1 - c_1 \dot{z}_1 + k_2(z_2 - z_1) + c_2(\dot{z}_2 - \dot{z}_1) - u \qquad (1)$$

$$m_2(\ddot{z}_2 + \ddot{s} + \ddot{x}_g) = -k_2(z_2 - z_1) - c_2(\dot{z}_2 - \dot{z}_1) + k_3(z_3 - z_2) + c_3(\dot{z}_3 - \dot{z}_2) \quad (2)$$

$$m_3(\ddot{z}_3 + \ddot{s} + \ddot{x}_g) = -k_3(z_3 - z_2) - c_3(\dot{z}_3 - \dot{z}_2) \quad (3)$$

$$m_b(\ddot{s} + \ddot{x}_g) = -k_0 s - c_0 \dot{s} + k_1 z_1 + c_1 \dot{z}_1 \quad (4)$$

where z_i is the horizontal displacement of the ith floor relative to the base, s is the horizontal displacement of the of base floor relative to the ground, $\ddot{x}_g$ is the earthquake horizontal acceleration, u is the actuator force exerted to the first floor of the building, and m_i, c_i, k_i, respectively, are mass, damping, and stiffness of the ith floor. Here, k_0 and c_0 are the stiffness and damping of the laminated rubber bearing. When $s \equiv 0$, Eqs. (1)-(4) reduced to the governing equations for vibration of a fixed-base structure similar to the one studied in [45]. Here, however, it is assumed that the control force, u, only applies to the first floor and there is no control force in the other floors.

It is advantageous to restate Eqs. (1)-(4) in the state space variable form. Introducing

$$x = [x_1, x_2, ..., x_8]^T \quad u = u \quad w = \ddot{x}_g \quad (5)$$

here

$$x_1 = z_1 \quad x_3 = z_2 \quad x_5 = z_3 \quad x_7 = s$$

$$x_2 = \dot{z}_1 \quad x_4 = \dot{z}_2 \quad x_6 = \dot{z}_3 \quad x_8 = \dot{s} \quad (6)$$

Eqs. (1)-(4) can be restated as

$$\dot{x} = Ax + Bu + Ew \quad (7)$$

where A, B and E are constant and have dimensions of 8×8, 8×1, and 8×1, respectively. These matrices are given in Appendix A.

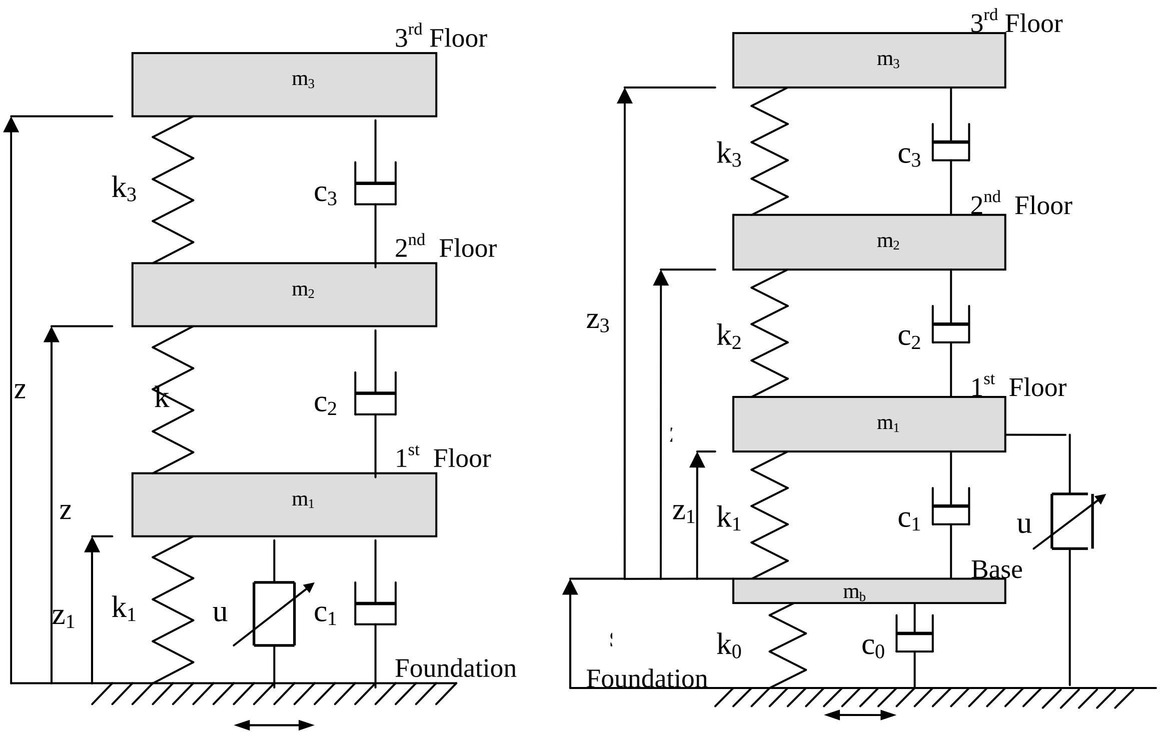
The design of the structural control system involves a compromise among conflicting goals. The acceleration levels of all stories should be kept low with minimum applied control forces. Therefore, the control system is optimized with respect to absolute acceleration and control forces of each floor. The performance index should, therefore, include the mean square values of $\ddot{z}_i + \ddot{s} + \ddot{x}_g$ and magnitude of the active force u(t). Thus, the performance index to be minimized can be written as

