Coupled Building Control Using Acceleration Feedback

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ABSTRACT: Connecting adjacent buildings for response reduction has been shown to be an effective method of structural control. Active coupled building control has been implemented in 2001 in the recently constructed Triton Square office complex in Tokyo, Japan. To date, active coupled building control using acceleration feedback has not been demonstrated. This paper reports on studies at the Structural Dynamics and Control/Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre Dame to experimentally verify active coupled building control employing acceleration feedback for the seismic protection of structures. Herein, a pair of 2-dof flexible building models with a DC servo-motor/ball-screw control mechanism are employed. Feedback control is incorporated, using the acceleration, as well as relative displacement, measurements at the top stories of the building models. The proposed approach is shown to be effective for reduction of structural vibration due to seismic excitation.

1 INTRODUCTION

Coupling adjacent buildings is a developing method of structural control for mitigating structural responses due to wind and seismic excitations. The concept is to allow two dynamically dissimilar structures to exert control forces upon one another to reduce the overall responses of the system. Coupled building control was first suggested 30 years ago in the United States by Klein, et al. (1972) and subsequently in Japan by Kunieda (1976). In the past decade coupled building control has received increasing attention. Researchers have proposed passive, active and smart damping control strategies to mitigate the adjoining building’s responses to wind and seismic excitations. Theoretical, experimental and practical research has traditionally focused on passive coupled building control. The Triton Square office complex in Tokyo, Japan, coupled 45-, 40- and 35-story buildings with two 35-ton active control actuators for wind and seismic protection this past year, in 2001. As such, active coupled building control is of recent interest.

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In the area of structural control, it is well-recognized that experimental verification of control strategies is necessary (Housner, et al. 1994a, 1994b). Thus, in addition to the numerous analytical studies to actively couple adjacent buildings for response mitigation, there has been significant experimental work. Mitsuta, et al. (1992) performed experimental tests on two adjacent single-degree-of-freedom (sdof) building models and adjacent single- and 2-dof building models. The building masses were coupled with an active control actuator, using displacement sensors for the feedback measurement. Yamada, et al. (1994) coupled a pair of 2-story and 3-story building models at the second story with a negative stiffness active control device and was able to effectively reduce the displacements of these low-rise building models. A number of experiments have been conducted on coupling two continuous plates, representing flexible high-rise structures (Fukuda, et al. 1996, Hori and Seto 1999, Kamagata, et al. 1996, Seto 1994, 1996, Seto, et al. 1994, 1995). These active control experiments have used one and two control actuators. The active control strategies for these experimental tests employ displacement measurements for feedback. The direct measurement of displacement on large-scale structures is difficult to achieve. Additionally, nearly all of the experimental tests performed to date have produced active control forces using electromagnetic actuators. (The exception being Yamada, et al. (1994) who used a spring in series with a stepping motor of rack and pinion mechanism to realize their negative stiffness control strategy). The idealized actuators have little device dynamics and thus control structure interaction is not significant in the resulting experiments. Since control structure interaction can have a significant effect on the ability of the control actuator to produce desired forces at the structures resonant frequencies, the inclusion of this phenomenon is important (Dyke, et al. 1995).

Active control strategies employing acceleration feedback have been shown in previous experiments to be effective for other civil structure applications, including an active bracing system (Spencer, et al. 1993), an active tendon system (Dyke, et al. 1994a, 1994b) and active mass driver systems (Dyke, et al. 1996, Battaini, et al. 2000). Additionally, acceleration feedback has been shown, through simulation, to be an effective method of response reduction for the active and smart damping coupled building problems (Christenson, et al. 1999a, 1999b, 2000, 2001, Hori, et al. 2000).

