STATE-OF-THE-ART IN HYBRID CONTROL AND ISSUES ON OPTIMUM SEISMIC OBSERVER AND DEVICE PLACEMENT

Hongping JIANG[1], Franklin Y CHENG[2] And Zunquan WANG[3]

SUMMARY

This paper presents a hybrid control system which consists of viscous fluid dampers and servovalve-controlled hydraulic actuators supported by K-braces on a seismic-resistant structure. The research focuses on evaluation of this hybrid system, development of seismic observer and optimal placement of control devices. Studies show that this hybrid system is more effective than active and passive systems for seismic response reduction, that the seismic observer works as effectively as full-state sensing yet simplifies the sensing system, and that optimally placed hybrid systems attain superior performance by virtue of requiring far less active control force.

INTRODUCTION

Research findings and practical applications [Soong, 1990; IASC, 1994] have shown that structural control is a promising alternative to protect civil engineering structures from seismic damage. There are four types of structural control systems: passive, semi-active, active and hybrid. Passive systems and semi-active dampers are simpler in mechanism, more reliable and less expensive, but their capacity is limited. Active systems have greater capacity but are less reliable and more expensive. Hybrid systems combine both active and passive techniques such as damper/actuator [Cheng and Tian, 1994; Cheng and Jiang, 1998a] and base-isolation/actuator systems [Agrawal and Yang, 1996]. Hybrid systems have received significant attention because they gain the capacity of active systems and the reliability of passive systems.

While structural control has greatly advanced, three major concerns still affect the application of active or hybrid control technique to full-scale structures. First is system complexity. Since seismic-resistant structures have numerous degrees of freedom, too many sensors and control hardware channels are required to implement an optimal control algorithm with full-state feedback. Second is reliable measurements. For seismic-resistant structures, accelerations are usually measured but the control algorithm requires that displacements and velocities be measured. Third is force-generating capacity of actuators. Seismic-resistant structures are usually more than hundreds of tons in weight. In order to significantly reduce their seismic response, the required control force could be hundreds of kilo-Newtons. Although current industrial technology makes such big actuators feasible, the high cost discourages their application.

In this paper, a hybrid control system consisting of servovalve-controlled hydraulic actuators, viscous fluid dampers and acceleration sensors is studied and evaluated. A seismic observer-controller technique is established to process acceleration measurements and to reduce system complexity. A statistical method is developed for optimum placement of control devices to address the concern of force-generating capacity of control devices. Seismic response in time-history of a building structure with the hybrid control system serves as a numerical example to demonstrate the effectiveness of the proposed contol strategy.

[1] *Engineering Programmer, TrusJoist MacMillan, 5995 Greenwood Plaza Blvd., Greenwood Village, CO 80111*
[2] *Curators' Professor of Civil Engineering, Univ. of Missouri, Rolla, MO 65409. Fax: (573)341-4729, Email: chengfy@umr.edu*
[3] *Ph.D. Candidate, Department of Civil Engineering, Univ. of Missouri, Rolla, MO 65409*

HYBRID DAMPER-ACTUATOR SYSTEM

Description of Hybrid Control System

Figure 1 illustrates a typical hybrid control system installed on the first floor of a structure and supported by a K-brace. An acceleration sensor and a load cell are employed to measure top-floor acceleration and active control force, respectively. The hybrid device consists of a viscous fluid damper and a servovalve-controlled hydraulic actuator. The damper comprises a hydraulic piston-cylinder filled with viscous fluid and a tube connecting the two chambers separated by the piston head. The actuator system consists of an actuator piston-cylinder, a servo valve, and a fluid pumping system. Cylinders of the damper and the actuator are bolted to the first floor of the structure, and pistons of the damper and the actuator are connected to the brace. Under the excitation of earthquake ground motion $\ddot{x}_g(t)$, the structure and the brace deform. For the damper, relative displacement between the brace and the first floor drives the piston moving in relation to the cylinder, and frictional force between the viscous fluid and the cylinder or the tube absorbs energy and thus reduces structural vibration. For the actuator, the servovalve changes fluid pressure in two actuator chambers by regulating flow direction and density between the fluid supply and actuator chambers. Pressure difference between the two chambers produces a control force, and this control force acts on the structure to reduce its vibration.

