Active Control in Structures

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Abstract:

In this paper the application of control theory to structural engineering has been presented from a structural engineering perspective. The objective of this paper is to summarize key steps that are required to design an active control system for a structure. Total acceleration feedback with H_2/LQG controller is used in this paper. The structural control device is made of tendon/pulley system. Multiple-input and single-input control systems were compared. It was shown that multiple-input control system could provide a more efficient design.

1.0 Introduction

Conventional seismic design of structures permits the reduction of forces for the design below the elastic level on the premise that inelastic action in well-detailed structures will dissipate significant amount of energy and as a result the structure will survive a severe earthquake without collapse. Significant damage in critical regions of structural members followed by degradation in hysteretic behavior results in inelastic behavior and therefore dissipation of energy. In this design philosophy the designer relies upon inherent ductility of structure to prevent catastrophic failure, while accepting a certain level of structural and nonstructural damage. In order to reduce the damage in structural elements, protective systems are ideal ways of modifying stiffness and viscous damping of structures. Designer can identify the distribution of damage and minimize it. Considerable attention has been paid to active and semi-active control research in recent years, with particular emphasis of wind and seismic response [Soong (1991), Spencer (1997)].

2.0 Background

The objective in a typical *H2/LQG* method is to find a control scheme that minimizes the control index given by equation (1). Based on the values of measurements the control force, u, will be computed, using the weighting factors of the designer choice (Q and R in equation 1). The control law that minimizes the value of J is given by a linear-state feedback.

$$J = \int_0^\infty (z^T Q\, z + u^T R u)\; dt \qquad (1)$$

Inter-story drift, z, is a reliable damage index and it was used in this study as an output parameter that had to be minimized by equation (1). Since displacements and velocities are not absolute and are dependent on the inertial reference frame in which they are measured, total acceleration was selected as the measurement. Accelerometers can provide inexpensive and reliable measurements of the total accelerations at the strategic points on the structure, making the use of absolute structural acceleration measurements for control force determination. The control law, which is obtained independent of the earthquake ground motion, will modify the damping and stiffness of the structure. A very large value of *Q* and very small value of *R* will assign less weight on the control force and may result in an expensive and in some cases impractical control design. On the other hand, a bigger weight for control force, *u*, may not provide sufficient modification in the response of the structure. For that reason, a set of values of *R/Q* was selected and for each of them a value of *u* was obtained using control law to minimize the control index. In order to find an optimum control index within the selected range of *R/Q*, the structure was subjected to the 1989 Loma Prieta earthquake that was recorded at the San Francisco International Airport.

3.0 Structural Model

A three-story shear building was considered in this study. Structural simplicity in this model did not affect the concept that was implemented in selecting an active control scheme. The objective is to find a control scheme that fits best for this system using tendon/pulley system.

3.1 Single Input Control using Tendon/Pulley System

A tendon/pulley system is a simple mechanical system that provides active forces at desired location. The system is comprised of brace tendons that are connected to an actuator through a pulley. The system control force is applied to the structure by the actuators through tendons. In Figure 1 the possible ways that a simple structure was upgraded with a tendon/pulley system is shown. In the same Figure the force that was applied to each of these system is shown. Five independent control cases were distinguished as shown in this Figure. This was mainly because a single-input control system was selected, and therefore forces in tendons were equal.