This paper discusses studies at the Structural Dynamics and Control/Earthquake Engineering Laboratory (SDC/EEL), http://www.nd.edu/~quake, at the University of Notre Dame to experimentally verify coupled building control employing acceleration feedback for the seismic protection of structures. Here a pair of 2-dof flexible building models with an active control actuator are employed. Acceleration feedback is incorporated, using the acceleration measurements at the top stories of the building models. The control forces are produced by a ball-screw servo-motor connecting the top stories of the two building models. The accelerations over both buildings are significantly reduced as observed in the reduction of the resonant peaks of the transfer functions and in the time response of the system to simulated ground motions.
2 EXPERIMENTAL SETUP

A schematic of the experimental setup discussed in this paper is shown in Figure 1. Components of the experiment include a coupled building model, shaking table, digital controller and spectrum analyzer.

The shaking table used is a small scale uniaxial earthquake simulator constructed by SMI Technology and located in the Structural Dynamics and Control/Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre Dame. The table has a maximum displacement of ±120 mm, and a maximum acceleration of ±1 g (with a 11.3 kg test load). The nominal operational frequency range of the simulator is 0-20 Hz. Because the shake table motor is inherently open loop unstable, position feedback, measured from the shake table motor, is employed to stabilize the table. The position control is obtained by a PD controller with displacement feedback.

The coupled building model consists of a pair of 2-dof building models, a servo-motor control actuator and accelerometers. The two 2-story building models were manufactured by Quanser Consulting Inc. The buildings are 305 mm by 108 mm in plan and 980 mm tall. The interstory height is 490 mm. The building models are constructed from rigid 12.7 mm thick plexiglas story levels and flexible aluminum strips, 1.59 mm thick, for columns. The height and stiffness of the buildings are similar with different story masses. Additional mass is secured to the story levels of building 1 (the building on the left in Figure 2) to ensure that the buildings are dynamically dissimilar. The story masses, including the additional mass on building 1 and the mass of the control actuator on the top stories of both buildings, are \( m_{11} = 3.22 \text{ kg}, \ m_{12} = 3.45 \text{ kg}, \ m_{21} = 0.47 \text{ kg}, \) and \( m_{22} = 0.83 \text{ kg} \) (\( m_{ij} \), where \( i \) indicates the building number and \( j \) indicates the story level). The buildings are located adjacent to one another and separated by a distance of 75 mm.

Figure 1: Schematic of Coupled Building Experiment.  
(\( \ddot{x}_g \) - ground acceleration; \( \ddot{x}_{ij} \) - acceleration of the \( j \)th story of building \( i \); \( \Delta x \) - relative displacement of the two buildings at the height of the coupling link; and \( u \) - control signal.)
When various natural frequencies of buildings to be coupled coincide, the ability of a control strategy to reduce responses is significantly degraded (Christenson, 1999). Thus, the frequencies of building 1 and building 2 are purposely adjusted (by adding mass to building 1 as previously identified) such that the four uncoupled natural frequencies are evenly spaced. The dynamic properties of the uncoupled buildings are determined with the control actuator disconnected, but left in-place. The natural frequencies of building 1 are 0.90 Hz and 2.70 Hz with corresponding damping ratios of 1% and 0.5% of critical. The natural frequencies of building 2 are 1.85 Hz and 5.73 Hz with corresponding damping ratios of 1% and 0.5% of critical. The coupled building model, as attached to the shaking table, is shown in Figure 2.

A control actuator is used to provide the forces to the coupled building system. The control actuator is pictured in Figure 3. The two buildings are coupled at the top stories. The actuator, manufactured by Quanser Consulting, is a DC servo-motor and ball-screw mechanism with a stroke of ±100 mm, as dictated by the length of the threaded rod. The stroke is further limited by the distance of separation of the two buildings (75 mm). This allowable stroke is an order of magnitude larger than necessary for sufficient control. A potentiometer is attached to the motor to measure the rotation of the actuator threaded rod. The relative displacement is related to the rotation of the motor through the pitch of the threaded rod attached to the servo-motor and passing through the ball-screw mechanism. The pitch of the threaded rod is 3.18 mm/turn. Because the servo-motor control actuator is inherently open loop unstable, position feedback is employed to stabilize the control actuator. The position control is obtained by a PD controller with displacement feedback provided by the potentiometer.
PCB capacitive DC accelerometers, model 3701G3FA3G, are employed to provide evaluation and measurement responses of the building stories. The accelerometers have a range of ±3 g and sensitivities of 1000 mV/g. The ground acceleration is measured by a DC accelerometer produced by Quanser Consulting, Inc.

