

CONTROL STRATEGIES FOR A STRUCTURAL CONTROL BENCHMARK STUDY: VERIFICATION BY EXPERIMENT

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Abstract

This paper completes a recent benchmark study in active structural control of a civil engineering structure. The previous work gave an analytical definition of a structure combined with actuators and sensors, along with 15 papers applying various control strategies to this common problem using the same evaluation and performance criteria. As actual implementation is the ultimate test of controller evaluation, this paper reports the experimental performance of these control strategies as applied to a 3-story model building with an Active Mass Driver (AMD).

Introduction

As the world's population grows and the number of buildings constructed in seismically-active urban areas increases, greater demand for the survival and functionality of buildings during and in the aftermath of earthquakes is required. Structural control of building vibration has made tremendous progress over the last two decades and has emerged as one of the viable technologies for providing structural serviceability and safety in the face of natural hazards such as strong earthquakes and high winds. One system that has been employed with success for mitigating wind-induced vibration and motion due to moderate earthquakes is the active mass driver (AMD) system. Structures with AMDs have been studied extensively through simulation, in the laboratory, and in full-scale implementation, each study with its own particular control strategies. However, little has been done to directly compare and contrast the wide array of control strategies available to the designer for such systems.

A recent analytical benchmark study by Spencer *et al.* (1998) defined a structural control problem and appropriate performance evaluation criteria. Other authors were invited to apply their choice of control algorithms to this common problem with identical evaluation criteria. This study, including the papers of the control designers, was published as a Special Issue of *Earthquake Engineering and Structural Dynamics* (Benchmark, 1998). This Special Issue serves as a useful explanation of various structural control design strategies and their application to this one common problem.

A controller, no matter how superior its analytical performance, is only as good as its performance in the ultimate test: actual implementation. The experimental portion of the problem is addressed herein, complementing the analytical portion by introducing the uncertainties of the physical world and testing. The experimental verification of each of the controller designs should reconfirm viability of controller design as well as highlight problems that might arise in actual implementation. The dynamic characteristics of the experimental structure are compared to the analytical evaluation model, and the performance of various control strategies on the experimental structure are compared and contrasted.

Review of Analytical Benchmark Definition

The benchmark structural control problem presented by Spencer *et al.* (1998) uses an analytical evaluation model that is derived directly from experimental data obtained at the Structural Dynamics and Control / Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre Dame. The structure — chosen because of the widespread interest in

this class of systems (Soong, 1990; Housner *et al.*, 1994; Spencer and Sain, 1997) — is a scale model of the three-story prototype building discussed in Chung *et al.* (1989), and employs an active mass driver for vibration control. The structure is subject to one-dimensional ground motion. The analytical model of the structure, including sensor and actuator dynamics, is described by the block diagram in Fig. 1 and by the state equations

$$\begin{aligned}\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}u + \mathbf{E}\ddot{x}_g \\ \mathbf{y} &= \mathbf{C}_y\mathbf{x} + \mathbf{D}_y u + \mathbf{F}_y\ddot{x}_g + \mathbf{v} = \begin{bmatrix} x_m & \dot{x}_1^a & \dot{x}_2^a & \dot{x}_3^a & \dot{x}_m^a & \dot{x}_g \end{bmatrix}^T + \mathbf{v} \\ \mathbf{z} &= \mathbf{C}_z\mathbf{x} + \mathbf{D}_z u + \mathbf{F}_z\ddot{x}_g = \begin{bmatrix} x_1 & x_2 & x_3 & x_m & \dot{x}_1 & \dot{x}_2 & \dot{x}_3 & \dot{x}_m & \dot{x}_1^a & \dot{x}_2^a & \dot{x}_3^a & \dot{x}_m^a \end{bmatrix}^T\end{aligned}\quad (1)$$

where the coefficient matrices in (1), which were distributed in a MATLAB[®] MAT-file as a part of the benchmark problem definition, represent the input-output behavior of the experimental structure up to 100Hz as tested in January 1995.