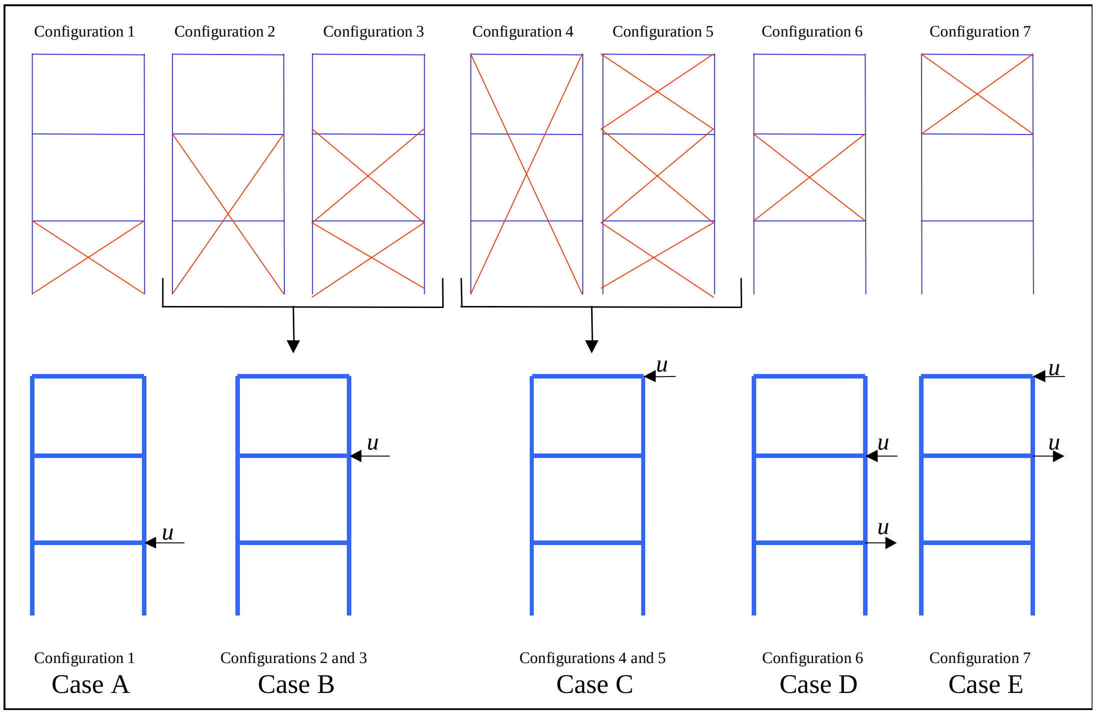

Figure 1 Single-Input Control Systems

An increase in control energy resulted in decrease in drift energy. Maximum drift energy occurred at zero control energy, which corresponded to a structure without active control. All the cases should converge to a single point at zero control energy. Maximum control force versus maximum drift is presented in Figure 2. As the maximum control force increased the maximum drift decreased. Cases B and C were the most efficient way of implementing this system to the structure, because control energies were much smaller than the others. Case A with weighting factors corresponding to a maximum control force of 201.08 kips was selected, because it represented a practical and constructable upgrade to the structure. The response of this system to the Loma Prieta earthquake was compared with an uncontrolled structure in Figures 3. The values of maximum drift and displacement at the roof of the uncontrolled system were 85% and 70% larger than those in an open loop system (Table 1). This was a significant improvement to the response of the structure.