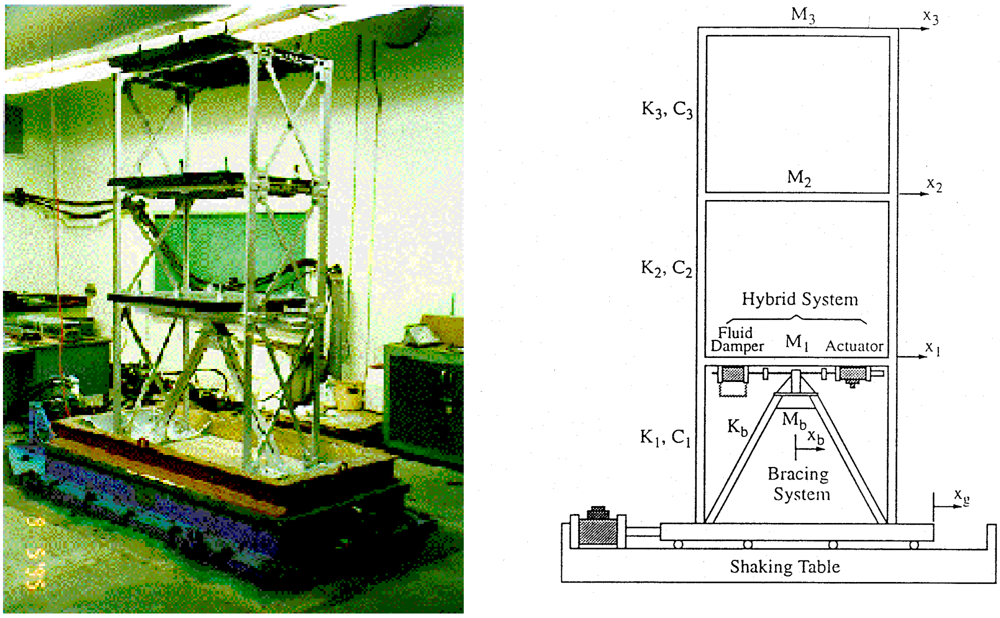

Figure 1: Structural model and hybrid control system for shaking table test

Model of the Structure with Hybrid Control

An open-loop model of the structure with hybrid control under earthquake excitation has been developed in state

$$\{\dot{Z}(t)\} = [A]\{Z(t)\} + [B_u]\{u(t)\} + \{B_r\}\ddot{x}_g(t) \quad (1)$$

variable representation as [Cheng and Jiang, 1998a]

where $\{Z(t)\}_{N\times 1}$ is state vector, $[A]_{N\times N}$ is plant matrix, $[B_u]_{N\times r}$ is coefficient matrix for vector of control commands $\{u(t)\}_{r\times 1}$ and $\{B_r\}_{N\times 1}$ is coefficient vector for reference input (i.e., earthquake excitation) $\ddot{x}_g(t)$. Different systems have different elements for these vectors and matrices. For an *n*-story shear building with hybrid control comprising *s* viscous fluid dampers and *r* servo valve-controlled hydraulic actuators supported by *m* K-braces, the state vector should include variables for dynamics of actuators, dampers and the structure, which are active control forces $\{f_a(t)\}_{r\times 1}$ and actuator valve displacements $\{c(t)\}_{r\times 1}$, passive control forces $\{f_p(t)\}_{s\times 1}$, structural displacements $\{x(t)\}_{(m+n)\times 1}$ and structural velocities $\{\dot{x}(t)\}_{(m+n)\times 1}$.

Optimal full-state feedback algorithms lead to the following control law in continuous time domain

$$\{u(t)\} = -[G]\{Z(t)\} \tag{2}$$

where $[G]$ is feedback gain matrix determined by optimal control algorithms. Substituting Equation (2) into Equation (1) yields the state equation of the closed-loop system (i.e., the controlled structure) as

$$\{\dot{Z}(t)\} = [A_c]\{Z(t)\} + \{B_r\}\ddot{x}_g(t) \tag{3}$$

and the plant matrix of the controlled structure

$$[A_c] = [A] - [B_u][G] \tag{4}$$

In seismic response control, accelerometers are widely used because they are the most reliable and the least expensive measurement method. Thus sensor output $\{y(t)\}$ includes accleration measurements which are not state variables $\{Z(t)\}$, but rather related to state variables, control command $\{u(t)\}$ and earthquake ground acceleration $\ddot{x}_g(t)$. The sensor output can be expressed as [Cheng and Jiang, 1998c]