The task of the control designer, then, is to design a stable, discrete-time controller with sampling period $T = 1$ ms, subject to several implementation constraints: (a) the sensor noise components are Gaussian rectangular pulse processes of 1 ms duration and root mean square magnitude 0.01 V; (b) there is a 200 μ s computation time delay in the digital controller; (c) the A/D and D/A converters at the controller input and output have 12-bit precision and a span of ± 3 V; (d) the controller may have no more than 12 states; and (e) the resulting actuator response must be within the bounds of the 6 hard constraints, $C_i \leq 1$, $1 \leq i \leq 6$, as defined below.

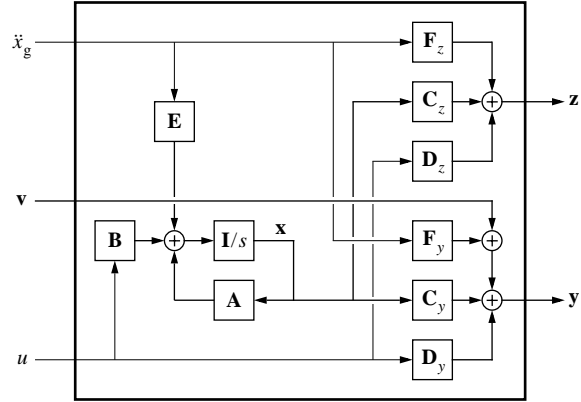


Figure 1: System block diagram.

The performance of the controller is then judged by 10 performance measures, J_i , $1 \leq i \leq 10$, as summarized in Table 1. The performance measures, weighted by nondimensionalization parameters (which are peak and RMS 3rd floor uncontrolled responses), are root mean square and peak structural responses (interstory drift and floor acceleration) and actuator responses (actuator displacement, velocity, and acceleration). The first five performance measures are root mean square responses to a family of Kanai-Tajimi excitation spectra (Soong and Grigoriu, 1993). The latter five performance measures are based on the corresponding “peak” responses to the NS records of the 1940 El Centro and 1968 Hachinohe earthquakes.

Table 1: Summary of performance evaluation criteria.

maximum RMS interstory drifts $J_1 = \max_{\omega_g, \zeta_g, i} \frac{\sigma_{d_i}}{\sigma_{x_{3o}}}$	maximum RMS floor accel. $J_2 = \max_{\omega_g, \zeta_g, i} \frac{\sigma_{\ddot{x}_i^a}}{\sigma_{\ddot{x}_{3o}^a}}$	RMS actuator displ. $J_3 = \max_{\omega_g, \zeta_g} \frac{\sigma_{x_m}}{\sigma_{x_{3o}}}$	RMS actuator velocity $J_4 = \max_{\omega_g, \zeta_g} \frac{\sigma_{\dot{x}_m}}{\sigma_{\dot{x}_{3o}}}$	RMS actuator accel. $J_5 = \max_{\omega_g, \zeta_g} \frac{\sigma_{\ddot{x}_m^a}}{\sigma_{\ddot{x}_{3o}^a}}$
peak interstory drifts $J_6 = \max_t \frac{ d_i(t) }{x_{3o}}$ El Centro Hachinohe	peak floor accel. $J_7 = \max_t \frac{ \ddot{x}_i^a(t) }{\ddot{x}_{3o}^a}$ El Centro Hachinohe	peak actuator displ. $J_8 = \max_t \frac{ x_m(t) }{x_{3o}}$ El Centro Hachinohe	peak actuator velocity $J_9 = \max_t \frac{ \dot{x}_m(t) }{\dot{x}_{3o}}$ El Centro Hachinohe	peak actuator accel. $J_{10} = \max_t \frac{ \ddot{x}_m^a(t) }{\ddot{x}_{3o}^a}$ El Centro Hachinohe

There are six constraints imposed in the analytical benchmark study that must be met by all controllers, three using RMS criteria and three with peak criteria. These constraints are prescribed to represent

the physical constraints of controllers in an experimental system as well as safety concerns in its operation. The constraints limit the command voltage, the actuator acceleration, and the actuator displacement, and are summarized in Table 2.

Table 2: Summary of constraints.

