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Paper No. 1543. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

DESIGN OF ROBUST CONTROLLERS FOR EARTHQUAKE STRUCTURAL DYNAMICS PROBLEMS WITH HYSTERETIC NONLINEARITIES

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ABSTRACT

Robust control methods are used to design a hybrid control system that includes an active tensioning system (ATS) and passive damping elements. The passive elements consist of hysteretic cladding connections designed to dissipate energy through interaction between the building cladding and the supporting structure. The hysteretic behavior of these damping devices introduces varying levels of uncertainty in the structural model, and this can cause significant performance degradation for the ATS for conventional controller designs. This study utilizes the H-infinity and Mu-synthesis methods to design a robust control system for this kind of a system. The simultaneous use of active control and passive control using hysteretic damping is referred to as a hybrid control system. Numerical examples are given using a 1/4 scale test model structure to demonstrate the stability and efficacy of these approaches. A companion 11WCEE paper also describes a design methodology for the design of the optimal hybrid system.

KEYWORDS

Active control; robust control; earthquake control; hybrid control; passive control; passive-active control

OBJECT

It is common practice to utilize structural ductility to control seismic response, and widespread success has been realized with this approach. But active control of buildings subjected to strong earthquakes is greatly complicated by the consequent development of inelastic, hysteretic response within the structure itself. When the inelastic members are deliberately engineered into the structure as passive control or damping elements, the result is often referred to as a "hybrid" control system. Early analyses of this problem have attempted to use different nonlinear control methods as well as other more informal approaches with varying degrees of success.

This paper describes an active controller design approach that is based on the use of robust controller design methods, that is, design methods that simultaneously attempt to provide both robust performance and robust stability. Robustness in this case implies an insensitivity to uncertainty in the problem parameters. These methods are capable of handling varying degrees of uncertainty (both structured and unstructured) in the inputs and outputs as well as in the plant (structure) itself.

Uncertainty in the earthquake input is obvious, but the inelastic, hysteretic behavior introduced into the structure by the passive damping components is also treated as a specified uncertainty in the plant (structure) itself. In this case, robustness means a strong tolerance to this uncertainty in the specification and behavior of the structure, and this is achieved at the expense of modest increases in the resulting controlled response.

Much of the details that are not presented in this paper due to the limited format are available in the doctoral dissertation by the present first author (Hsu, 1995).

METHODS

The traditional approach to design of an active control system is to employ an optimal design strategy that minimizes a quadratic performance index. In particular the Linear Quadratic Regulator (LQR) design approach minimizes a quadratic performance index that is a function of the full state response and the control vectors. The resulting control law can be expressed in terms of the solution of a particular matrix Riccati equation. The resulting design is well known to be highly robust against uncertainty at the plant input represented in the form of phase and gain variations, and the LQR design provides very good phase and gain margins (margin before the controller may become unstable). The practical problem with LQR designs is the requirement for full state feedback, that is the controller must have measurements of all state variables, e.g., displacements and velocities for ALL degrees of freedom in the plant (building structure). The so-called Linear Quadratic Gaussian (LQG) approach relaxes the requirement for full-state feedback by including a dynamic compensator to effectively estimate the unmeasured states. However, the resulting design offers no guarantee of minimum stability margin (in terms of gain and phase margins) compared to the LQR design, that is the system may not be robust against gain variation and phase shift. The so-called Loop Transfer Recovery method attempts to recover the LQR robustness properties at the input of the plant, but this is achieved by sacrificing optimality in the sense of minimizing the quadratic performance index for the originally defined disturbance. A detailed treatment of these approaches is provided by Maciejowski (1989), and a general discussion of the robustness properties of the LQR, LQG and LTR methods in the building structural control problem is presented in Calise, *et al.* (1993).