$$\{y(t)\} = [C]\{Z(t)\} + [D_u]\{u(t)\} + \{D_r\}\ddot{x}_g(t) \tag{5}$$

Equations (1) and (5) form the analog state equation of the entire system. For a digital control system with zero-order hold and sampling period T, the values of $\{Z(t)\}$, $\{u(t)\}$ and $\ddot{x}_g(t)$ at the k^{th} sampling time (i.e., at $t = kT$, $k = 0,1,2,\dots, +\infty$) are denoted as $z(k)$, $u(k)$ and $r(k)$, respectively; the following relationship holds true during time interval $kT \le t < (k+1)T$ ($k = 0,1,2,\dots, +\infty$)

$$\begin{aligned} &\{Z(t)\} = \{Z(kT)\} = z(k), \quad &\{y(t)\} = \{y(kT)\} = y(k) \\ &\{u(t)\} = \{u(kT)\} = u(k), \quad &\ddot{x}_g(t) = \ddot{x}_g(kT) = r(k) \end{aligned} \tag{6}$$

and the entire system in discrete time domain can be described as

$$\begin{aligned} \hat{z}(k+1) &= A\hat{z}(k) + B_u u(k) + B_r r(k) + L[y(k) - \hat{y}(k)] \\ \hat{y}(k) &= C\hat{z}(k) + D_u u(k) + D_r r(k) \end{aligned} \tag{7}$$

SEISMIC OBSERVER TECHNIQUE

Observer technique is widely applied in modern control systems to estimate unmeasured state variables for the full-state feedback controller. However, this observer technique implicitly assumes that enough state variables are measured. This makes it inapplicable to seismic response control which may have accelerometers but no state sensor. In order to estimate state variables from acceleration measurements, a seismic observer was established [Cheng and Jiang, 1998c; Jiang, Cheng and Wang, 1999] for hybrid control systems as

$$\begin{aligned} \hat{z}(k+1) &= A\hat{z}(k) + B_u u(k) + B_r r(k) + L[y(k) - \hat{y}(k)] \\ \hat{y}(k) &= C\hat{z}(k) + D_u u(k) + D_r r(k) \end{aligned} \tag{8}$$

Then the controller uses estimated states $\hat{z}(k)$ to generate the control signal $u(k)$. Thus the control law becomes

$$u(k) = -G\hat{z}(k) \tag{9}$$

Equation (8) is the mathematical model of the proposed seismic observer. A seismic response control system with this observer, called seismic observer-controller system, is then described by a combination of Equations (7), (8) and (9). A simulation diagram of this system is shown in Figure 2. Note that the seismic observer-controller system only requires measurements of $u(k)$, $r(k)$ and $y(k)$; no additional device is needed because this observer can be realized by the computer software for controller implementation. It has been proven [Cheng and Jiang, 1998c] that the proposed seismic observer-controller system has exactly the same transfer function from input $r(k)$ to output $y(k)$ as the full-state sensing and feedback system, expressed as

