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ACTIVE RESPONSE CONTROL OF BUILDING STRUCTURES UNDER SEISMIC EXCITATIONS

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SUMMARY

The major aim of this work is the experimental verification of active control strategies under realistic conditions. Structural control experiments were carried out using a scaled down multi-degree-of-freedom model. The model was subjected to simulated seismic base motion produced by a shaking table and control was accomplished using a system of prestressing tendons connected to a servo-controlled hydraulic actuator.

Experimental as well as simulation results show that simple and effective control laws can be implemented when practical considerations such as time delay and spillover compensation are taken into account.

INTRODUCTION

As active control research progresses from its conceptual phase to the implementation phase, an overriding question is whether or not a simple control system can be effective in response control of complex structures under severe transient loads such as earthquakes (Ref. 1). In an attempt to answer this question, a series of experiments were planned (Fig. 1) which were designed to lead to a demonstration of active control concepts using a full-scale structure in the near future.

An active tendon system was chosen for study and encouraging experimental results based on the single-degree-of-freedom structural model have been reported elsewhere (Refs. 2,3). A comprehensive experimental study using the three-degree-of-freedom model has been completed and is reported in this paper. The multi-degree-of-freedom model provides opportunities for study and verification of a number of control strategies which were not possible in the earlier study. These include modal control, time delay in the modal space and control and observation spillover compensation. Moreover, further verification of a simulation procedure can be carried out which gives added confidence in using simulation procedures for extrapolating active control results to more complex situations.

CONTROL ALGORITHMS, MODAL CONTROL AND TIME DELAY COMPENSATION

The present study tested several instantaneous optimal control algorithms (Ref. 4) along with the classical linear global optimal control law (Ref. 5). The instantaneous optimal control laws do not require solving the Riccati matrix equation as required in the classical optimal control, resulting in computational advantages particularly when the number of degrees of freedom of the structure under control is large.

In actual structural applications, implementation feasibility and economic considerations require simple control schemes using a limited number of sensors and controllers. Modal control is thus of interest in which only a small number of critical modes are controlled while leaving the residual modes uncontrolled. As a consequence, the induced control and observation spillover may significantly degrade the structural performance (Ref. 6).

Modal control and spillover effects were studied in this series of experiments. Experiments were first performed when all three modes were under control. They were then repeated when the first fundamental mode was the only controlled critical mode.

A phase shift method for time delay compensation was developed and successfully applied to the single-degree-of-freedom structural control experiments (Ref. 2). This procedure was extended to the multi-degree-of-freedom case by applying a phase-shift correction in each mode. From a pre-calculated feedback gain matrix for the ideal system, the modified real system feedback gain matrix through modal phase-shift corrections can be constructed using modal transformations.

EXPERIMENTAL SET-UP AND RESULTS

The basic experimental set-up consisted of a three-story 1:4 scale frame with one tendon control device. The control was supplied by a servocontrolled hydraulic actuator through a system of tendons attached to the first floor. The state variable measurements were made by means of strain gage bridges installed on the columns just below each floor slab. For each set of the strain gage bridges, the signal from one strain gage bridge was used as the signal of measured storydrift displacement between adjacent stories, while the signal from the second set was further passed through an analog differentiator to yield measured storydrift velocity. The base acceleration and the absolute acceleration of each floor were directly measured by the use of accelerometers installed at the base of the structure and on the floor slabs. A block diagram showing the measured system and the control procedure is given in Fig. 2.

The base motion of the model was supplied by a shaking table with banded white noise and an earthquake accelerogram as inputs. Under white noise excitation, modal properties were identified from the frequency response functions for system identification. Moreover, it provided a preliminary examination of the system performance including structural, sensor and controller dynamics for more realistic inputs that were to follow. The N-S component of El-Centro acceleration record was used in the experiment. However, it was scaled to 25% of its actual intensity to prevent inelastic deformation in the model structure during uncontrolled vibrations.