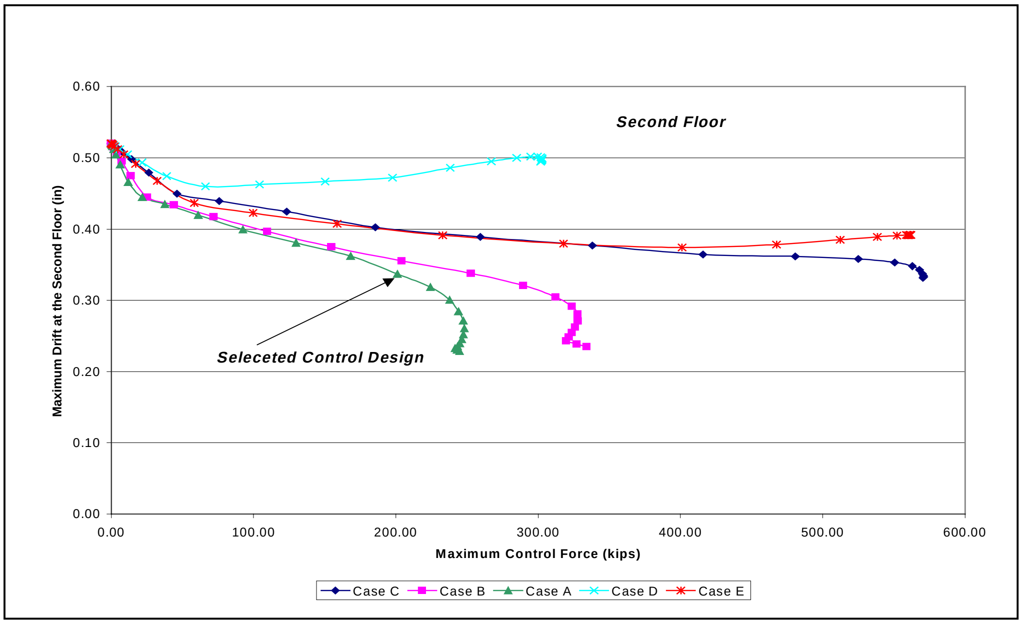

Figure 2 Maximum Control Force vs. Maximum Drift

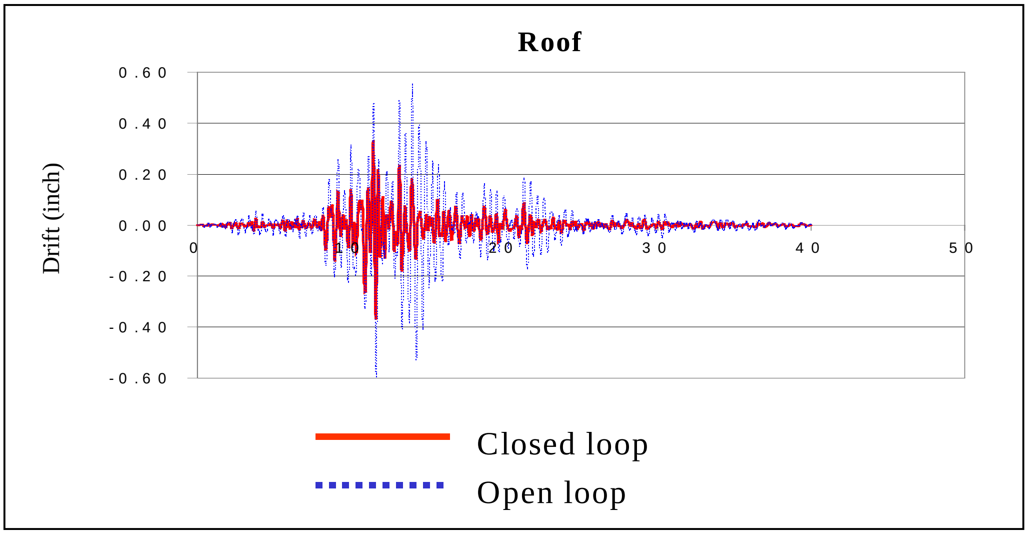

Figure 3 Response Drift Time-Histories of the Open and Closed Loops

3.2 Multiple-Input Control System using Tendon/Pulley System

It is possible to design a system with more than one control system, all of which independent of each other. Figure 4 shows how a multiple-input control system can be implemented to a structure using tendon/pulley mechanism. In both Case F and Case G there were three actuators that were connected to tendons. In case F all of them were located at the ground level, whereas in Case G they were located at each floor. Case F can be viewed as a simplified model of a larger structure, in which three single-frame are part of a much larger structure, each of which has its own single-input control system. As expected, maximum drift energy reduced with the increase of the maximum control energy.