$$J = \lim \frac{1}{2T} \int_0^T \{ \begin{bmatrix} \ddot{z}_1 + \ddot{s} + \ddot{x}_g \\ \ddot{z}_2 + \ddot{s} + \ddot{x}_g \\ \ddot{z}_3 + \ddot{s} + \ddot{x}_g \end{bmatrix}^T \begin{bmatrix} \rho_1 & 0 & 0 \\ 0 & \rho_2 & 0 \\ 0 & 0 & \rho_3 \end{bmatrix} \begin{bmatrix} \ddot{z}_1 + \ddot{s} + \ddot{x}_g \\ \ddot{z}_2 + \ddot{s} + \ddot{x}_g \\ \ddot{z}_3 + \ddot{s} + \ddot{x}_g \end{bmatrix} + u^T \rho_4 u \} dt \quad (8)$$

where ρ_i are weighting parameters (reflect designer preferences) determining the amount of emphasis that the control law places on the acceleration of different floors and the corresponding control forces. After substitution for the accelerations using Eqs. (1)-(4) and the state variables introduced in Eq. (6), the performance index is expressed in a form that is quadratic in the state space variables and the input vectors. i.e.,

$$J = \lim_{T \to \infty} \frac{1}{2T} \int_0^T (x^T Q_1 x + 2x^T N u + u^T R u + 2x^T Q_{12} w + w^T Q_2 w)\, dt \qquad (9)$$

Here Q_1, R and Q_2 are symmetric, time-invariant weighting matrices such that $R > 0$ and $Q_n = Q_1 - NR^{-1}N^T \geq 0$ and N, Q_{12} are constant matrices.



a. Fixed base b. base isolated

Figure 1. Structural model of a three-story building

3. Optimal Preview Control

In this section, fundamentals of optimal preview active control strategy are outlined. In optimal control theory, a measure of system performance is generally introduced. For the present vibration suppression problem during earthquakes, the performance measure takes the form of a quadratic cost-function containing terms relating to the floor absolute accelerations and control forces. (Here the performance index given by (9) is used.) It is assumed that the earthquake excitation input $\ddot{x}_g(\tau) \equiv w(\tau)$ for $\tau \in [t, t+t_P]$ is measured by the preview sensors. That is, the preview information about the ground excitation $\ddot{x}_g(t)$ up to t_P ahead of current t is available. The method for finding a continuous time optimal preview control law was given by Tomizuka [39] and Hac [40]. Their main result may be restated in the following problem statement:

Problem Statement. Consider a system that is governed by the state space equation given by (4) and with preview time t_P on the excitation $\ddot{x}_g(t)$. (i.e. $\ddot{x}_g(\sigma), \sigma \in [t+t_P]$ is known.) The optimal preview control problem reduces to finding a control law $u(t) = f(x(t), \ddot{x}_g(\sigma), \sigma \in [t+t_p])$ that minimizes the quadratic performance index given by (6). Now let

$$A_n = A - BR^{-1}N^T \ , \ Q_n = Q_1 - NR^{-1}N^T \tag{10}$$

and assume that Q_n is nonnegative definite, and $Q_n = T^T T$; then if the pair (A_n, B) is stabilizable and the pair (A_n, T) is detectable, the optimal preview control law is given by

$$u(t) = -R^{-1}[(N^T + B^T P)x(t) + B^T r(t)] \tag{11}$$

where P is the positive definite solution of the Algebraic Riccati equation

$$PA_n + A_n^T P - PBR^{-1}B^T P + Q_n = 0 \tag{12}$$

and the vector $r(t)$ is given by

$$r(t) = \int_0^{t_p} e^{A_c^T \sigma}(PD + Q_{12})w(t+\sigma)d\sigma \tag{13}$$

where A_c is the close loop system matrix given by

$$A_c = A - BR^{-1}\left(N^T + B^T P\right) = A_n - BR^{-1}B^T P \tag{14}$$

A_c must have eigenvalues with negative real parts, so that the system be asymptotically stable. Consequently, the exponential function in Eq. (13) will decrease with time and hence, the integral defining r(t) places more emphasis in the preview control law on the input in the near future than on that further ahead in time. Proof of optimal preview control law given by (11)-(14) was given by Hac [40] through the use of calculus of variation.

The optimal control *u(t)* given by (11) consists of two terms. The first term is the feed-back part, which is the identical to that for an optimal control in the absence of preview sensors. The second term is the feed-forward part, which takes advantage of the preview information available. When no preview is available, only the feedback term remains and the control system reduces to the commonly used optimal feedback control strategy.

4. Responses to El Centro Earthquake

In this section, responses of a three-story building subject to the accelerogram of El Centro 1940 earthquake are studied. It is assumed that the floors have the same mass, stiffness and damping. The cases of an unprotected structure and base-isolated structure with active control with and without preview are compared. The weighting constants used in the performance index given by (8) and the calculated closed loop system poles are listed in Table 1.

For the base-isolated structures, a laminated rubber bearing (LRB) base isolation system with a natural period of 2 sec (natural frequency of 0.5 Hz) is used in the analysis. Unless stated otherwise, a fixed value of structural damping of $c/m = 0.1\text{s}^{-1}$ is also assumed. (This corresponds to a modal damping coefficient of about 0.001 to 0.01 for the fundamental natural period of 0.1 to 1 sec.) For the LRB base isolation system a damping of $c_o/m = 2$ (a damping coefficient of 0.3) is considered.

4.1 Sample sesponses

Figure 2 shows sample absolute acceleration ($\ddot{z}_3 + \ddot{x}_g$) time histories of the top floor of the fixed-base structure with a fundamental natural period of 0.5 sec and a damping coefficient of 0.004 for unprotected, active and active with 0.12 sec preview. This figure shows that the acceleration level of the unprotected building reaches to more than 1.5 g, while the presence of an active control system significantly reduces the acceleration response of the structure. In particular, the preview control system appears to be highly effective in reducing the acceleration level. (In this case the peak acceleration reduces to less than 0.4 g.) The acceleration time histories of first and second floors of the structure have features similar to those shown in Figure 2, and therefore are not shown in here.