The classical closed-loop optimal control was first studied with all three modes under control. After carrying out the variational procedure, it was found that there was only a slight increase in natural frequencies (stiffness) but damping factors were increased from 1.62%, 0.39% and 0.36% to 12.77%, 12.27% and 5.45%.

The spillover problem was investigated by selecting the first fundamental mode as the controlled critical mode. The critical modal quantities were reconstructed from the measurements at all floors. When fewer output measurements were available, the estimated critical modal quantities were actually affected by the observation spillover to the residual modes. Even worse, the time delay was compensated as if the outputs were contributed by the critical modes alone. The combined effect of observation spillover and time delay made the system unstable.

In the presence of modelling errors and measurement noise, the first modal quantities could not be reconstructed perfectly and small contribution of the residual modes to the feedback signal was unavoidable. Because of small stability margins (small damping factors) for the second and third modes, the model structure was very sensitive to these errors. To circumvent this problem, the command control signal was passed through a low-pass filter before driving the actuator in order to eliminate the effect of the residual modes. However, no perfect filter exists; the higher the order is the filter, the sharper is the cutoff frequency, but the longer is the time delay. As a compromise, a third-order Butterworth filter with a cutoff frequency of 5 Hz was selected but the time delay was increased from 35 msec. to 88 msec.

Acceleration frequency response functions as shown in Fig. 3 was constructed by using banded white noise excitation. For the case of three controlled modes, significant damping effect was reflected from the decrease in peak heights due to its small active stiffness. It was shown that all three modes were under control with one controller in the presence of time delay. For the case of one controlled mode, the peak of the first mode was decreased but the peaks of the second and third modes were increased. Due to the effect of control spillover, the performance of the controlled system was not better than that of the uncontrolled one.

Under El Centro excitation, significant reduction in acceleration was achieved with three controlled modes. In addition to the reduction in peak magnitudes, the effect of active damping was clearly evident. With only one controlled mode, only the first fundamental mode was controlled but the excitation frequency was distributed over all three modes. Due to the control spillover, the control effect was greatly degraded (Fig. 4).

The instantaneous optimal control algorithms were studied with all three modes under control using the seismic excitation. The absolute accelerations and storydrifts were measured and some typical results are shown in Figs. 5 and 6. The maximum response values measured during the experimental study, along with the reduction produced by the active control compared to the uncontrolled case, are shown in Table 1. The average reductions (control efficiencies) are only 27%-36% due to the use of only one controller in this study. The closed-loop control is slightly more efficient than the others, close to open-closed-loop performance. All three algorithms proved to be feasible to implement for response reduction.

Good agreement was achieved between analytical and experimental results. Some discrepancies were observed in the uncontrolled test due to controller-structure interaction. However, for the controlled cases, most of the damping force was contributed by the feedback force. Therefore, the influence of controller-structure interaction was negligible and excellent agreement was observed. With one controlled mode, the control force was of a lower magnitude and of a lower frequency, leading to a better performance of the actuator and hence excellent agreement was achieved.

DISCUSSIONS AND CONCLUSIONS

Experiments of active control of a three-story building structure with one controller have been carried out successfully under realistic conditions.

However, it should be noted that, since controller dynamics was an integral part of the structural dynamics, the structure was no longer a conventional one. As a consequence, the damping factors for the second and third modes were relatively small because of the controller location. The reduced stability margins made the structure vulnerable to instability when these modes remained uncontrolled.

In modal control, the structural stability was very sensitive to modeling errors as modes leaked out to the feedback signals without time delay compensation. Since no perfect filter exists, such leakage could not be eliminated. The leakage, however, could be minimized by passing the control signals through a real filter at the expense of a larger time delay. Because of control spillover, it is suggested that critical modes be selected in such a way that the residual modes are not excited by the environmental loads.

Time delay compensation using the phase shift approach was successfully implemented in the multi-degree-of-freedom case. It is particularly effective when the dominant frequencies are well known as in the case of seismic excitations.