$$T(z) = Y(z)\_\,R(z) = (C - D_u G)(zI - A + B_u G)^{-1} B_r + D_r \tag{10}$$

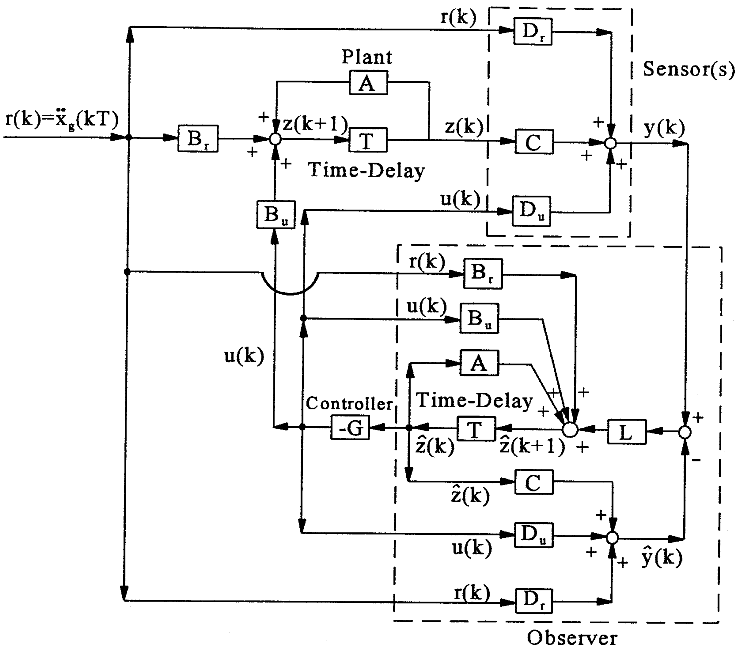

Figure 2: Simulation diagram of observer-controller system

This means that the observer-controller system works as effectively as the full-state sensing and feedback system for seismic response reduction. With this observer, the required number of sensors (including accelerometers) for the implementation of full-state feedback algorithms is reduced due to the observability requirement as follows. An N^{th} order system described by Equation (7) is observable if and only if its observability matrix M_o, which is defined by Equation (11), is of full rank N.

$$M_o = \begin{bmatrix} C \\ CA \\ CA^2 \\ \cdots \\ CA^{N-1} \end{bmatrix} \tag{11}$$

In the observer model expressed by Equation (8), only matrix L is unknown. The determination of L is called observer design. The criterion for picking L is that $\hat{z}(k)$ should tend to $z(k)$ as soon as possible. Let error function

$$\tilde{z}(k) = z(k) - \hat{z}(k) \tag{12}$$

Then from Equations (7), (8) and (9)

$$\tilde{z}(k+1) = (A - LC)\tilde{z}(k) = A_L \tilde{z}(k) \tag{13}$$

where

$$A_L = A - LC\text{, and } A_L^T = A^T - C^T L^T \tag{14}$$

A comparison of Equations (14) and (4) shows that the observer design is similar to the controller design except that the dynamics of A^T are improved by C^T instead of A by B_u. Thus L^T can be determined by optimal control algorithms. Kalman filter is an example of optimal observer.

OPTIMUM PLACEMENT OF CONTROL DEVICES

Stochastic seismic response of controlled structures

By assuming earthquake ground motion $\ddot{x}_g(t)$ as a stationary Gaussian random process with a zero mean value, the stochastic seismic response of controlled structures was developed as [Cheng and Jiang, 1998b]

$$\sigma_{z_k}^2 = \sum_{i=1}^{n}\left(f_{ki}^2 \sigma_{q_i}^2 + g_{ki}^2 \sigma_{\dot{q}_i}^2\right) + \sum_{i=1}^{m} \alpha_{k,n+i}^2 \sigma_{n+i}^2 \tag{15}$$

In Equation (15), there are two additional terms in stochastic seismic response of controlled structures compared to that of uncontrolled structures. These terms are $\sum_{i=1}^{m}\alpha_{k,n+i}^{2}\sigma_{n+i}^{2}$ for dynamics of control devices and $\sum_{i=1}^{n} g_{ki}^{2}\sigma_{\dot{q}_i}^{2}$, which means that the stochastic response of a controlled structure is related not only to modal coordinate $q_i(t)$ but also to the first derivative of the modal coordinate $\dot{q}_i(t)$.

Optimization problem definition

Equation (15) gives the variance of structural response and required control force. Design values of control force and structural response are proportional to the root-mean-square (RMS) value with the factor μ determined by the required probability of system safety. The goal of optimal device placement is to maximize system effectiveness, i.e., to reduce structural response with the least control force. If the control objective is to reduce the response at freedom *l* of the structure, the optimal location of control devices is where the smallest RMS value of control force is required to achieve a control objective. Thus the optimization problem is expressed by

$$\begin{aligned} &\text{Minimize} \quad \{\sigma_f(x)\} \\ &\text{Subject to} \quad \sigma_g(x) = \sigma_0, 1 \le x \le N \end{aligned} \qquad (16)$$

where σ_f is objective function for optimum device placement; it can be RMS value of active force, passive force or their weighted summation; σ_g is control objective which can be RMS structural displacement, velocity or drift; σ_0 is desired structural response level; *x* is design variable; for a one-bay multi-story building structure, *x* is story number where a control device is placed; and *N* is the total number of stories in the building. If there are more than two control devices, *x* is a vector and each element of *x* refers to the location of one control device.