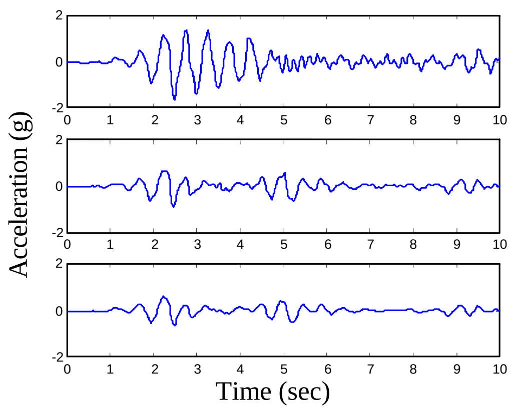


Figure 2. Time histories of third floor absolute acceleration for fixed-base structure with andwithout active control systems

For a structure with a laminate rubber bearing base isolation system the time histories of absolute acceleration of the top floor ($\ddot{z}_3 + \ddot{s} + \ddot{x}_g$) for the cases that an active control system with and without preview are also present are shown in Figure 3. The response of unprotected building is also shown in this Figure for comparison. It is observed that the rubber bearing base isolation even without an active system reduces the absolute acceleration to almost one-tenth of that of the fixed-base structure. The hybrid combination of the LRB and the active systems further reduces the acceleration responses. In particular, the LRB and preview control reduced the acceleration level to about 0.15g.

Similarly, Figure 4 shows the absolute acceleration responses for second and first floors of the building. It is seen that the laminated rubber bearing base isolation with an active control system, especially the one with active and preview, provides considerable protection for all floors of the building against earthquake. Using base-isolation and active preview system, Figures 3 and 4 show that the absolute accelerations levels reduces by a factor of five to ten with respect to unprotected structure.

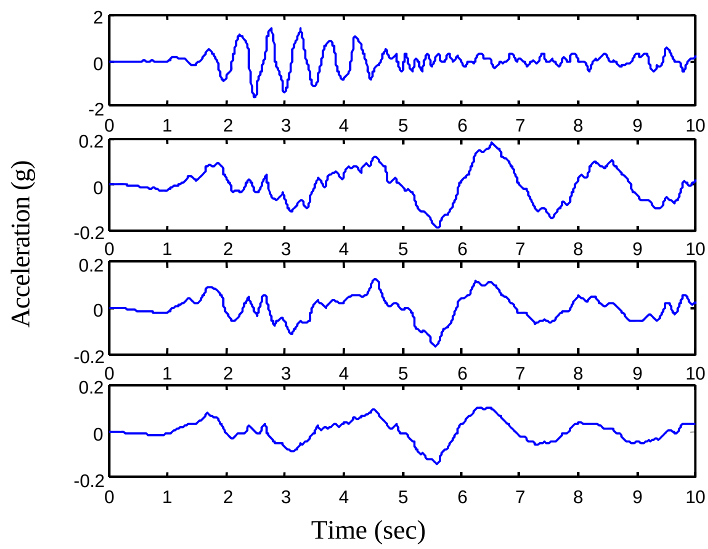
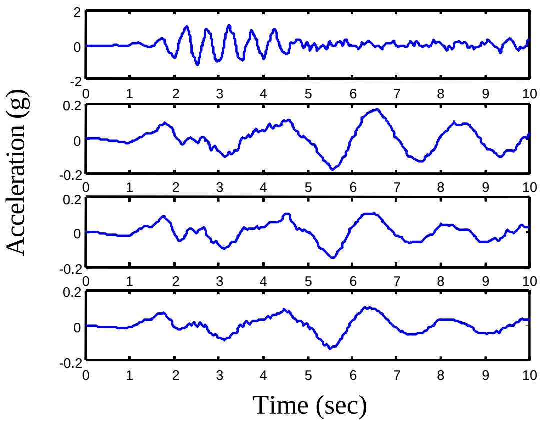
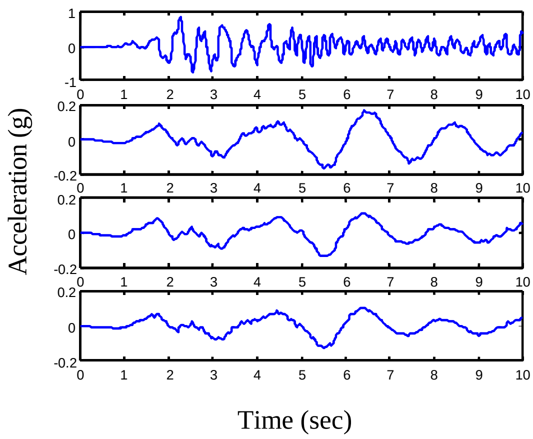


Figure 3. Time histories of third floor absolute acceleration for base-isolated structure with and without active control system Comparison with the unprotected fixed-base structure

Figure 5 shows the acceleration time histories of the base floor of the base-isolated structure with and without active control systems. It is seen that the acceleration levels of the base floor of the base-isolated structure are comparable to those of the upper floors. This show that the structure with a LRB base isolation system behaves roughly as a rigid body and do not amplify the earthquake ground excitation. Figure 5 also shows that the preview control improves the absolute acceleration responses compared with respect to active system, although the difference is not significant for the base-isolated building.



a). Second floor



b). First floor

Figure 4. Time histories of absolute acceleration for fixed base and base isolated