Good agreement was obtained between analytical and experimental results. Small discrepancies, however, were present which were primarily due to controller-structure interactions. In the uncontrolled test, the structural motion induced slight actuator displacement which was continuously corrected to zero by the servo-controlled system. Therefore, damping force was a complicated function of the actuator mechanism. However, for the controlled cases, most of the damping force was contributed by the feedback force so that the influence of the interactions was negligible.

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Control Algorithms	FLOOR	Relative Displacement			Storydrift Displacement			Absolute Acceleration			MAX. Control Force
		Value	Red.	$\overline{\text{Effi.}}$	Value	Red.	$\overline{\text{Effi.}}$	Value	Red.	$\overline{\text{Effi.}}$	
		in.	%	%	in.	%	%	g	%	%	lbs
UncontroL	1	0.2134			0.2134			0.1576			
	2	0.4594			0.2621			0.2210			
	3	0.6323			0.1787			0.3223			
Open-loop Control	1	0.1444	33.3	29.3	0.1444	33.3	28.7	0.1156	26.6	26.8	137.53
	2	0.3324	27.6		0.1952	25.5		0.1605	27.4		
	3	0.4622	26.9		0.1299	27.4		0.2373	26.4		
Open-closed-loop Control	1	0.1370	35.8	36.2	0.1370	35.8	35.4	0.1146	27.3	29.9	239.78
	2	0.2898	36.9		0.1694	35.4		0.1576	28.6		
	3	0.4060	35.8		0.1162	35.0		0.2129	33.9		
Closed-loop Control	1	0.1255	41.2	36.7	0.1255	41.2	35.1	0.0990	37.2	33.6	180.28
	2	0.2978	35.2		0.1777	32.2		0.1468	33.6		
	3	0.4189	33.7		0.1216	32.0		0.2256	30.0		