In the present study, active control systems are designed using so-called H-infinity and Mu-synthesis methods. These methods are concerned with maintaining acceptable performance in the presence of uncertainty in the dynamic system. H-infinity methods use singular value scaling techniques to characterize permissible uncertainty in the controlled system. Glover and Doyle (1989) present a well-known two-Riccati equation state-space solution for the optimal H-infinity controller. In this approach, uncertainties are considered as unstructured, thus the resulting controllers are seen to be conservative for the plant with different sources of uncertainty. Mu-synthesis methods reduce this conservatism by using the structured singular value μ, and can achieve the same or better stability and performance specifications in the presence of structured plant uncertainty. However, these methods also increase the order of the resulting controllers, and this can lead to designs that cannot be realized in practice. In such case, model order reduction methods or fixed-order control synthesis techniques (Sweriduk, *et al.* 1993) can be used to achieve practical controller designs.

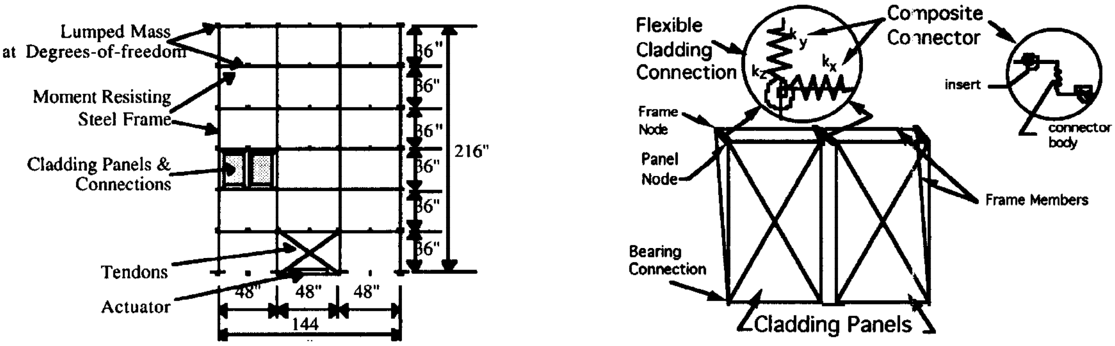


Fig. 1. Building analytical model including cladding and connector elements

These robust controller design methods were applied to a 1/4 scale 6 story case study building that has been extensively studied by the authors in previous work (Goodno, *et al.* 1995; Hsu, *et al.* 1995). Figure 1 shows the 2-D computer building model with an active tendon control device attaching to the center bay of the structure. The controller designs were developed for a simplified reduced order model (with one translational degree of freedom per floor). Figure 2 shows the block diagram of the generalized building model where the block $(s\,\mathrm{I}-\mathrm{A})^{-1}$ represents the nominal building. The blocks Δi and Δk are infinity norm bounded stable transfer function matrices which represent uncertainty from the unmodelled actuator dynamics and from nonlinearity due to the presence of passive elements, respectively. The input w_{21} and w_{22} are the energy norm bounded but otherwise unknown input (earthquake) and the sensor noise. The controllers were designed to minimize the relative floor displacements with a limited control effort, while ensuring system stability in the face of the worst case uncertainty scenario, i.e., given that w equals to all inputs and z all the output in Figure 2, then the robust

control problem is to find a stabilizing controller which minimizes the μ value of the transfer function from w to z (Calise, *et al.* 1993).
In parallel with the robustness consideration and controller design, the synthesized controllers are also simulated in a specially enhanced version of the well-known DRAIN-2D program which is used for the dynamic response analysis of inelastic 2D structures. This version was modified to incorporate dynamic controllers along with the necessary actuators and control elements (Hsu, 1995). These simulations include the presence of passive control elements in the form of ductile cladding connections that introduce hysteretic action between floors coupled through the cladding panels. The simulations were carried out for earthquakes with differing spectral and temporal characteristics (Hsu, *et al.* 1995; Hsu, 1995).

RESULTS

The design of a satisfying controller which meets the stability and performance criterion took several iterative steps in the synthesis and the simulation. Figure 3 shows the results of the robust stability (RS) and robust performance (RP) tests for the candidate controller. Robust stability is a measure which indicates the ability of the closed-loop system to remain stable if the true plant (building structure) deviates from the "nominal" plant. The Robust performance measure evaluates the performance of a control system in the face uncertainties in the plant, where performance implies the ability to meet the control design objective.