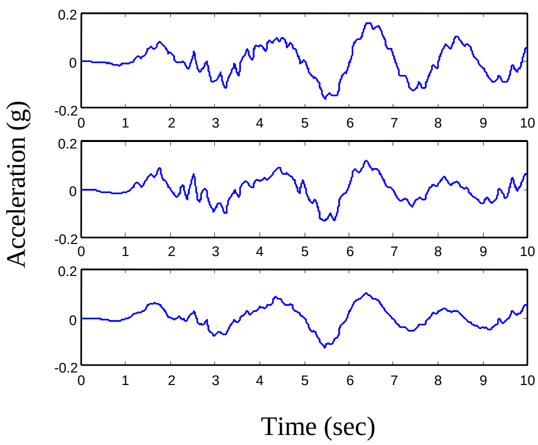


Figure 5. Absolute acceleration time histories at the base floor of the

base-isolated structure

For the unprotected and base-isolated structures with and without active and active with preview control systems, Figures 6 and 7 show the time histories of the top floor displacement responses during the El Centro 1940 earthquake. Active systems, especially with preview, reduce the peak displacement of third floor for both fixed-base and base-isolated structures. It is seen from Figure 6 that the unprotected building has a peak lateral displacement of about 9 cm, while that of the protected building with active systems is less than 3 cm. This figure shows that the active system is highly effective for reducing the structural vibration during earthquakes. Figure 7 shows the LRB by itself reduces the third floor displacement to one fifth of that for the fixed-base structure. The presence of active systems then further reduces to displacement response of the structure.

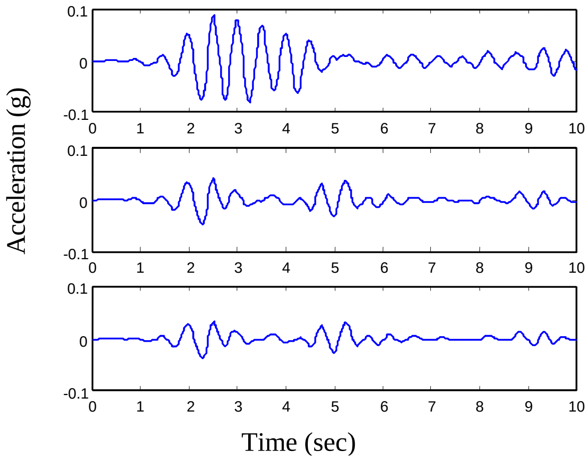


Figure 6. Time histories of third floor displacement for fixed-base structure with and without active control system

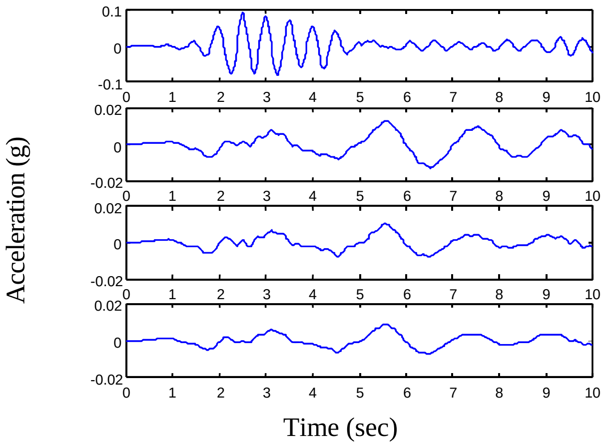


Figure 7. Time histories of third floor displacement for base-isolated structure with and without active control system. Comparison with the unprotected fixed-base structure

Time histories of the base displacement responses of the base-isolated structure with and without active devices are shown in Figure 8. This figure shows that base displacement of the base-isolated building reaches to about 18 cm in the absence of active control devices. The presence of active system reduces the base displacement response of the structure. For the hybrid combination of the LRB and the preview active control, the peak base displacement is less than 10 cm. The preview system allows the actuator to react to the fore-coming earthquake excitation and improves acceleration and displacement responses. A careful examination of the result shows that the preview controller activates the actuators before the base of the structure encounters the earthquake shock.

It should be emphasized that the performance index given by Eq. (8) is focused to reduced the absolute acceleration responses and the needed control force. Nevertheless, the presence of the control system reduces the base displacement responses. The reduction in base displacement of the base-isolated structure is critical to their aseismic design, specially, when there are severe limitations in their base movements.

For the fixed-based and base-isolated structure with active control with and without preview, the control forces (per unit mass) are shown in Figure 9. It is observed that the control force accelerations are of the order of 0.6 g for the fixed-base structure and of the order 0.1 g for the structure with the LRB base isolation system. That is the presence of base isolation system reduces the required control force for active control by a factor of six. Figure 9 also shows that the trend of variation of the control forces follows that of the earthquake ground acceleration. The control forces for the active system with and without preview are comparable, while the acceleration levels for the preview control are slightly lower than those without the preview sensors.

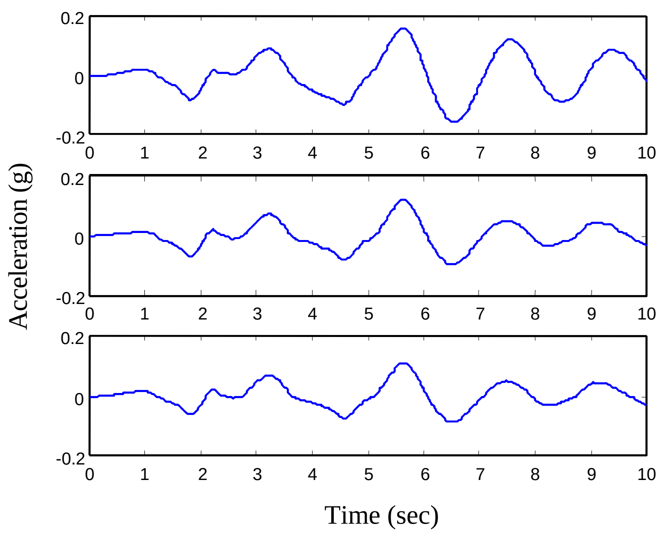


Figure 8. Time histories of base displacement for base-isolated structure with and without active control systems