Solution procedure

There is no efficient algorithm to solve the general optimization problem for control device placement (Cheng and Jiang, 1998c). Since seismic-resistant structures have a limited number of stories to install the control devices, an enumerative algorithm by direct-searching is implemented by MATLAB .m code as follows.

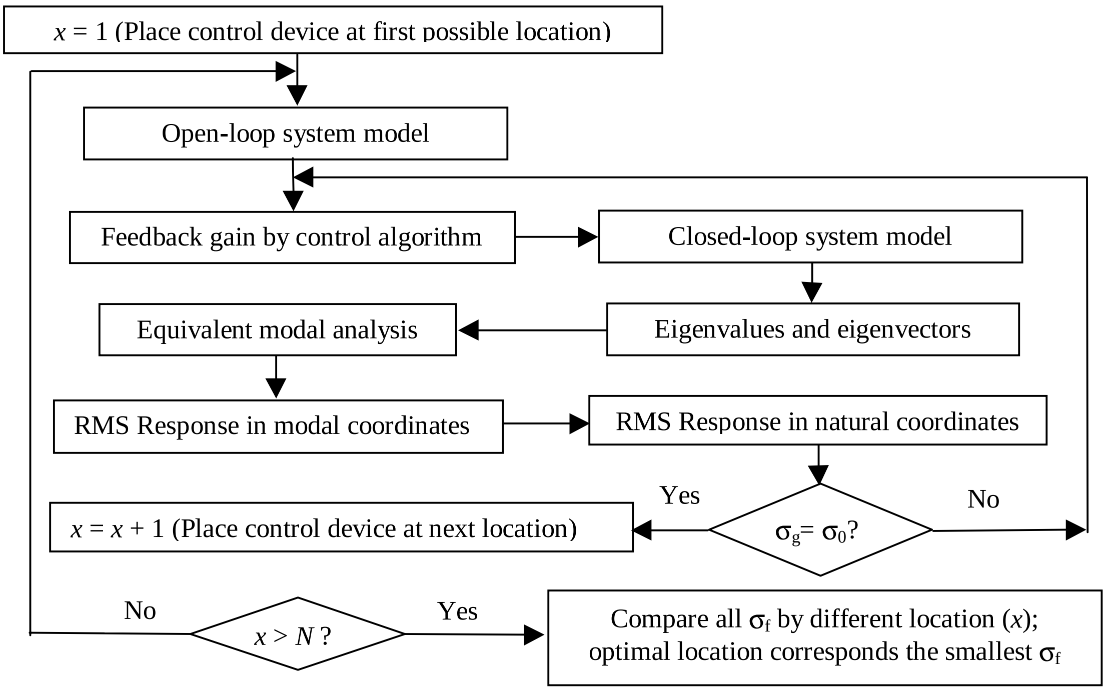

Figure 3: Flow of solution procedure for optimal placement problem

NUMERICAL EXAMPLE

The hybrid control system in Figure 1 serves as an example here. The Kanai-Tajimi spectrum models earthquake ground motion with ω_g =15.6 rad/sec and ζ_g =0.60. The hybrid device comprises a Moog 760-102A servovalve-controlled hydraulic actuator and a viscous fluid damper with Maxwell parameters C_0 = 21.041 kN-sec/m and λ_0 =0.05 Sec. An accelerometer is installed at the top floor and a load cell is employed to measure active control force for actuator stabilization and observer design. Structural properties are: mass coefficients M_1 =593.8, M_2 =590.2, M_3 =576.6 (kg); natural frequencies f_1 =2.622, f_2 =9.008, f_3 =17.457 (Hz); damping ratios ζ_1=0.364%, ζ_2=0.354%, ζ_3=0.267%. K-brace properties are: M_b =12.6 kg, K_b =1549.33 kN/m. For dynamic time-history analysis, scaled N-S component of the El-Centro earthquake, May 18, 1940 is adopted (amplitude and frequency scale factors are 0.3 and 2, respectively). State variables include three displacements and three velocities of the structure, displacement and velocity of the K-brace, active control force, actuator valve displacement, and passive control force. Thus this system is an 11th order system. MATLAB .m code is employed to analyze the system. LQG and pole assignment control algorithms are the basis for the controller and observer design.

