Research and Development of Active Control Systems

by Tsu T. Soong

Abstract

Research and development of full-scale active control systems has been a main focus of this research project involving researchers and engineers from MTS Systems Corporation of Minneapolis, the Takenaka Corporation and Kayaba Industries of Japan, as well as NCEER researchers. The major objective was to develop two full-scale active systems, an active bracing system and an active mass damper system, so that implementational issues could be identified and addressed, their performance under actual wind loads and earthquakes could be evaluated, and design guidelines for these systems could be developed.

Through a carefully planned analytical and experimental program, this research effort has led to implementation of these systems in full-scale structures. Observed performance of these systems under actual wind and earthquake loads shows that the concept of active control, originated more than 20 years ago, has led to the successful development of active devices for civil engineering structural control.

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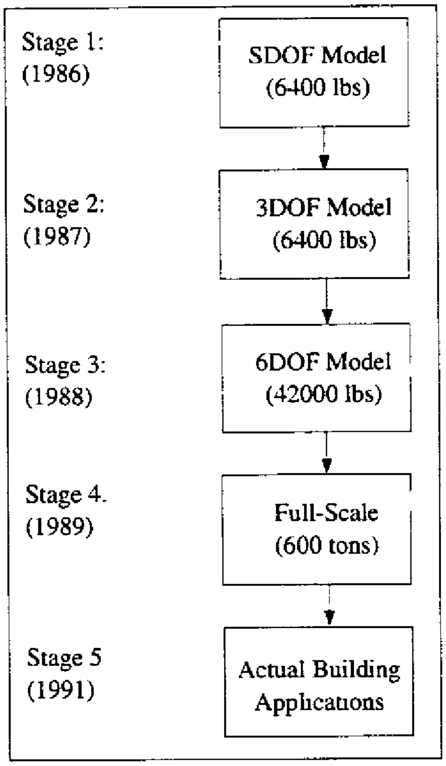
Objectives and Approach

The objective of NCEER's research program in active control systems was to research, design and implement full-scale active bracing systems and active mass damper systems.

The approach to this research was to perform analyses and extensive computer simulations. A comprehensive experimental program was developed, involving structures ranging from simple structural models to full-scale structures.

This research task is part of NCEER's Building Project. Task numbers are 86-3021, 87-2001, 88-2001, 89-2201, 90-2201, 91-5121, 92-5601, and 93-5121.



■ Figure 1 Active control experimental program

Accomplishments

Comprehensive experimental as well as analytical studies began in 1986. A series of carefully planned experimental programs using increasingly complex structural models was carried out. As figure 1 shows, the experiments progressed from Stage 1 with a simple structural model to Stage 4 where a full-scale dedicated test structure was used for testing and performance verification. Furthermore, two systems have been installed in actual buildings (Stage 5 in figure 1) and their performances under actual wind and earthquake loadings are being closely monitored and evaluated.

Stages 1-3

The model structures increased in weight and complexity as the experiments progressed from Stage 1 to Stage 3 so that more control features could be incorporated into the experiments The model structure studied during the first stage was a three-story steel frame modeling a shear building by the method of mass simulation, whose top two floors were rigidly braced to simulate a single-degree-of-freedom system. The model was mounted on a shaking table which supplied the external load. The control force was transmitted to the structure through two sets of diagonal prestressed tendons mounted on the side frame.

Several significant features of these experiments are noteworthy. First, they were carefully designed so that a realistic structural control situation could be investigated. Efforts made towards this goal included making the model structure dynamically similar to a real structure, working with a carefully calibrated model, using realistic base excitation, and requiring more realistic control forces. Secondly, these experiments permitted a realistic comparison between analytical and experimental results, which made it possible to perform extrapolation to real structural behavior. Furthermore, important practical considerations such as time delay, robustness of control algorithms, modeling errors and structure-control system interactions could be identified and realistically assessed (Chung et al., 1988; Chung et al., 1989).

Experimental results showed significant reduction of structural motion under the action of the simple tendon system. For example, a reduction of over 50% of the first-floor maximum relative displacement could be achieved. This is due to the fact that the control system was able to induce damping in the system from a damping ratio of 1.24% in the uncontrolled case to 34.0% in the controlled case (Chung et al., 1988).