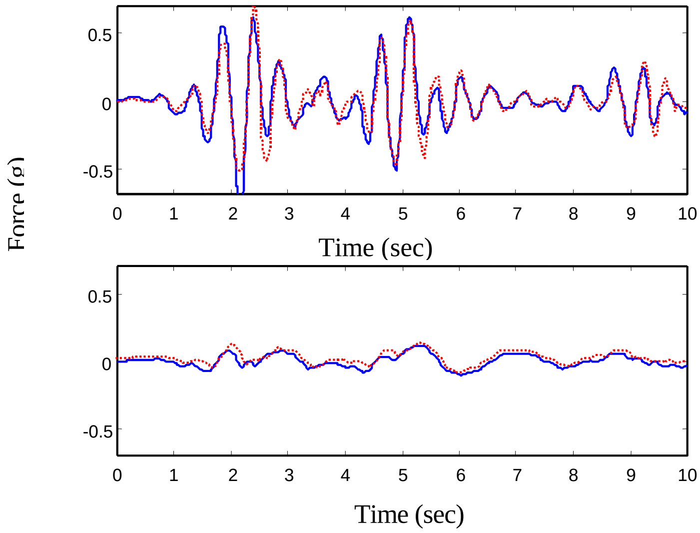


Figure 9. Time histories of control force for active, active and preview systems
(a) Fixed base structure (b) Base isolated structure

The Fourier spectra of the third floor acceleration responses for the unprotected fixed-base building and laminated rubber bearing base-isolated structure with and without active control systems are shown in Figure 10. Frequency contents of the acceleration responses may be clearly seen from this Figure. It is observed that the spectral energy is focused at frequencies below 10 Hz. The Fourier spectra of the unprotected and base isolation structure show noticeable peaks, respectively, at frequencies of 2, 5.6 and 8 Hz, and 0.5, 3.5, 6.4 and 8.3 Hz (corresponding to the fundamental frequencies of these structures). Comparison of the Fourier spectra in Figure 10 shows that the use of base isolation system with and without active control significantly reduces the amplitudes of the sharp peaks of the fixed-base structure, while the rest of the spectrum remains roughly unchanged. These observations indicate the mechanisms by which the LRB and active control devices suppress the structural vibrations. That is the LRB base isolation system, particularly in combination with active control, eliminates the resonance peaks in the Fourier spectra, thereby reducing the peak structural responses. The presence of preview sensors further improves the system performance.

It should be emphasize that the weighting constants in the performance index given by Eq. (8) are design parameters that balance the reduction in the acceleration level and the amount of control force needed. Increasing the weighting constants for the control force, ρ_4, leads to the decrease in the needed control force, at the expense of increase in the floor accelerations, $\ddot{z}_i + \ddot{s} + \ddot{x}_g$. In contrast, when it is feasible to exert large amount of control force, the corresponding weighting constant can be decreased, which leads to further suppression of the acceleration responses.

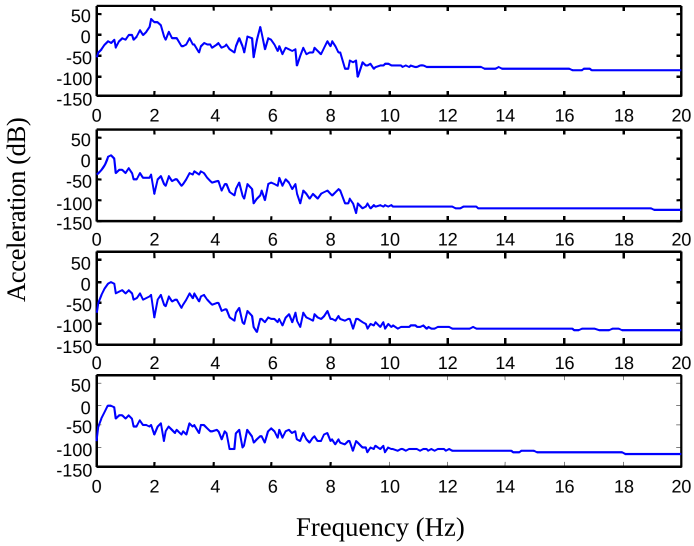


Figure 10. Power spectral density of absolute accelerations for fixed base and base-isolated structure with and without active control systems

4.2 Response spectra

To perform a comprehensive comparison of the performance of the active control systems with and without preview for different structures, the absolute acceleration response spectra are evaluated. Response spectra are also commonly used for dynamic design of major structures against earthquakes. The peak absolute accelerations of the structure, $\ddot{z}_i + \ddot{x}_g \,|_{max}$ (fixed-base) and $\ddot{z}_i + \ddot{s} + \ddot{x}_g \,|_{max}$ (base-isolated), for a range of fundamental natural period of the structure, T_1, between 0.1 to 1 sec are evaluated and the corresponding third floor response spectra curves are plotted in Figures 11 and 12. The damping coefficients of c/m=0.1 s^{-1} for the structure are also assumed. Figure 11 shows that the peak third floor acceleration of the unprotected structure varies significantly with the structure fundamental period and could reach to about 2.5 g. The response spectra of the structure with active control systems are rather smooth curves and have much lower amplitudes. The peak acceleration response of the structure with an active system with preview is about 0.4 g. That is, the active system with preview reduces the peak acceleration of unprotected structure by a factor of six. The acceleration of the active control without preview is about 0.8 g. This figure shows that the active control, particularly with preview, significantly reduces the floor peak accelerations of the unprotected structures. Response spectra curves of second and first floor (not shown here due to space limitation) have similar general feature to that shown in Figure 11, except that the acceleration levels are lower.