Effectiveness of hybrid control system

In order to show the effectiveness of hybrid control, earthquake responses and required control forces are evaluated for three cases: 1) hybrid control, 2) active control with hydraulic actuator, and 3) passive control with viscous fluid damper. To compare active control force in the active and hybrid systems, their maximum closed-loop displacement responses at the third floor are set at 0.508 cm. As shown in Figure 4, maximum required active control force for the hybrid control system is 609.4 N, which is only 56% of that for the active system. Figure 5 shows that maximum displacement at the third floor for the passive system is 0.6228 cm. This can be reduced to 0.3867 cm for the hybrid control system, which is only 62% of that for the passive system. These results clearly show that a hybrid control system is more effective in mitigating earthquake damage than a passive one. Requiring less active control force than an active system gives the hybrid system a further advantage: hybrid devices are easier to make and cheaper to use for full-scale application.

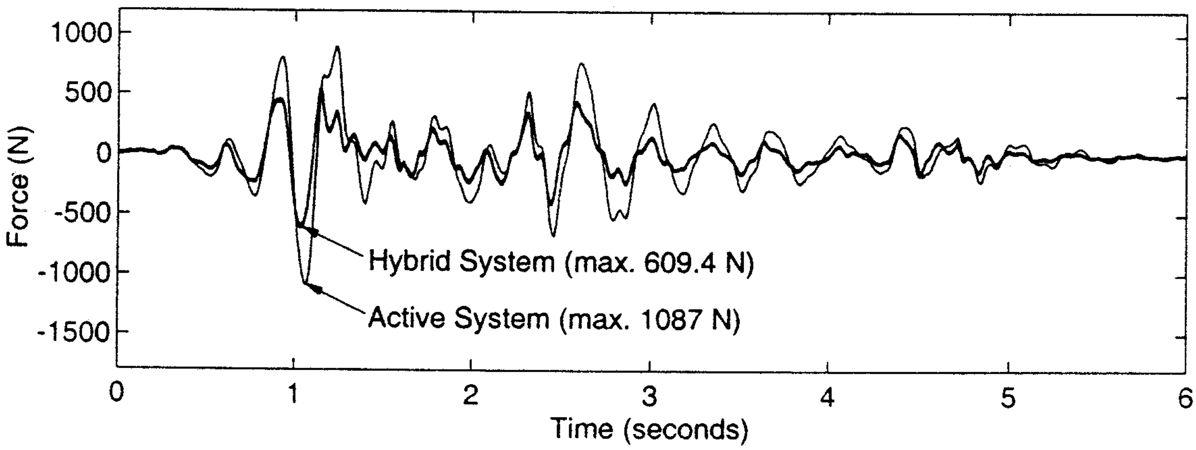

Figure 4: Comparison of required active control forces

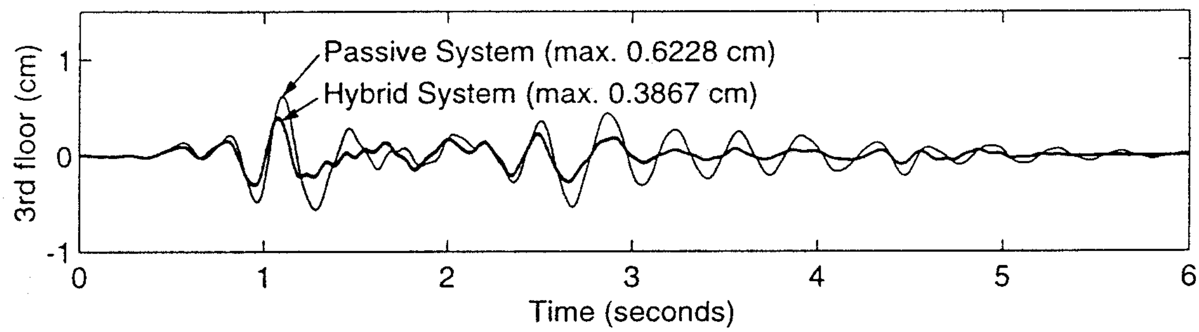

Figure 5: Comparison of displacement responses at third floor

Effectiveness of observer-controller system

With an accelerometer at the top floor and a load cell for active control force, numerical results indicate that observability matrix M_o is of full rank 11, so the system is observable. This means that the observer-controller system requires only four sensors: the accelerometer, the load cell, and two sensors for the earthquake excitation $\ddot{x}_g(t)$ and control command $u(t)$. To implement full-state feedback