RMS command voltage $\max_{\omega_g, \zeta_g} \sigma_u \leq 1 \text{ V}$	RMS actuator accel. $\max_{\omega_g, \zeta_g} \sigma_{\ddot{x}_m^a} \leq 2g$	RMS actuator displ. $\max_{\omega_g, \zeta_g} \sigma_{x_m} \leq 3 \text{ cm}$
peak command voltage $\max u(t) \leq 3 \text{ V}$	peak actuator accel. $\max \ddot{x}_m^a(t) \leq 6g$	peak actuator displ. $\max x_m(t) \leq 9 \text{ cm}$
El Centro Hachinohe	El Centro Hachinohe	El Centro Hachinohe

Experimental Structure

The analytical evaluation model of the structure, including actuator and sensor dynamics, used in simulation was computed from experimental transfer functions measured in January 1995. The experimental structure is an actively controlled, three-story, single-bay, model building considered by Dyke *et al.* (1994, 1996). The test structure, shown in Fig. 2, is designed to be a scale model of the prototype building discussed by Chung *et al.* (1989) and is subject to one-dimensional ground motion.

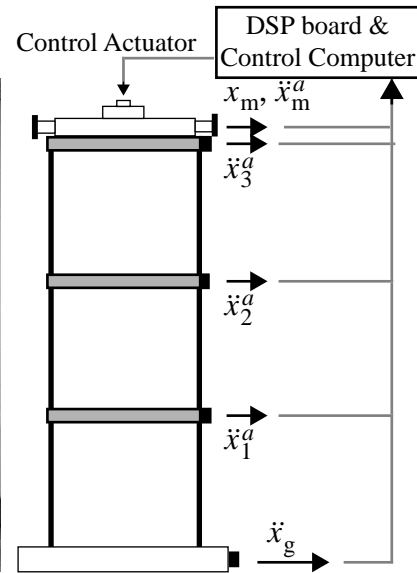
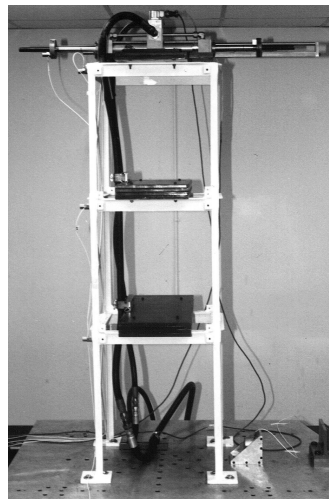


Figure 2. Experimental setup.

The building frame is constructed of steel, with a height of 158 cm. The floor masses of the model total 227 kg, distributed evenly between the three floors, and the mass of the structural frame is 77 kg. The time scale factor is 0.2; thus, the natural frequencies of the model are approximately five times those of the prototype. The first three modes of the model structural system in January 1995 were at 5.81 Hz, 17.68 Hz and 28.53 Hz, with associated damping ratios given, respectively, by 0.33%, 0.23%, and 0.30%.

For control purposes, a simple implementation of an active mass driver (AMD) was placed on the third floor of the structure. The AMD consists of a single hydraulic actuator with steel masses attached to the ends of the piston rod. The moving mass for the AMD was 5.2 kg, and consisted of the piston, piston rod, and steel disks bolted to the end of the piston rod. The total mass of the structure, including the frame and the AMD, was 309 kg.

Current Dynamic Characteristics of Structure

During the course of experimentation between January 1995 and this study, cracks were initiated in the vertical columns in the first story of the experimental structure. The cracks were welded, but the resulting structure had some slight changes in its

Table 3: Natural frequencies of original and repaired structure.

Original Structure	Repaired Structure	Percent Reduction
5.81 Hz	5.56 Hz	4.30%
17.68 Hz	16.97 Hz	4.02%
28.53 Hz	27.88 Hz	2.28%