Figure 12 shows the acceleration response spectra curves for the third floor of the base-isolated structure with and without active systems. Comparing with Figure 11, it is observed that the peak acceleration responses of the base isolated building are lower by a factor of eight than those of the fixed base building. The hybrid combinations of the active control with the LRB system further reduce the peak accelerations experienced by the structure. In particular, the presence of the preview control reduced the peak acceleration to about 0.12 g and 0.2 g, respectively, for structures with natural periods of 0.1 and 1 sec. Figure 12 also shows an increase in the peak acceleration responses with the natural period of the structure.

Absolute acceleration response spectra for the base floor of the base-isolated structure with and without active control systems are shown in Figure 13. Again, it is seen that the base floor acceleration is quite low and the presence of active system especially with preview further reduces the peak acceleration levels by a factor of about 1.5 to 2. Comparing Figures 12 and 13, is noticed that the base isolated structure does not amplify the base excitation especially for stiff structures. A slight amplification is notices as the structure becomes for flexible (for T_1 close to 1 sec).

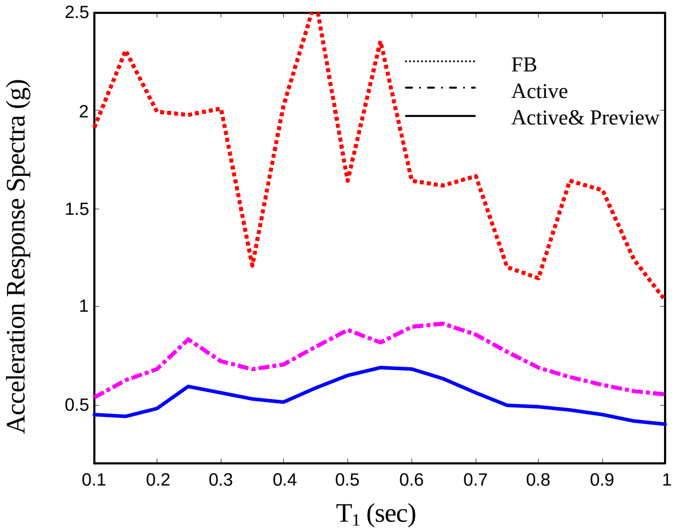


Figure 11. Third floor absolute acceleration response spectra for fixed-base structure with and without active control systems

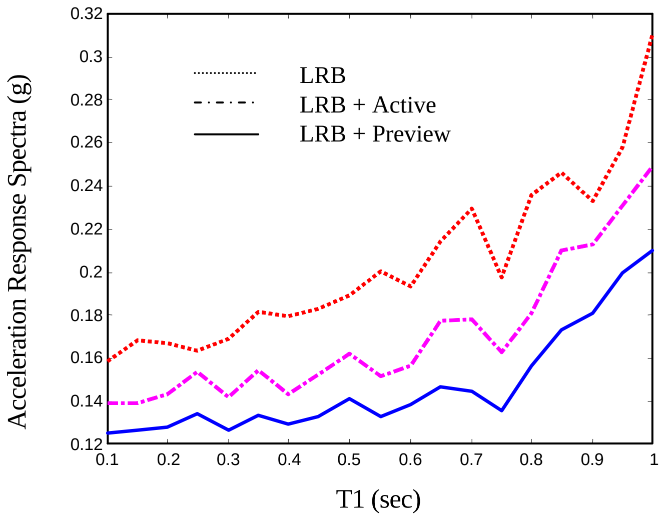


Figure 12. Third floor absolute acceleration response spectra for base-isolated structure with and without active control systems

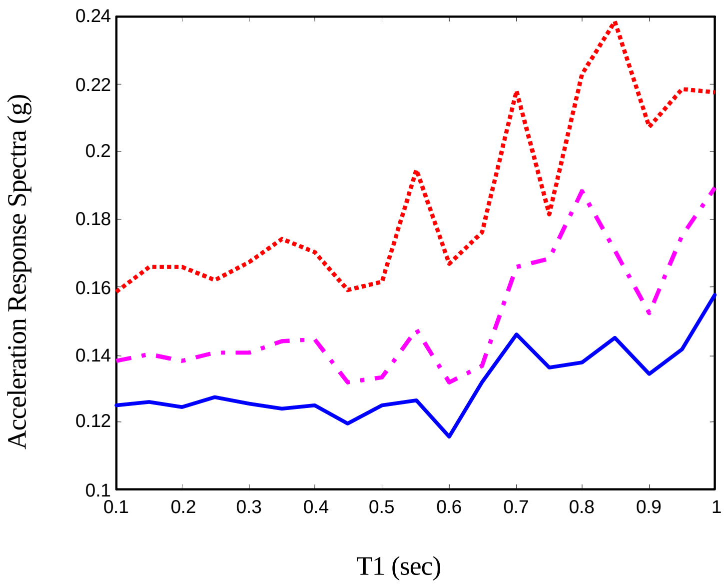
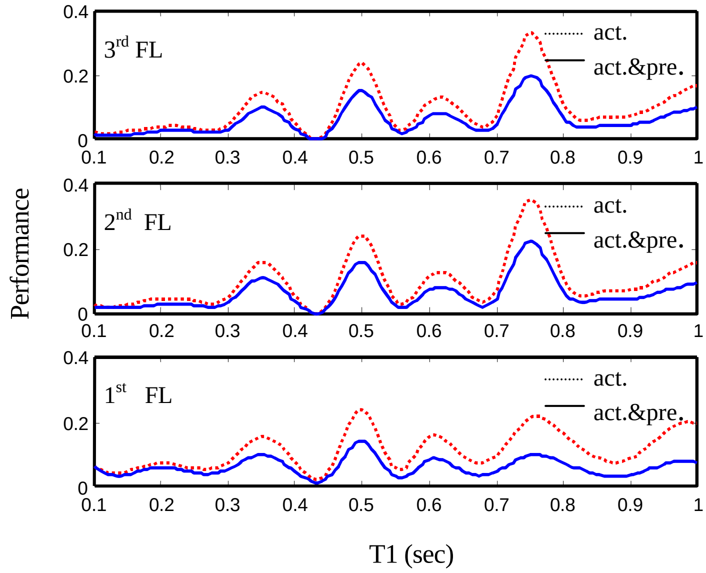