algorithms without observer, 11 sensors and 11-channel hardware must be used. Consistent with the theory, Figure 6 shows that closed-loop response of the observer-controller system is exactly the same as that of full-state feedback. Thus the seismic observer works as effectively as full-state sensing yet requires far fewer sensors which reduces system complexity.

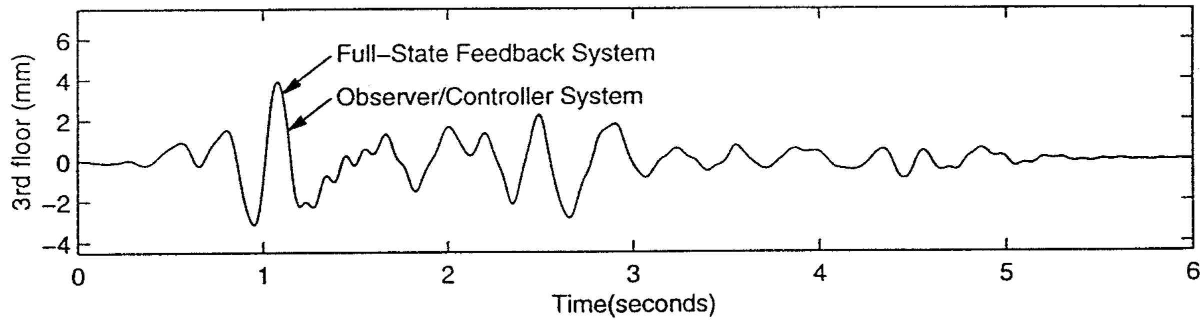

Figure 6: Comparison of closed-loop displacement responses

Optimum placement of hybrid control device

The spectral density G_0 can be any value for determining optimum location of the control device because the RMS values of both control forces and structural responses are proportional to $\sqrt{G_0}$. To simplify the problem, let G_0 =1. If the third floor displacement is the control goal and its required RMS value is 0.04, and if active control force is the objective for optimum placement of control devices, the optimization problem becomes

$$\begin{aligned} &\text{Minimize} \quad \{\sigma_{fa}(x)\} \\ &\text{Subject to} \quad \sigma_{x3}(x) = 0.04, 1 \le x \le 3 \end{aligned} \tag{17}$$

Using the proposed method, it is found that the RMS values of active control forces are 41.7, 283.4, and 143.5 for the hybrid device at the first, second and third floor, respectively. Thus, the objective function is minimum when x = 1; i.e., the first floor is the optimum device location.

Significance of optimum device placement

The proposed optimum location of the hybrid control device is based on a statistical method. In order to verify this optimization method and show the effectiveness of the optimally-placed hybrid system, dynamic response in time-history of the system is evaluated for the following three controller locations: first, second, and third floor.