The digital controller is a MultiQ I/O board (http://www.quanser.com/english/html/solutions/fs_soln_hardware.html) with the WinCon (http://www.quanser.com/english/html/solutions/fs_soln_software_wincon.html) realtime controller installed in a PC. The controller is developed using Simulink (1998) and executed in real time using WinCon. The MultiQ I/O board has 13-bit analog/digital (A/D) and 12-bit digital/analog (D/A) converters with eight input and eight output analog channels. Eight digital encoders are also available. The Simulink code is converted to C code using the Real Time Workshop in MATLAB (1999) and interfaced through the WinCon software to run the control algorithms on the CPU of the PC.

The spectrum analyzer is a 4-input/2-output PC-based spectrum analyzer manufactured by DSP Technology. The device has a 90 dB signal to noise ratio and includes 8-pole elliptical anti-aliasing filters, programable gains on the inputs/outputs, user selectable sample rates and a MATLAB user interface. These features allow for direct acquisition of high quality data and transfer functions for system identification and response analysis.

3 SYSTEM IDENTIFICATION

A critical precursor to the control design is the development of an accurate dynamic model of the structural system. For this study, the approach used for system identification is to construct a mathematical model to replicate the input/output behavior of the system (Dyke, et al. 1996). As indicated in Figure 1, the inputs to the coupled building model are the ground acceleration (\( \ddot{x}_g \)) and the control input to the actuator (\( u \)), and the available outputs are the four story accelerations (\( \ddot{x}_{ij} \), where \( i \) indicates the building number, and \( j \) indicates the story height) and the relative displacement of the two buildings at the height of the coupling link (\( \Delta x \)).

First, experimental transfer function data is obtained and curve-fit to determine mathematical representations of the frequency responses. The transfer functions are experimentally determined from the ground acceleration and the control input to the accelerations of each story and the relative displacement of the top of the buildings. These ten experimental transfer functions are each curve-fit to determine the poles and zeros of the system. Since the transfer functions represent the input/output relationships for a single physical system, a common denominator, of 8th order, is assumed for the elements of each column of the transfer function matrix. Figure 4 compares the experiment transfer functions of the coupled building system for the story acceleration outputs to the curve-fit transfer functions used to develop the model. At low frequencies the curve-fit and experimental transfer functions are different. This can be attributed to the difficulty in exciting the building system at frequencies below 1 Hz. At higher frequencies the curve-fit and experimental transfer functions again deviate. This difference results from the high frequency vibration of the buildings’ columns, which are not represented in the curve-fit models. However, the transfer functions do match well within the frequency range of concern, 1-6 Hz. The following transfer function matrix is thus determined:
Figure 4. Comparison of the Experimental and Curve-Fit Transfer Functions. 
(Experimental --- ; Curve-Fit --- )
Next, the transfer function input/output behavior of the coupled building system is transformed to a multi-input multi-output state space minimal realization. Each column of the transfer function matrix in Eq. (1) is transformed to a state space realization in controller canonical form and balanced (MATLAB, 1999). The two state space models are combined by simply stacking the two models. The dynamics of the coupled building system are redundantly represented in this combined, stacked, state space model. A minimal realization of the system is found by performing a model reduction on the 16-state system. The resulting 9-state, state space model preserves the salient qualities of the coupled building system and is represented mathematically as

\[
\begin{bmatrix}
H_{x_{11}g}(i\omega) & H_{x_{11}u}(i\omega) \\
H_{x_{12}g}(i\omega) & H_{x_{12}u}(i\omega) \\
H_{x_{21}g}(i\omega) & H_{x_{21}u}(i\omega) \\
H_{x_{22}g}(i\omega) & H_{x_{22}u}(i\omega) \\
H_{\Delta x\Delta u}(i\omega)
\end{bmatrix}
\]  