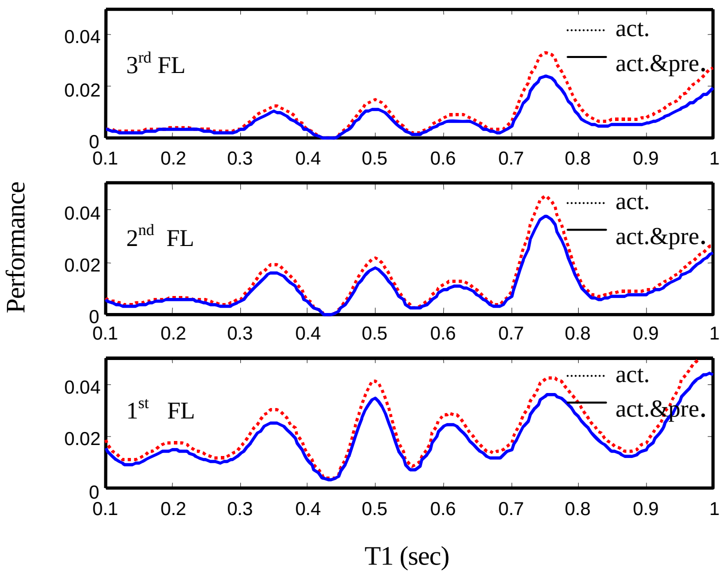
Figure 13. Base floor absolute acceleration response spectra for base isolated structure with and without active control systems

4.3 Mean-square acceleration

Another important measure of vibration intensity is the mean-square absolute acceleration responses, $E\{(\ddot{z}_i + \ddot{x}_g)^2\}$ (for the fixed-base structure) and $E\{(\ddot{z}_i + \ddot{s} + \ddot{x}_g)^2\}$ (for the base-isolated structure). Here $E\{\ \}$ stands for the expected value (ensemble average). Mean-square response is particularly important for evaluating accumulative structural damage and low cycle fatigue. We define the performance (mean-square performance) as the ratio of the maximum mean-square absolute acceleration response of the structure with an active control to that of the unprotected structure. For different floors, performances of active control without preview are compared with those with preview for a range of structural natural period in Figure 14. Clearly, both active control systems for fixed-base and base-isolated structures shown respectively in Figures 14(a) and 14(b) significantly reduce the mean-square acceleration responses during earthquakes. Figure 14 further shows that the preview active control is more effective in reducing the mean-square responses when compared with the control without preview. For certain ranges of T_1 the system with preview is about 30% more effective. From Figure 14(a) it is noticed that using active and preview active systems for fixed-base structures, respectively, improves the mean-square performance by a factor of about 10 to 20. Comparing Figures 14(a) with 14(b), similar improvement is noticed when the LRB base isolation system is used. In particular, Figure 14(b) shows the mean-square performance of the hybrid combination of the LRB and active device improves, respectively, by a factor of 200 and 140 for active and preview active systems. This shows that the hybrid system is highly effective in protecting the structure against earthquakes.



a). Fixed base structure



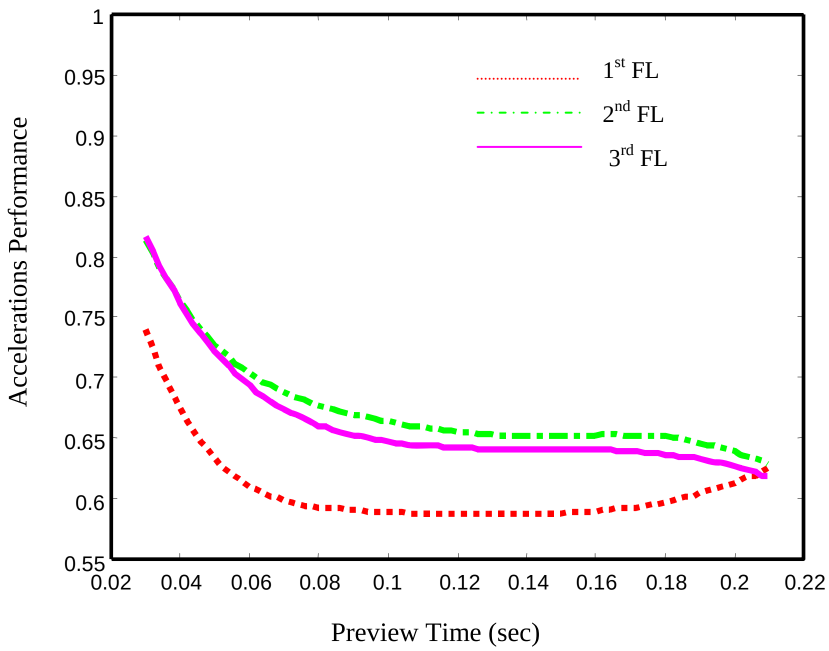
b). Base isolated structure

Figure 14. Absolute acceleration performance for structure with active, and active and preview control system relative to unprotected structure