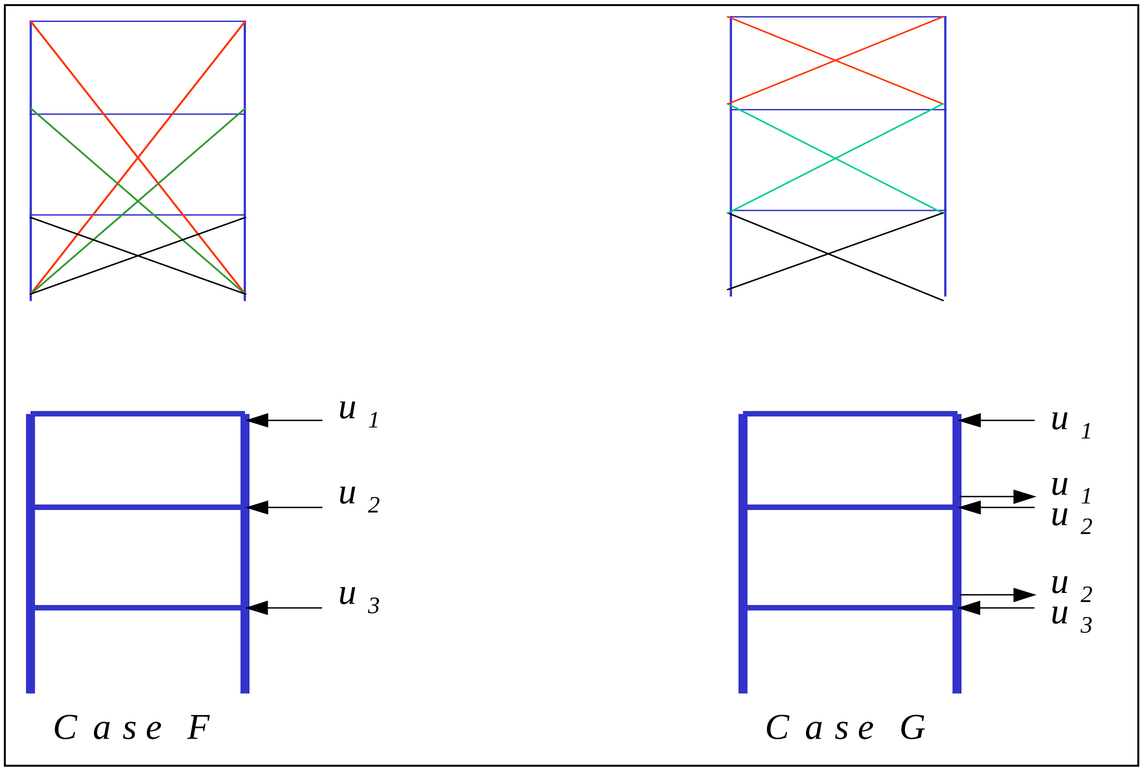

Figure 4 Multiple-Input Control Scheme

Figure 5 shows the maximum control force versus the maximum drift for Cases F and G. Case G with a weighting factor corresponding to a maximum control force of 110.57 kips at the roof, 111.71 kips at the second floor, 92.42 kips at the first floor was selected. The response of this system to the Loma Prieta earthquake was compared with an uncontrolled structure in Figures 6. The values of maximum drift and displacement at the roof for an open loop system were 78% and 47% larger than those in a close loop system (Table 1). This was a significant improvement to the response of the structure. Although the modification of the response that was resulted from the multiple-input system was smaller than that of the single-input control system, the required force in multiple-control system was smaller (Table 1).

A. Single-Input Control System							Open Loop System		Ratio of Open to Closed-Loop	
	Maximum Control Force		Maximum Drift		Maximum Displacement		Maximum		Maximum	
Location	Force (kips)	Energy (kip^2)	Drift (in)	Energy (in^2)	Disp. (in)	Energy (in^2)	Drift (in)	Disp. (in)	Drift (in)	Disp. (in)
Roof	0.00	0.00	0.32	3.15	0.89	25.30	0.60	1.51	1.85	1.70
Second Floor	0.00	0.00	0.34	3.60	0.71	15.21	0.52	0.98	1.54	1.38
First Floor	201.08	1118800.90	0.38	4.26	0.38	4.26	0.46	0.46	1.22	1.22

B. Multi-Input Control System							Open Loop System		Ratio of Open to Closed-Loop	
	Maximum Control Force		Maximum Drift		Maximum Displacement		Maximum		Maximum	
Location	Force (kips)	Energy (kip^2)	Drift (in)	Energy (in^2)	Disp. (in)	Energy (in^2)	Drift (in)	Disp. (in)	Drift (in)	Disp. (in)
Roof	110.57	359554.29	0.34	4.27	1.03	48.14	0.60	1.51	1.78	1.47
Second Floor	111.71	377457.74	0.39	6.53	0.77	25.19	0.52	0.98	1.32	1.28
First Floor	92.42	277353.38	0.39	6.30	0.39	6.30	0.46	0.46	1.20	1.20

C. Comparision of Single and Multi-Input Control System

Type of Control System	Vectorial Sum of Control Force (kips)	Energy (kip^2)
Multi-Input	182.33636	590490.08
Single-Input	201.08	1118800.90
Single/Multi	1.10	1.89