(1)

where

\[
\dot{x}(t) = Ax(t) + B \begin{bmatrix} \ddot{x}_g(t) \\ u(t) \end{bmatrix}
\]

\[
z(t) = C_x x(t) + D_z \begin{bmatrix} \ddot{x}_g(t) \\ u(t) \end{bmatrix}
\]

\[
y(t) = C_y x(t) + D_y \begin{bmatrix} \ddot{x}_g(t) \\ u(t) \end{bmatrix} + v(t)
\]

where \( A [9x9], B [9x2], C_z [4x9], D_z [4x2], C_y [3x9] \) and \( D_y [3x2] \) are the state space matrices determined by the system identification described previously in this section, \( x(t) \) is the state space vector, \( z(t) = \begin{bmatrix} \ddot{x}_{11} & \ddot{x}_{12} & \ddot{x}_{21} & \ddot{x}_{22} \end{bmatrix}^T \) are the regulated outputs, \( y(t) = \begin{bmatrix} \ddot{x}_{12} & \ddot{x}_{22} & \Delta x \end{bmatrix}^T \) are the available measurements, and \( v(t) \) is the measurement noise.

Control structure interaction (CSI) has been shown to have a profound effect on the ability for the control actuator to produce control forces at the resonant frequencies of the structures under control. Accounting for CSI is essential to achieving high quality control (Dyke, et al. 1995). By performing system identification in the manner described here, CSI is fully incorporated in the resulting design model.

**4 CONTROL STRATEGY**

The focus of this study is to experimentally verify the coupled building concept using acceleration feedback for the seismic protection of structures. Typically, for tall flexible buildings, the
The dynamic response of concern is the absolute story accelerations. The objective of the control strategy is to reduce the maximum story accelerations over both buildings. Thus, the regulated outputs, \( z(t) = [\ddot{x}_{11} \ \ddot{x}_{12} \ \ddot{x}_{21} \ \ddot{x}_{22}]^T \), are the absolute accelerations at each story. The available measured quantities, \( y(t) = [\dddot{x}_{12} \ \dddot{x}_{22} \ \Delta x]^T \), are the top story absolute accelerations and the relative displacement of the buildings.

An \( H_2/LQG \) approach (Spencer 1994, 1998a, Stengel 1986) is used to design the active control strategy for the coupled building model. A second order filter is augmented to the model of the structural system to shape the spectral content of the ground excitation in the \( H_2/LQG \) design and analysis. The objective function is given by

\[
J = \lim_{\tau \to \infty} \frac{1}{\tau} \int_0^\tau \{ z^T(t)Q z(t) + u^2(t)\} dt
\]

where \( Q \) is a weighting matrix for the regulated outputs which is selected such that the responses of interest are minimized and \( u(t) \) is the control signal sent to the actuator. The \( H_2/LQG \) control strategy is designed to minimize root mean square (rms) story accelerations over both buildings. The selection of the weighting matrix \( Q \), which weights a linear combination of the absolute story accelerations, determines the particular control strategy. The optimal weighting matrix is determined iteratively to be

\[ Q = \text{diag} [3.6633 \ 3.8125 \ 6.2826 \ 4.7449] \]

This weighting matrix was selected to insure that the maximum accelerations over both buildings are effectively reduced.

The resulting \( H_2/LQG \) output feedback compensator is given by

\[
\dot{q}(t) = A_c q(t) + B_c y(t) \\
u(t) = C_c q(t)
\]

where \( A_c [13x13] \), \( B_c [13x3] \) and \( C_c [1x13] \) are the state space matrices and \( q(t) \) is the state space vector for the \( H_2/LQG \) output feedback compensator.

The method of “emulation” is used for the design of the discrete-time controller. Using this technique, the continuous-time controller of Eq. (4) is ‘emulated’ with an equivalent digital filter using a bilinear transformation. The resulting discrete system is given by

\[
\ddot{q}(k+1) = A_d \ddot{q}(k) + B_d \ddot{y}(k) \\
u(k+1) = C_d \ddot{q}(k)
\]

where \( A_d [13x13] \), \( B_d [13x3] \) and \( C_d [1x13] \) are the discrete state space matrices of the feedback compensator and \( \ddot{q}(k) \) is the discrete state space vector, \( \ddot{y}(k) \) is the discrete measurements at the \( k \)th time step and \( u(k+1) \) is the discrete control signal. The sampling rate of the controller is 0.01 sec, which is greater than 10 times the closed-loop system bandwidth. The equivalent discrete system adequately represents the behavior of the emulated continuous-time system over the
frequency range of interest. Digital control is achieved with a MultiQ I/O board with the WinCon realtime controller.