At Stage 2, rigid bracings on the top two floors of the model structure were removed in order to simulate a three-degree-of-freedom system. This multi-degree-of-freedom model provided opportunities for study and verification of a number of control features which were not possible in the Stage 1 study. These included modal control, time delay in the modal space, and control and observation spillover compensation. Moreover, further verification of simulation procedures could be carried out, providing added confidence in the use of simulation for extrapolating active control results to more complex situations. Experimental results compared favorably with analytical results obtained under the same conditions and showed that the motion of all three floors can be effectively controlled using a single actuator when control design is carefully carried out.

As a further step in this direction, a substantially larger and heavier six-story model structure was fabricated for Stage 3 of this experimental undertaking. It was also a welded space frame utilizing artificial mass simulation (Reinhorn et al., 1989).

Multiple tendon control was possible in this case and the following arrangements were included in this phase of the experiments.

- A single actuator was placed at the base with diagonal tendons connected to a single floor.

- A single actuator was placed at the base with tendons connected simultaneously to two floors, thus applying proportional control to the structure.

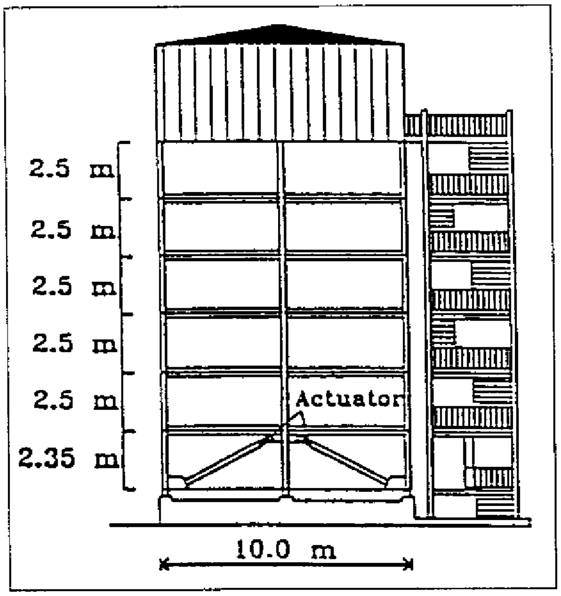
- Two actuators were placed at different locations on the structure with two sets of tendons acting independently.

Another added feature at this stage was the testing of a second control system, an active mass damper, on the same model structure, thus allowing a performance comparison of these two systems. Furthermore, control requirements and control efficiencies realized in this series of experiments were extrapolated to the full-scale case, leading to a preliminary design of the full-scale active bracing system and simulation study in order to assess its performance capabilities when installed in an actual structure (Soong et al., 1991).

Stage 4

Full-scale test structure

A dedicated full-scale test structure was erected for performance verification of an active mass damper and an active bracing system under actual seismic ground motions. Located in Tokyo, Japan, the structure was a symmetric two-bay six-story building as shown in figure 2. It was constructed of rigidly connected steel frames of rectangular tube columns and W-shaped beams with reinforced concrete slabs at each of the floors. Having rectangular columns, the two orthogonal directions were not structurally identical. Weighing 600 metric tons, the structure was designed



■ **Figure 2**
Full-scale structure

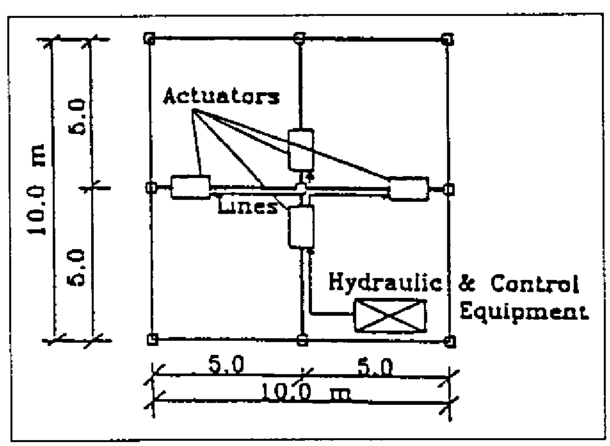
as a relatively flexible structure with a fundamental period of 1.1 seconds in the strong direction and 1.5 seconds in the weak direction, in order to simulate a typical high-rise building The structure was constructed without claddings except for the top story (sixth floor), which housed the active mass damper. Due to lack of cladding and simple connections, the structure has very low damping in the dominant modes (between 0.5% and 1% of critical).