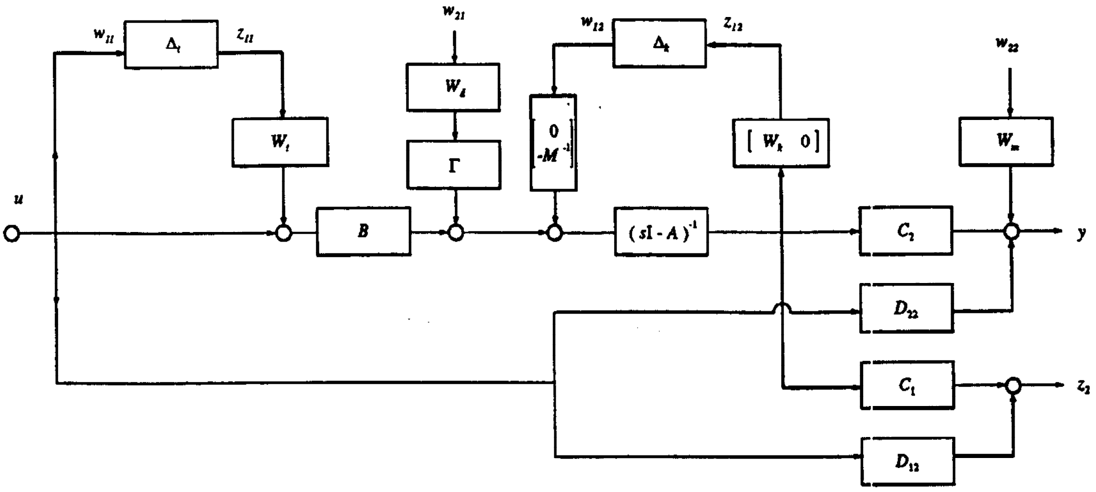
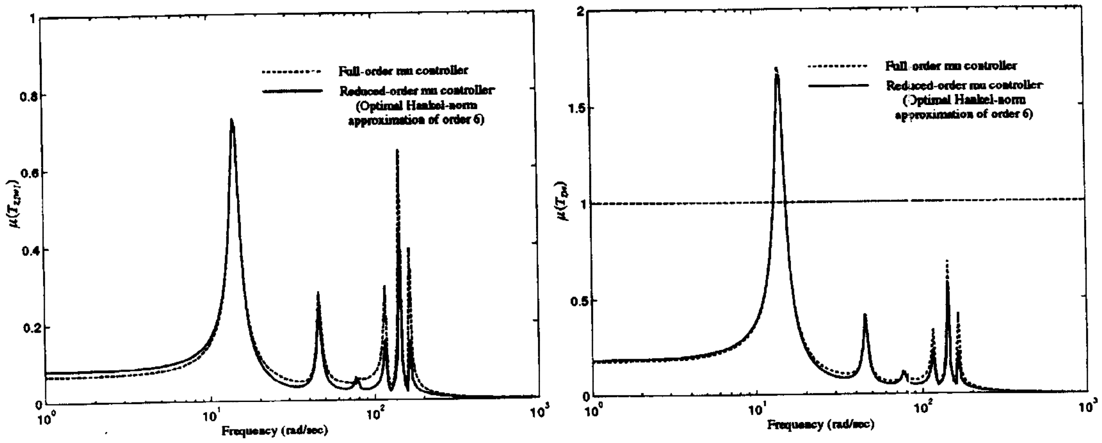


Fig. 2. System Model for the Robust Active Control System



(a) RS test (b) RP test

Fig. 3. Robust Stability (RS) and Robust Performance (RP) tests for full-order and reduced-order mu controllers