A consequence of modeling continuous structures with a finite number of modes is that at certain frequencies (for this experiment at frequencies above 6 Hz) the structure is not well represented by the design model. Care must be taken during the design of the controller to insure sufficient roll-off of the control effort at higher frequencies.

5 EXPERIMENTAL RESULTS

Two series of tests are conducted to evaluate the performance of the actively controlled coupled building system subjected to ground excitation. First, a frequency domain examination is conducted whereby the transfer functions are observed. Second, the buildings are subjected to simulated earthquakes, and the time histories are considered. Root mean square (rms) response reduction is observed, to illustrate the increased damping of the active control strategy.

To provide a baseline for comparison of the active control strategy, two other configurations are considered: the uncoupled building system and the rigidly connected building system. The uncoupled system is realized by simply disconnecting the screw mechanism from the actuator motor. The actuator components are not removed from the top story of the buildings. The rigidly connected building system is realized with a zero control signal \( u(t) = 0 \) to the control actuator.

5.1 Frequency Analysis

The coupled building system is subjected to a 10 Hz bandlimited white noise ground excitation. The frequency response functions from the ground acceleration to the story accelerations are measured for the actively controlled coupled building system as well as for the uncoupled and rigidly connected systems. Transfer functions from the ground acceleration to the story accelerations are shown in Figure 5 for the uncoupled, rigidly connected and controlled building systems. The analytical active control transfer function is also shown in Figure 5. The analytically expected results compare reasonably well to the experimental active control transfer functions.

An \( H_\infty \) measure of the performance of the active coupled building is considered. The \( H_\infty \) norm of a transfer function matrix is a measure of the upper limit of the ratio of the root mean square (rms) of the output vector to the rms of the input (Spencer, et al. 1994). The \( H_\infty \) norm is measured as the peak value of the transfer function and it represents the maximum rms gain of that response. For this reason, an \( H_\infty \) measure is associated with a “worst case” control design. Thus, as a measure of performance for the actively controlled building configurations, the peak value of the transfer functions are indicated in Table 1. Both peak values for frequency ranges in the neighborhood of resonant peaks (e.g. 0-2 Hz, 2-4 Hz, and 4-8 Hz) and the maximum peak value over all frequencies are provided.

When the buildings are uncoupled, the resonant peaks of building 2 (\( H_{x_{31}x_{g}} \) and \( H_{x_{22}x_{g}} \)) are larger in magnitude than the resonant peaks of building 1 (\( H_{x_{11}x_{g}} \) and \( H_{x_{21}x_{g}} \)). Rigidly connecting the two buildings has the effect of reducing the resonant peaks of building 2 by 3% and 14%, while increasing the resonant peaks of building 1 by 8% and 7%. Thus, rigidly connecting two adjacent buildings is seen to not benefit the coupled building system as a whole.
In contrast, the active control strategy reduces the magnitude of the resonant peaks of all stories over the uncoupled and rigidly connected building systems. The resonant peaks are reduced from 37%-90% over the uncoupled buildings and from 37%-92% over the rigidly connected buildings. The peak values of the active control transfer functions are reduced by 37%, 55%, 80% and 82% over the uncoupled transfer functions. The peak values of the active controlled transfer functions are reduced by 50%, 65%, 78% and 68% over the rigidly connected transfer functions. Active coupled building control is seen to significantly reduce the peak value of the transfer functions, as well as all resonant peaks of the coupled building system, providing increased seismic protection.