Active Bracing System (ABS)

As shown in figures 2 and 3, the active bracing system (ABS) consisted of solid diagonal tube braces attached at the first story of the building. The control system enabled longitudinal expansion and contraction of the braces by means of hydraulic servocontrolled actuators, inserted between the brace elements and forming an internal part of the bracing system. The control system also included a hydraulic power supply, an analog and digital controller, and analog sensors. Servovelocity seismometers were installed in each principal direction of the building with an output range of ±100 cm/sec. The velocity sensors were located on the ground, at the first, third, and sixth floors of the building. These same sensors could provide acceleration information up to ±1000 cm/sec^2. Additional transducers were mounted at each floor to monitor building behavior. Each actuator was equipped with a displacement transducer (LVDT) which was used to adjust the length of the brace via the servovalve loop. A more detailed description of the active bracing system can be found in Soong et al. (1991) and Reinhorn et al. (1993)

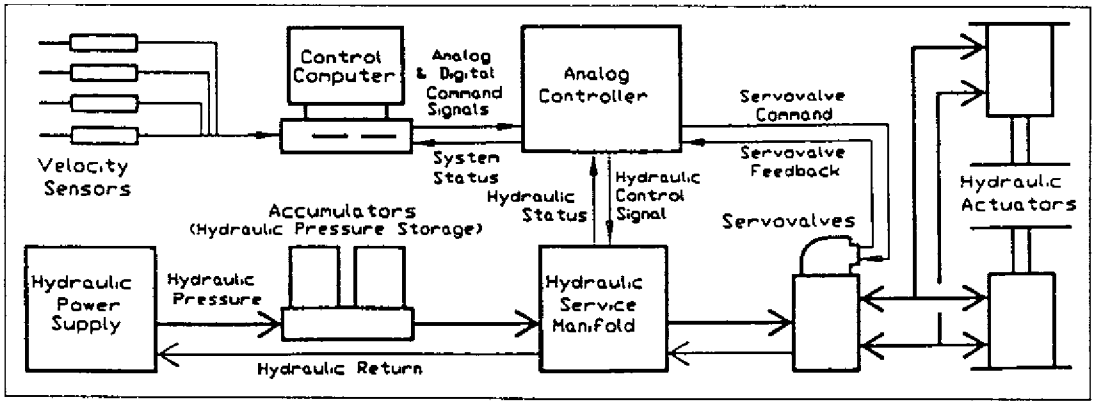
Several important issues had to be addressed in order to ensure safe and efficient operation of the system; one of which dealt with automated control operation. The hydraulic power for the active bracing system needs to be continuously available, yet it is not practical to have the hydraulic system operating constantly. For this reason, the system had to be designed in such a way that the hydraulic system remained in a ready, but dormant state, with the control software capable of bringing the system to full operation. To accomplish this, the control software had to be able to monitor the status of the control hardware, and adjust the state as necessary. In addition, the hydraulic system had to be capable of almost instantly supplying full power to the active braces.

These requirements led to special modifications of the standard control hardware as well as



■ **Figure 3**
Top view of ABS

■ **Figure 4**
Block diagram of ABS



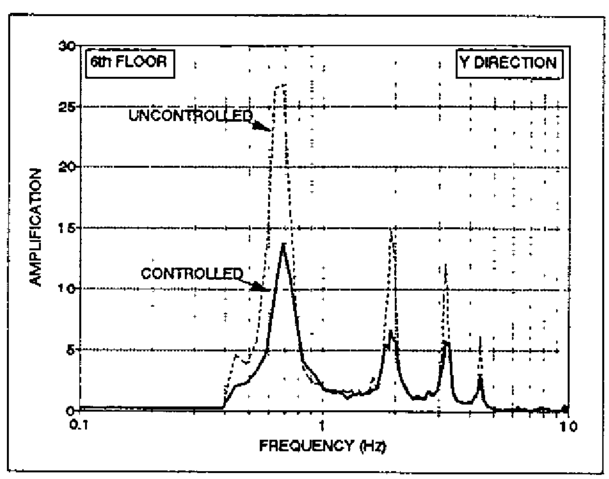
the addition to the control program of subroutines with the logic for starting, stopping, and monitoring the status of the system. A simplified block diagram of the control system hardware is shown in figure 4. The hydraulic power required for rapid starts was stored in the accumulators, which could supply enough power to allow the hydraulic pump to reach full pressure operation The accumulators could also drive the actuators for approximately one minute, longer than most major earthquakes, in the event of a power failure. The ability of the computer to regulate the system was provided through a series of digital connections between the computer and the analog controller. Digital communications allowed the computer to control the hydraulic system, and to monitor the status of the system hardware.