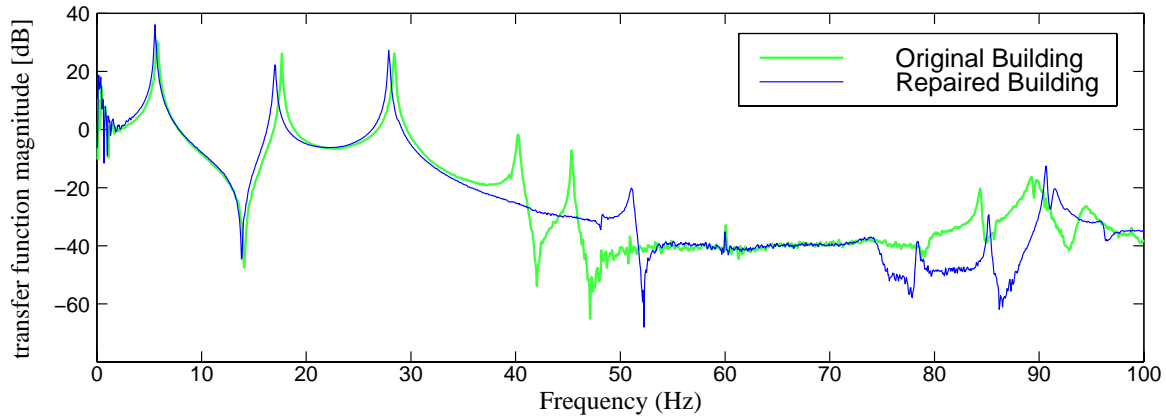


Figure 3: Transfer function magnitude of original and repaired structure.

characteristics. The differences between the original structure (January 1995) and this study (Fall 1998) may be demonstrated by examining the transfer functions. Fig. 3 shows the transfer function magnitude, for the original 1995 and repaired 1998 structures, from base excitation \ddot{x}_g to the absolute acceleration at the second floor \ddot{x}_2^a . Effectively, the natural frequencies of the repaired structure are slightly lower than in the original structure used to develop the analytical evaluation model for the benchmark study; the natural frequencies are listed in Table 3. Though unintended, this frequency shift is akin to the rigidity degradation often seen in structures after an earthquake. Thus, this poses an additional challenge to controllers, that of robustness to plant modeling uncertainties and changes.

Experimental Performance Results

All of the controllers submitted as a part of the structural control benchmark study that may be cast in linear state space form¹ were tested in the Structural Dynamics and Control / Earthquake Engineering Laboratory (SDC/EEL) at the University of Notre Dame. (The controllers are listed in Table 4 at the end of this paper.) Some of the controllers were closed-loop unstable with structural response growing rapidly before safety constraints shut the system down. Obviously, performance evaluation for such controllers are not included here. The data shown below is limited to a maximum of 5 controllers per benchmark paper to not unduly bias the results toward those that submitted many controllers.

Figure 4 shows a comparison of several of the key performance evaluation measures. The dominant ranges of the performance values may be seen in the histograms in Fig. 5. Several general observations may be made. First, there is a high positive correlation between the decrease in interstory drift and floor accelerations for the various controllers. The correlation is higher for RMS than for peak values, probably in part to the fact that none of the control designs addressed peak response minimization directly. Second, a trade-off exists between smaller structural response, as determined by interstory drifts, and the control effort, as indicated by actuator velocity. This trade-off is apparent in spite of the wide variety of control design methods and control designers — in fact, it supports the argument that, properly used, each of the control design methods may achieve similar ranges of performance, control effort, robustness, etc. Third, the “peak” values J_{6-10} show remarkably less scatter (*i.e.*, smaller coefficients of variation) for the structural responses but the same or higher for the actuator responses.

1. The fuzzy controllers of Battaini *et al.* require specialized fuzzy hardware chips unavailable at Notre Dame. The sliding mode controllers of Adhikari *et al.* included nonlinear terms and, consequently, were not immediately amenable to the linear controller paradigm currently implemented.