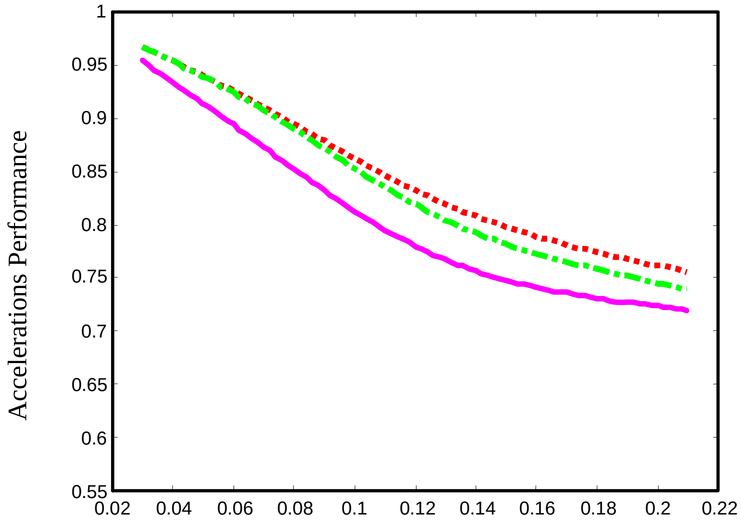
4.4 Effect of preview time

To study the effect of preview time, mean-square acceleration responses of the structure for a range of preview time in the range of 0.02 to 0.2 sec are evaluated and the results are shown in Figure 15. The fundamental natural period of the structure is kept fixed at 0.5 sec. In this figure, the relative performance is defined as the ratio of the mean-square absolute acceleration relative to that for active control without preview (i.e., $t_p = 0$). Figures 15(a) and 15(b), respectively, show the effect of preview time on the relative performance of the control system for the fixed-base and the base-isolated structures. It is noticed that the mean-square acceleration magnitude for all floors reduces as the preview time increases. The rate of decrease in the relative performance is quite sharp for small values of preview time, but remains roughly constant for large for t_p. This figure shows that the for value of the preview time of about 0.1 to 0.12 sec for the relative performance of the fixed-base structure levels off. The relative performance of the base isolated structure appears to decrease with the preview time up to 0.2 sec. That shows that the preview control system performance will improve if the sensors can provide preview information about the earthquake excitations for longer time.

It should be emphasize that a large increase in the preview time will not produce significant improvement in the performance. This is because r(t) as defined by Eq. (13) is not significantly affected by an increase in t_p, due to the exponentially decaying term in the integral (with exponent depending on the closed loop matrix, A_c, which is asymptotically stable.) However, optimization of the preview time for different structures requires further study and is left for a future work.



a). Fixed base structure



Preview Time (sec)

b). Base isolated structure

Figure 15. The effect of preview time on absolute acceleration performance with respect to its respective active system

5. Conclusions

Performances of passive, active, preview active, and hybrid control systems for protection of building during earthquake are studied. Responses of a generic three-story fixed-base and base-isolated structure with active and preview active control systems subject to El Centro 1940 earthquake are evaluated and the results are compared with those for the unprotected structure. On the basis of the results presented, the following conclusions are drawn:

1. Use of laminated rubber bearing base isolation system provides considerable protection for compact stiff structures against earthquakes.
2. Base-isolated structures behave as a rigid body during earthquakes and do not amplify the earthquake ground acceleration.
3. Properly designed optimal active control systems are highly effective in reducing the peak structural vibrations for fixed-base structure during earthquakes.
4. Hybrid combination of base-isolation and active control provides considerable protections for structures during a seismic event.
5. The acceleration response spectra of a structure with an active control system with preview sensors are significantly lower than those of the fixed-base structure and the corresponding base-isolated building.
6. Mean-square responses of the structure with a hybrid LRB and an active control

device are much lower than those of an unprotected structure.

7. Optimal preview control leads to lower mean-square acceleration responses when compared with those for an active system without preview.
8. Short time preview information of the earthquake ground acceleration is sufficient for improving the performance of the control.
9. The performance of the control system improves with an increase in the preview time up to a certain value. Further increase in the preview time beyond about 0.1 to 0.12 sec does not produce a significant improvement for the fixed-base structure.
10. For base-isolated structures, an increased preview time leads to improved performance for $t_p < 0.2$ sec.
11. Magnitudes of the control forces for optimal active control with and without preview are approximately the same, while the preview control is more effective.
12. The magnitude of the required control force reduces significantly for the base-isolated when compared with the fixed-base system.

Acknowledgements: The authors would like to thank Dr. James Carroll and Dr. Ratan Jha of Clarkson University for many helpful discussions.

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APPENDIX A

The explicit expressions for the system matrices are listed in this appendix. The state space matrices are:

$$A=\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -\frac{k_1+k_2}{m_1}-\frac{k_1}{m_b} & -\frac{c_1+c_2}{m_1}+\frac{c_1}{m_b} & \frac{k_2}{m_1} & \frac{c_2}{m_1} & 0 & 0 & \frac{k_0}{m_b} & \frac{c_0}{m_b} \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ \frac{k_2}{m_2}-\frac{k_1}{m_b} & \frac{c_2}{m_2}+\frac{c_1}{m_b} & -\frac{k_2+k_3}{m_2} & -\frac{c_2+c_3}{m_2} & \frac{k_3}{m_2} & \frac{c_3}{m_2} & \frac{k_0}{m_b} & \frac{c_0}{m_b} \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ -\frac{k_1}{m_b} & \frac{c_1}{m_b} & \frac{k_3}{m_3} & \frac{c_3}{m_3} & -\frac{k_3}{m_3} & -\frac{c_3}{m_3} & \frac{k_0}{m_b} & \frac{c_0}{m_b} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ \frac{k_1}{m_b} & -\frac{c_1}{m_b} & 0 & 0 & 0 & 0 & -\frac{k_0}{m_b} & -\frac{c_0}{m_b} \end{bmatrix}$$

$$B=\begin{bmatrix} 0 \\ -\frac{1}{m_1} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad E=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ -1 \end{bmatrix}$$