Figure 5. Experimental Transfer Functions of Story Accelerations to Ground Acceleration. (Uncoupled - · · ·; Rigid —; Active ——; Active-analytical - - - -)

\[
H_{x_{12}x_{g}}(i\omega) \\
H_{x_{22}x_{g}}(i\omega) \\
H_{x_{11}x_{g}}(i\omega) \\
H_{x_{21}x_{g}}(i\omega)
\]
5.2 Simulated Ground Motions

The coupled building system is next subjected to simulated earthquakes. The simulated earthquakes are produced by integrating twice the acceleration records, accounting for the integration constant, scaling the signal to an appropriate magnitude for the small scale shake table, and scaling the time by a factor of 1/5 for dynamic similitude. The resulting signal is used as the input signal to the shake table. Unlike a transfer function iteration (Spencer, et al. 1998b), this method does not reproduce exactly the ground accelerations, however it does capture the essence of each earthquake sufficiently for the analysis purposes in this study.

The coupled building system is subjected to four simulated earthquakes, which are derived from: (i) El Centro. The N-S component recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940. (ii) Hachinohe. The N-S component recorded at Hachinohe City during the Tokachi-oki earthquake of May 16, 1968. (iii) Northridge. The N-S component recorded at Sylmar County Hospital parking lot in Sylmar, California, during the Northridge, California earthquake of January 17, 1994. (iv) Kobe. The N-S component recorded at the Kobe Japanese Meteorological Agency (JMA) station during the Hyogo-ken Nanbu earthquake of January 17, 1995.

The time history responses for the rigidly connected and actively controlled cases are shown in Figures 6-9. It should be noted that the active control strategy provides little help to reduce the peak accelerations. The peak acceleration response can be likened to a response to an impulse load, resulting from scaling the time of the earthquakes by a factor of 1/5, is difficult to control and does not provide a good measure of the effectiveness of the active control strategy. The root
Figure 6. Time History Response to El Centro Simulated Ground Acceleration.
(Rigid ; Active )
Figure 7. Time History Response to Hachinohe Simulated Ground Acceleration.
(Rigid —- ; Active —— )
Figure 8. Time History Response to Northridge Simulated Ground Acceleration.
(Rigid ; Active )
Figure 9. Time History Response to Kobe Simulated Ground Acceleration.
(Rigid ; Active )
Mean square (rms) responses do provide a good measure and are computed for each earthquake, for a 40 second duration beginning at the start of each earthquake. The rms responses provide an indication of the ability of the active control strategy to add damping to the coupled building system. These rms accelerations for uncoupled, rigidly connected and actively controlled coupled building configurations are presented in Table 2.