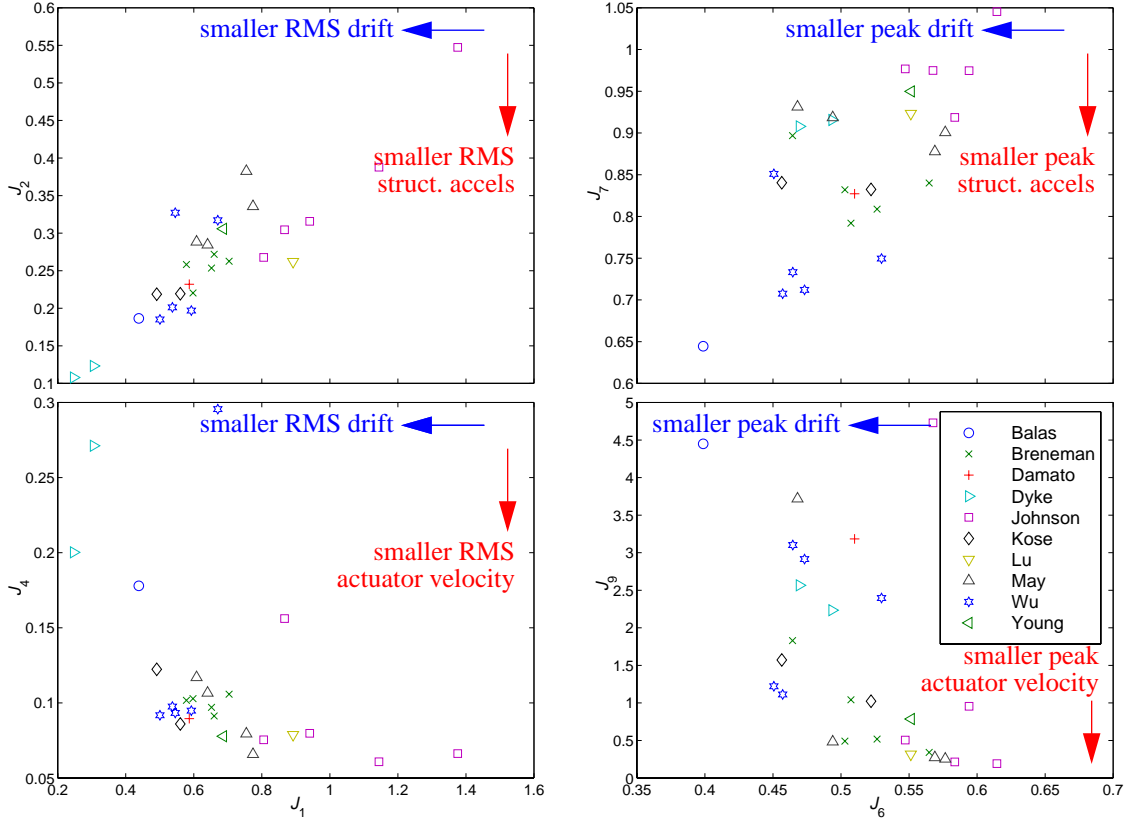


Figure 4: Comparison of experimental performance measures.

Conclusions

Testing different controller types on a common test structure provides valuable insight into the nature of control designs. Some of the practical knowledge gained from this benchmark study are:

- Some controllers were unstable when tested experimentally even though they were stable during analytical tests. This highlights the necessity of including robustness concerns in design of controllers for these systems.
- For higher amounts of actuator force, larger reductions in the amounts of interstory drift and floor accelerations are obtained. Reductions in performance criteria such as interstory drifts were generally proportional to the amount of energy put into the system.
- From the viewpoint of performance, no particular controller design method stands out as the “best”. Rather, most demonstrate the trade-offs typical of