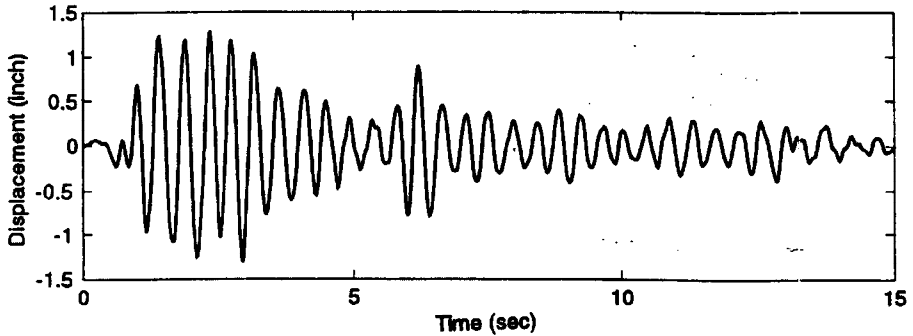
There is a practical drawback to this approach, however. The dimension of the resulting controller (referred to as full-order mu controller) has an order of 41, while the order of the generalized plant in Fig. 2 is 13. Such a large order controller is usually not preferred in practice because it introduces much faster dynamics that are characteristic of the plant and can be difficult to properly implement. By applying the optimal Hankel norm approximation technique (Glover, 1984), a reduced-order mu controller of order 6 was obtained. Results are presented in Figure 3 superposed with those of the full-order design. It can be readily seen that there is no significant difference between the two controllers, and the closed-loop properties (RS and RP) are preserved.

Figure 4 shows the top floor displacement time histories of the model structure when subjected to the 1940 El Centro earthquake NS record using different control configurations. The maximum top floor displacement for the uncontrolled structure was 1.80 inches. With the active control operating, the maximum displacement response is reduced to 1.31 inches (a 27% reduction). The maximum actuator control force was 7.4 kips.

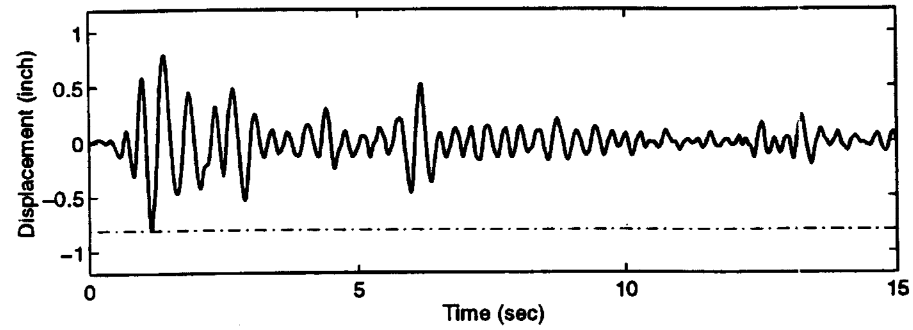
The combination of the robust controller and passive hysteretic damping elements is capable of reducing the resulting seismic response by 57 % or more (comparing to the uncontrolled case). The presence of the passive elements also reduced the required control forces by 25% (maximum control force is 5.5 kips). More significantly, these controller designs are shown to remain stable and functioning even when the stiffness of the building structure is reduced by as much as 40%. This dramatic demonstration of the robust stability that is provided in the Mu-synthesis approach has strong implications for safe and predictable performance in the face of significant seismic-induced damage to the structure.

CONCLUSIONS

The utility of using robust controller designs to accommodate uncertainties in both the input (earthquake) and the plant (building structure) are strikingly demonstrated for example building designs that incorporate hybrid combinations of passive damping and active control. The passive damping is provided in this case by cladding-structure interaction through ductile connections, but the methods are applicable to other types of hysteretic damping that may involve changes in the stiffness of the structure as well.



(a) Active control system alone



(b) Hybrid passive/active control system

Fig. 4. Top floor displacement time histories for the study building and the 1940 El Centro NS component.

ACKNOWLEDGEMENT

The support of the National Science Foundation through Grants BCS-9202039 and CMS-9402572 is gratefully acknowledged. However, the findings and opinioins expressed here are those of the authors and do not represent the position of the NSF.

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