Table 1 Single-Input and Multiple-Input Control Systems vs. Open-Loop System

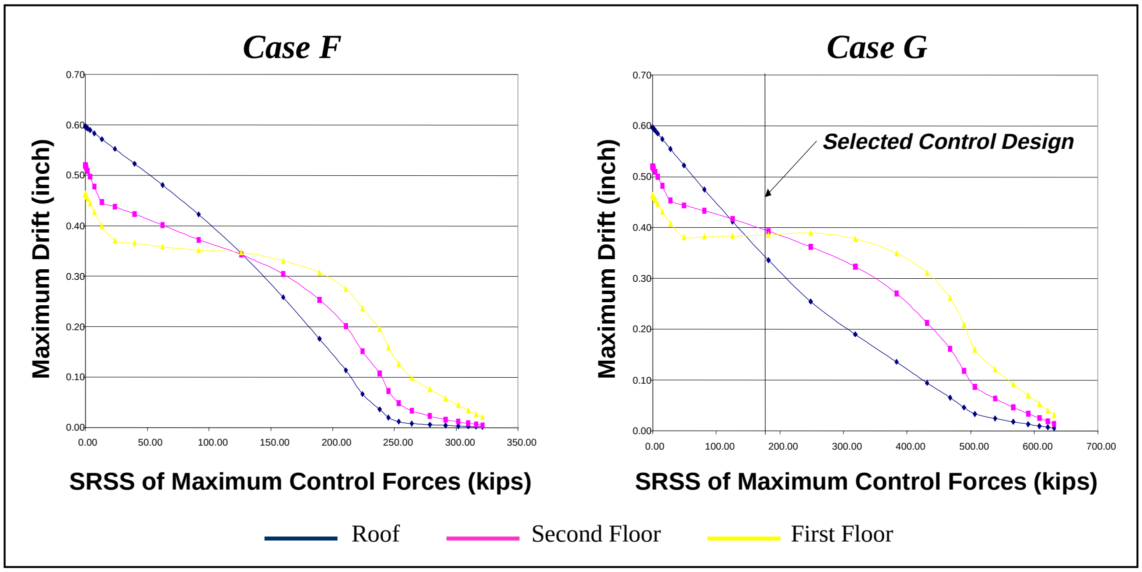

Figure 5 Maximum Control Force vs. Maximum Drift for Multiple-Input Control Systems

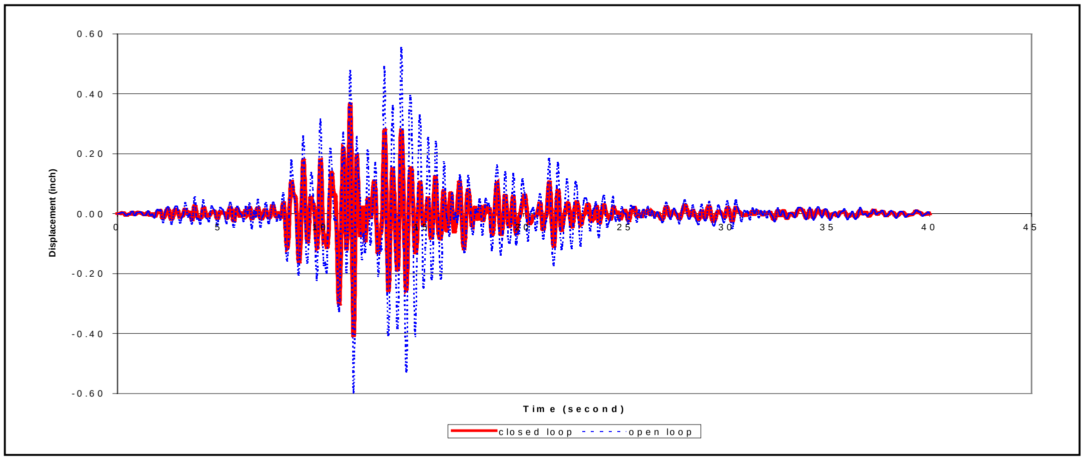

Figure 6 Response Drift Time-Histories of the Multiple-Input Control Systems

4.0 Conclusions and recommendations for Future studies

A practical design procedure for the application of active control system to a simple structure was presented. It was illustrated that different structural schemes along with the control system can modify the response of the structure in different ways and therefore by comparison one can select the optimum control design. It was shown that multiple-input control system could result in an efficient control design. Comparison of multiple-input control system needs to be performed in a bigger scale structure to demonstrate its superiority in large structural systems.

It is important to note that the size of structure and therefore the number of degrees of freedom are an important factor in the whole computation effort. It is essential to use reduce-order methods to make the computation practical for a real structure. Using observablity and controllability of the structure, one can eliminate many degrees of freedom. This is an important issue for any real design and serious consideration need to be taken for that.

5.0 Reference

1. Soong (1991). “An overview of Active Structural Control under Seismic Loads”, T. T. Soong, S.F. Masri, G. W. Housner, Earthquake Spectra Magazine, Earthquake Engineering Research Institute, Volume 7, number 3, August 1991.
2. Spencer (1997). “Controlling Buildings: A New Frontier in Feedback”, B.F. Spencer and Michael K. Sain, Special Issue of the IEEE Control System Magazine on Emergency Technology, Vol. 17, No. 6, December 1997.