Table 2: RMS Performance of Coupled Building System to Simulated Earthquakes

<table>
<thead>
<tr>
<th></th>
<th>COUPLED BUILDING CONFIGURATION</th>
<th></th>
<th>ACTIVE % REDUCTION</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Uncpld</td>
<td>Rigid</td>
<td>Active</td>
<td>Uncpld</td>
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<tr>
<td>El Centro</td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>$\tilde{x}_{11}^{\text{rms}}$</td>
<td>1.42 m/sec$^2$</td>
<td>0.76 m/sec$^2$</td>
<td>0.52 m/sec$^2$</td>
<td>64%</td>
<td>32%</td>
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<tr>
<td>$\tilde{x}_{12}^{\text{rms}}$</td>
<td>1.49 m/sec$^2$</td>
<td>1.00 m/sec$^2$</td>
<td>0.51 m/sec$^2$</td>
<td>66%</td>
<td>49%</td>
</tr>
<tr>
<td>$\tilde{x}_{21}^{\text{rms}}$</td>
<td>2.29 m/sec$^2$</td>
<td>2.48 m/sec$^2$</td>
<td>1.12 m/sec$^2$</td>
<td>52%</td>
<td>55%</td>
</tr>
<tr>
<td>$\tilde{x}_{22}^{\text{rms}}$</td>
<td>2.09 m/sec$^2$</td>
<td>1.03 m/sec$^2$</td>
<td>0.87 m/sec$^2$</td>
<td>59%</td>
<td>16%</td>
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<td>Hachinohe</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>$\tilde{x}_{11}^{\text{rms}}$</td>
<td>0.47 m/sec$^2$</td>
<td>0.35 m/sec$^2$</td>
<td>0.15 m/sec$^2$</td>
<td>69%</td>
<td>57%</td>
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<tr>
<td>$\tilde{x}_{12}^{\text{rms}}$</td>
<td>0.46 m/sec$^2$</td>
<td>0.42 m/sec$^2$</td>
<td>0.16 m/sec$^2$</td>
<td>65%</td>
<td>62%</td>
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<tr>
<td>$\tilde{x}_{21}^{\text{rms}}$</td>
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<td>1.11 m/sec$^2$</td>
<td>0.29 m/sec$^2$</td>
<td>75%</td>
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<td>$\tilde{x}_{22}^{\text{rms}}$</td>
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<td>0.44 m/sec$^2$</td>
<td>0.31 m/sec$^2$</td>
<td>82%</td>
<td>30%</td>
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<tr>
<td>Northridge</td>
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<tr>
<td>$\tilde{x}_{11}^{\text{rms}}$</td>
<td>0.68 m/sec$^2$</td>
<td>0.61 m/sec$^2$</td>
<td>0.34 m/sec$^2$</td>
<td>51%</td>
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<td>$\tilde{x}_{12}^{\text{rms}}$</td>
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<td>35%</td>
<td>46%</td>
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<td>$\tilde{x}_{21}^{\text{rms}}$</td>
<td>1.87 m/sec$^2$</td>
<td>1.63 m/sec$^2$</td>
<td>0.73 m/sec$^2$</td>
<td>61%</td>
<td>55%</td>
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<td>$\tilde{x}_{22}^{\text{rms}}$</td>
<td>2.30 m/sec$^2$</td>
<td>0.70 m/sec$^2$</td>
<td>0.53 m/sec$^2$</td>
<td>77%</td>
<td>24%</td>
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<tr>
<td>Kobe</td>
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<td>$\tilde{x}_{11}^{\text{rms}}$</td>
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<td>1.28 m/sec$^2$</td>
<td>0.66 m/sec$^2$</td>
<td>55%</td>
<td>48%</td>
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<td>$\tilde{x}_{12}^{\text{rms}}$</td>
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<td>1.42 m/sec$^2$</td>
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<td>27%</td>
<td>44%</td>
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<td>$\tilde{x}_{21}^{\text{rms}}$</td>
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<td>2.39 m/sec$^2$</td>
<td>1.56 m/sec$^2$</td>
<td>28%</td>
<td>35%</td>
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<tr>
<td>$\tilde{x}_{22}^{\text{rms}}$</td>
<td>1.82 m/sec$^2$</td>
<td>1.46 m/sec$^2$</td>
<td>0.95 m/sec$^2$</td>
<td>48%</td>
<td>35%</td>
</tr>
</tbody>
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Similar to the results observed in the frequency analysis, for the uncoupled buildings the larger rms accelerations for each of the four simulated earthquakes were for building 2 ($\tilde{x}_{21}^{\text{rms}}$ and $\tilde{x}_{22}^{\text{rms}}$). When the buildings are rigidly connected the story accelerations of building 2 are reduced. However, the rms accelerations at the top floor of rigidly connected building 1 actually increase.
during the Northridge and Kobe simulate earthquakes. This is similar to what was observed in the frequency analysis when the buildings were rigidly connected. Additionally, the rms accelerations of the first story of rigidly connected building 2 \( (\dot{x}_{21}^{\text{rms}}) \) are shown to increase over the uncoupled responses for the El Centro and Kobe simulated earthquakes. Again here, rigidly connecting the buildings results in a trade-off of performance, reducing acceleration responses at some stories while increasing the acceleration responses at other stories, thus not benefiting the coupled building system as a whole.