Table 1. Results Using Instantaneous Optimal Control

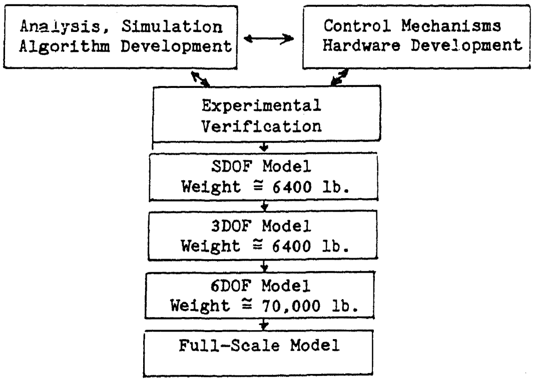

Fig. 1. Active Control Development Plan

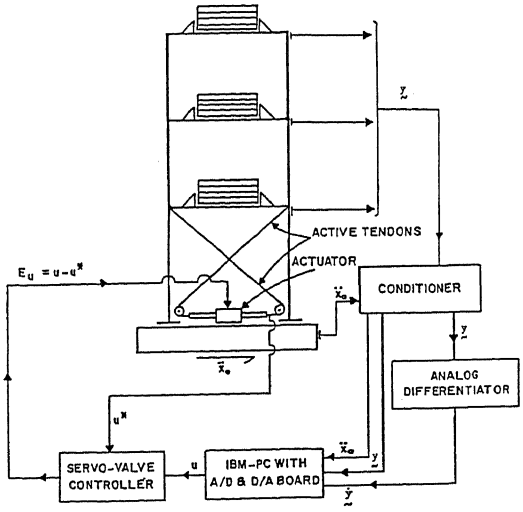

Fig. 2. Experimental Set-up

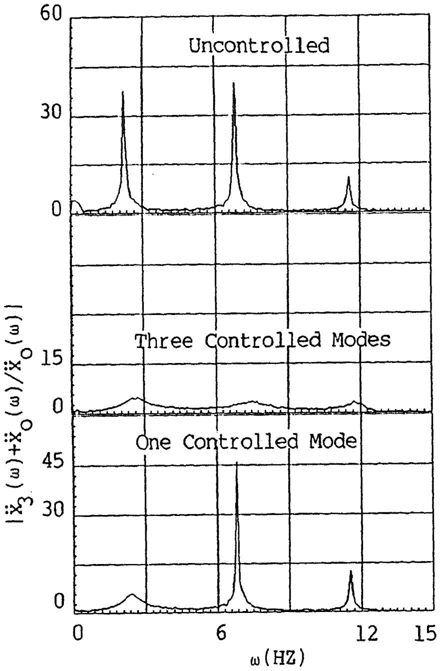

Fig. 3. Third-Floor Acceleration Frequency Responses

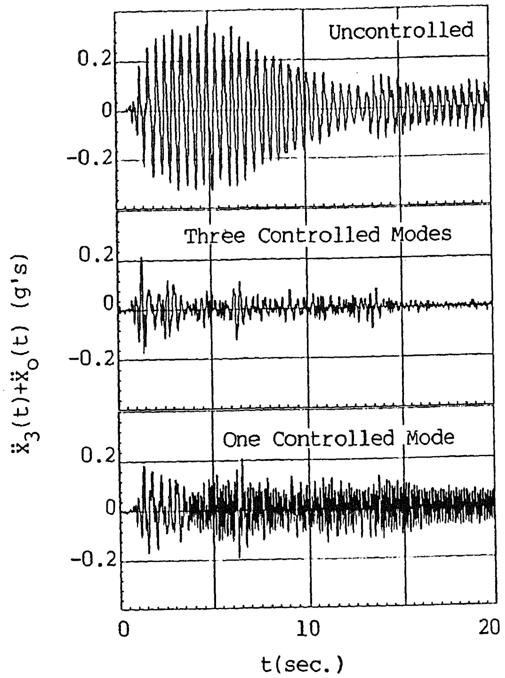

Fig. 4. Third-Floor Absolute Accelerations

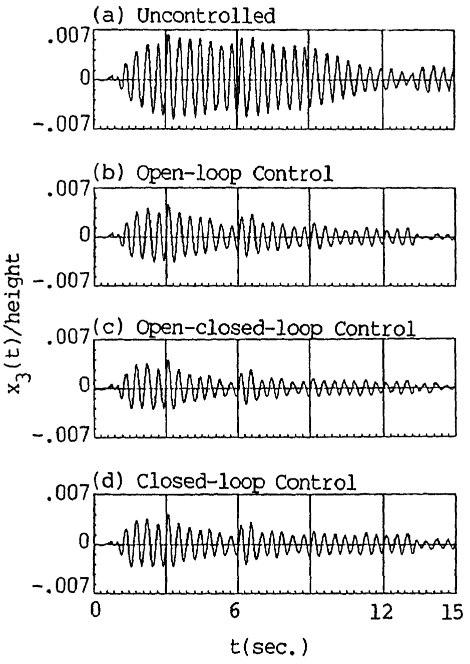

Fig. 5. Third-Floor Relative Displacements

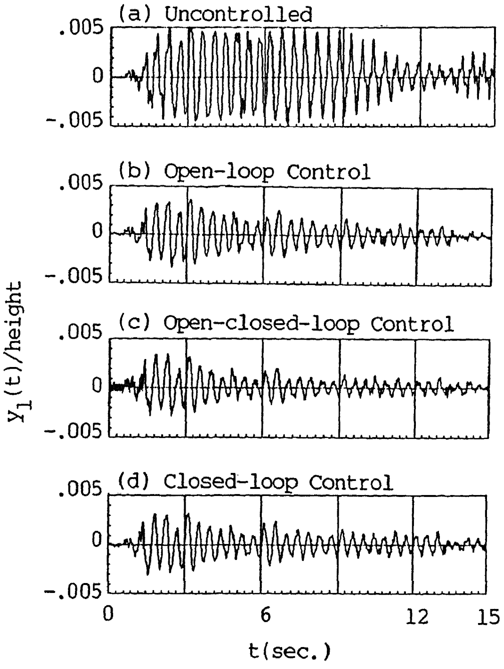

Fig. 6. First-Floor Storydrift Displacements