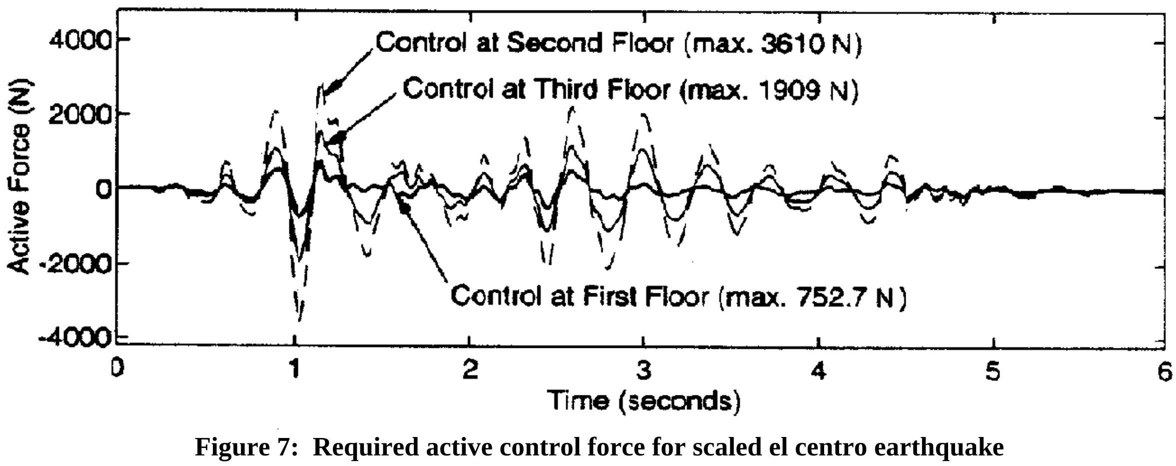

Figure 7: Required active control force for scaled el centro earthquake

Maximum displacement at the third floor is control goal and the active control force is optimization objective. For each case, maximum displacement at the third floor is set at 0.508 cm. Under the excitation of scaled El-Centro earthquake, required active control forces for the three cases are compared in Figure 7. Maximum required active forces are 752.7, 3610.2 and 1908.9 (N) for the hybrid device at the first, second, and third floor, respectively. Clearly, the first floor is optimum because the least active control force is required. This matches the proposed statistical method which does not require the complex calculation of time-history response. Results also show that location of control devices greatly influences the effectiveness of the control system. For example, if the hybrid device is not optimally located but at the second floor, instead, 4.8 times larger active control force is required than for an optimally placed system to achieve the same control objective.

CONCLUSIONS

In this paper, promising strategies are developed for a hybrid control system comprising a viscous fluid damper and an active control system using a servovalve-controlled hydraulic actuator and acceleration sensors. This study shows that this hybrid system requires less active control force than an active system and has greater ability to reduce seismic structural response than a passive system. A seismic response control system with the proposed observer-controller strategy works as effectively as a full-state sensing and feedback system, yet needs far fewer sensors and is able to handle acceleration measurements. The location of control devices greatly influences their effectiveness; and the proposed method for optimum device placement is simple and general because it does not require complex solution of response time-history and does not depend on excitation records. Therefore, a hybrid control system with optimum device placement and observer-controller technique is a promising and practical alternative for structural seismic response reduction for it is easier to manufacture, implement and maintain a much smaller hydraulic actuator and a much simpler sensing and data acquisition system. This research improves the applicability of seismic response control to full-scale structures.

ACKNOWLEDGMENTS

The authors gratefully acknowledge partial financial support for the paper and its presentation from NSF grant CMS-9703725 and from the Intelligent Systems Center and the Manufacturing Research and Training Center at University of Missouri-Rolla.

REFERENCES

Agrawal, A.K. and Yang, J.N. (1996), “Hybrid control of seismic response using nonlinear output feedback”, *Proceedings of 12th ASCE Conference on Analysis and Computation*(Ed. F.Y. Cheng), pp339-349.

Cheng, F.Y. and Jiang, H. (1998a), “Stability and effectiveness of hybrid control for seismic-resistant structures”, *Proceedings of 6th US National Conference on Earthquake Engineering*, Seattle, Washington.

Cheng, F.Y. and Jiang, H. (1998b), “Hybrid control of seismic structures with optimum placement of control devices”, *ASCE Journal of Aerospace Engineering*, 11, 2, pp52-58.

Cheng, F.Y. and Jiang, H. (1998c), “Optimal control of a hybrid system for seismic excitations with state observer technique”, *Journal of Smart Materials and Structures*, 7, 5, pp654-663.

Cheng, F.Y. and Tian, P. (1994), “Generalized optimal active and hybrid control for seismic structures”, *Proceedings of 1st World Conference on Structural Control*, 2, TP1:21-30.

Jiang, H., Cheng, F.Y. and Wang, Z. (1999), “Development of observer-controller technique for vibration reduction of seismic-resistant structures”, *Proceedings of US-Korea Workshop on New Frontiers in Infrastructural and Seismic Problems,* Seoul.

International Association of Structural Control (IASC) (1994), *Proceedings of First World Conference on Structural Control*, Los Angeles, California.

Soong, T.T. (1990), *Active Structural Control: Theory and Practice*, Longman Scientific & Technical, New York.