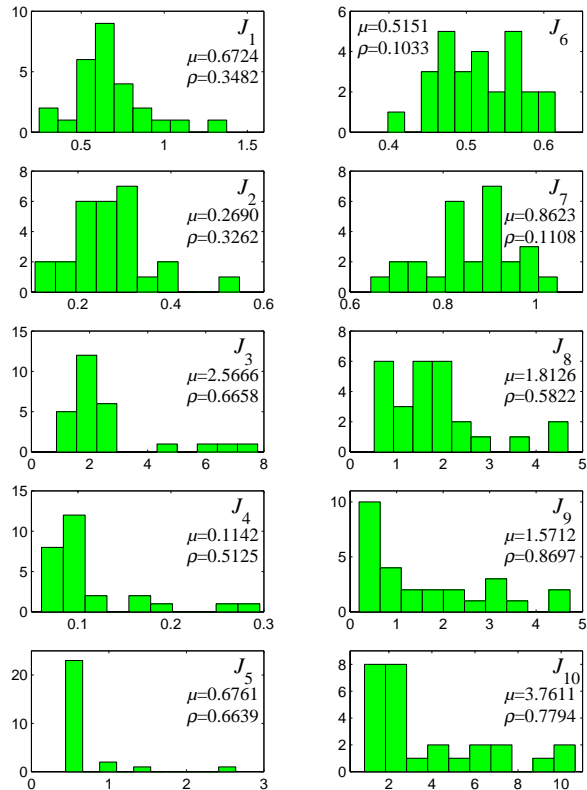


Figure 5: experimental performance histograms.

multiobjective problems. All of the design methods can be effective in the hands of a skilled designer.

(Further details of this experimental comparison, as well as analytical comparisons, may be found in Johnson *et al.* (1999).)

Acknowledgments

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Table 4: List of AMD controllers.

Authors, Ctrl Type	Controller	U*	T†	P‡	Authors, Ctrl Type	Controller	U*	T†	P‡	
Adhikari, Yamaguchi, & Yamazaki, sliding mode	El Centro design				Kose, Jabbari, Schmitendorf, & Yang, L₂	cont_a	×			
	Hachinohe design					cont_b		×	×	
	Kanai-Tajimi design					cont_c		×	×	
				cont_d		×				
Balas, μ synthesis	—		×	×	Lu & Skelton, covariance	2nd iteration	×			
Battaini, Casciati, & Faravelli, fuzzy	3×3 mbrshp, FOH					3rd iteration		×	×	
	5×5 mbrshp, ZOH				May & Beck, probabilistic	det EQ, det freq		×	×	
Breneman & Smith, H_∞	#1 [x _i 12u]		×	×		prob EQ, det freq		×	×	
	#2 [x _i 10u]		×	×		det EQ, prob freq		×	×	
	#3 [x _i ³ 10u]		×	×		prob EQ, prob freq		×	×	
	#4 [x _i x _i 8u]		×			Panariello, Betti, & Longman, H₂ ensemble training	#1 (min ctrl effort)	×		
	#5 [x _i x _i ³ 8u]		×	×	#2 (min ctrl effort)		×			
	#6 [x _i x _i ³ 7u]		×		#3 (min struct resp)		×			
	#7 [x _i 8x _m 8u]		×		#4 (min struct resp)		×			
	#8 [x _i 12 x _m 12u]		×		Wu, Yang, & Agrawal, LQG, sliding mode	lqg, 1 sensor		×		
	#9 [x _i 8 x _m ³ 8u]		×	×		lqg, 3 sensors		×		
	#10 [x _i 12u]		×			lqg, 5 sensors		×	×	
#5s1 [x _i x _i ³ 8u]		×		cmsc, 1 sensor			×			
#5s2 [x _i x _i ³ 8u]		×		cmsc, 3 sensors			×	×		
#5s3 [x _i x _i ³ 8u]		×		cmsc, 5 sensors			×	×		
#5s4 [x _i x _i ³ 8u]		×		cmscc, 1 sensor		×				
#5s5 [x _i x _i ³ 8u]		×		cmscc, 3 sensors			×	×		
#5s6 [x _i x _i ³ 8u]		×		cmscc, 5 sensors		×				
D'Amato & Rotea, multiobj. H₂ , 8th-order			×	×		Young & Bienkiewicz, μ synthesis			×	×
Dyke, H₂	14th-order		×	×					×	×
	16th-order		×	×				×	×	
			×	×				×	×	
Johnson, Voulgaris, & Bergman, mixed H₂/H_∞	H ₂ (min all outputs)	×						×	×	
	H ₂ (min act. resps.)		×	×				×	×	
	mixed H ₂ /H _∞ #1		×	×				×	×	
	mixed H ₂ /H _∞ #2		×	×				×	×	
	H ₂ /H _∞ (rbst stblty)		×	×				×	×	
LQG sample ctrlr		×	×				×	×		

* U = experiment closed-loop unstable
† T = tested
‡ P = included in plots
⊠ controller analytically unstable