The active control strategy is able to reduce all of the rms accelerations. The active control strategy reduces the rms responses of the story accelerations by 52-66% over the uncoupled buildings and by an additional 16-55% over the rigidly connected buildings for the El Centro simulated earthquake. Active control reduces the rms acceleration responses by 65-82% over the uncoupled buildings and by 30-73% over the rigidly connected buildings for the Hachinohe simulated earthquake. Active control reduces the rms acceleration responses by 35-77% over the uncoupled buildings and by 24-55% over the rigidly connected buildings for the Northridge simulated earthquake and 27-55% over the uncoupled buildings and 35-48% over the rigidly connected buildings for the Kobe simulated earthquake. The active control strategy is seen to significantly reduce all of the coupled building system’s acceleration responses to four different simulated historical earthquakes.

6 CONCLUSIONS

Coupled building control using an acceleration feedback active control strategy is accomplished in an experiment connecting two adjacent flexible building models with a DC servo-motor ball-screw control actuator. Measurements for the active LQG controller are the top story accelerations of both buildings and the relative displacement of the buildings at the top stories, the location of the coupling link. The buildings are subjected to white noise excitation, where the transfer functions for the active control strategy is compared to uncoupled and rigidly connected building systems. The coupled building system is also subjected to simulated earthquakes, whereby the rms responses of the time histories are compared.

The active control strategy reduces the magnitude of the resonant peaks of all stories of both buildings. The peak values of the active control transfer functions are reduced by 37%, 55%, 80% and 82% over the uncoupled transfer functions. The peak values of the active controlled transfer functions are reduced by 50%, 65%, 78% and 68% over the rigidly connected transfer functions.

When excited by simulated historical earthquakes, the active control strategy is able to reduce all of the rms accelerations, significantly. The active control strategy reduces the rms responses of the story accelerations by 52% to 82% over the uncoupled and 16% to 73% over the rigidly connected building for the El Centro and Hachinohe simulated earthquakes. The active control strategy reduces the rms responses of the story accelerations by 27% to 77% over the uncoupled and 24% to 48% over the rigidly connected buildings for the Northridge and Kobe simulated earthquakes.

Coupled building control using acceleration feedback is shown to be an effective method of coupled building control. The maximum accelerations of the coupled building system are significantly reduced. This is observed in the reduction of the resonant peaks of the transfer functions and in the time response of the coupled building system to simulated historical earthquakes.
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REFERENCES


NOTATION

\( A, B, C_z, D_z, C_y, D_y \) state space matrices for the coupled building design model
\( A_e, B_e, C_e \) state space matrices for the \( H_2/LQG \) output feedback compensator design
\( A_d, B_d, C_d \) discrete state space matrices for \( H_2/LQG \) output feedback compensator design

\( \Delta x \) relative displacement of bldg 1 and bldg 2 at location of coupling link (cm)
\( E[-] \) expected value operator
\( H_{ab}(i\omega) \) transfer function from \( b \) to \( a \)
\( |H_{ab}(i\omega)| \) magnitude of transfer function from \( b \) to \( a \)
\( J \) objective function for the \( H_2/LQG \) output feedback compensator design
\( m_{ij} \) building \( i,j \)th story level mass (kg)
\( q(t) \) state space vector for the \( H_2/LQG \) output feedback compensator
\( \bar{q}(k) \) discrete state space vector for the \( H_2/LQG \) output feedback compensator
\( Q \) weighting matrix for the regulated outputs
\( u(t) \) control signal to actuator (volts)
\( u(k + 1) \) discrete control signal to actuator (volts)
\( v(t) \) measurement noise (m/sec^2 and cm)
\( \omega \) frequency (rad/sec)
\( x(t) \) state space vector for coupled building design model
\( \ddot{x}_g \) ground acceleration (m/sec^2)
\( \ddot{x}_{ij} \) building \( i,j \)th story acceleration (m/sec^2)
\( y(t) \) measured outputs, \( \begin{bmatrix} \ddot{x}_{12} & \ddot{x}_{22} & \Delta x \end{bmatrix}^T \)
\( \hat{y}(k) \) discrete measured outputs
\( z(t) \) regulated outputs, \( \begin{bmatrix} \ddot{x}_{11} & \ddot{x}_{12} & \ddot{x}_{21} & \ddot{x}_{22} & \Delta x \end{bmatrix}^T \)