Another important issue is system reliability. In order to properly protect the system and the structure from damage in the event of a full or partial failure of the control system, a number of fail-safes were added to both the hardware and the software.

The long term maintenance of the system is also an important consideration. If strict tolerances are not met, the continuous wear can lead to degradation in the system performance, and even to failure. The standard maintenance must include manual inspection and verification of the system components on a regular basis.

The structure has been subjected to several recent earthquake motions and its response was recorded while the ABS system was automatically activated during each of these episodes. The ground motion was simultaneously recorded and was used with an analytical model to estimate the probable response of the structure in the uncontrolled mode. The responses at several locations of the structure during two recent earthquakes show that the ABS was able to produce a somewhat uniform reduction of modal responses as indicated in the transfer functions shown in figure 5. The controlled response has lower peaks and wider distributions around the peak, indicating damping increase

To validate the analytical procedures used for predicting actual system performance, the observed response was compared with that estimated using the time step analysis and the identified properties of the system. The control forces were estimated using the uncompensated gains. Results show that the differences in the peaks



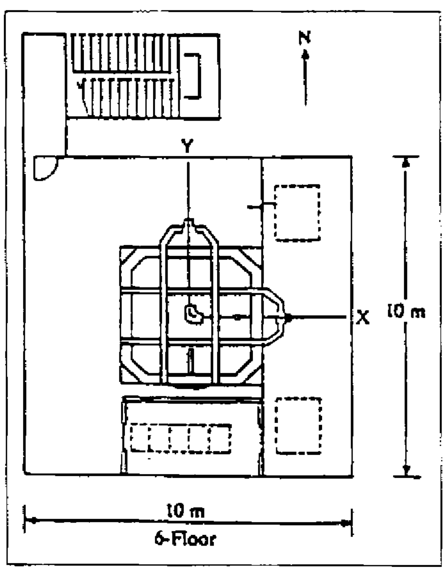
■ **Figure 5**
Acceleration transfer function at sixth floor (April 14, 1992)

are less than 10%, while the RMS differences are less than 2%. Considering inherent imperfections in the structural system, the analytical predictions seem to be adequate for interpreting the structural response and for designing new systems.

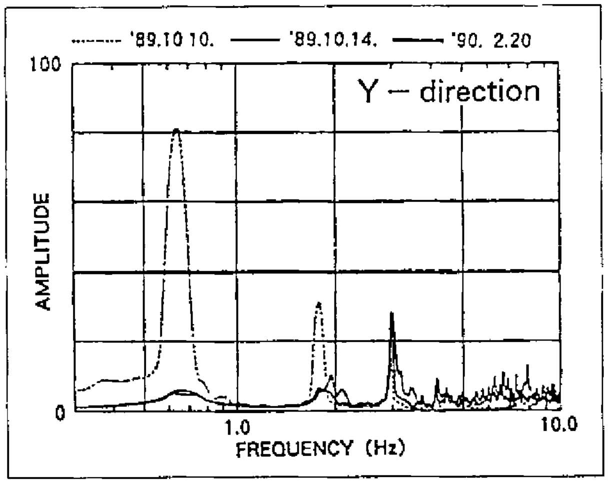
Active mass damper (AMD)

The active mass damper (AMD) was housed in the enclosure on the sixth floor. An outline of this device is shown in figure 6, which consisted of a suspended six-ton mass capable of responding instantaneously to structural vibrations induced by wind or earthquakes. A complete description of the AMD system and some observed results are given by Aizawa et al. (1990). The structural response could be controlled in two directions by two electrohydraulic servoactuators, which were installed along orthogonal directions

While both the ABS and AMD were installed in the same structure, structural control was performed by only one system at a time. The control effect of the AMD system was examined during the Izu-Oshima earthquake on October 14, 1989 and on February 20, 1990. An example of the structural response in the frequency domain is shown in figure 7, where the transfer function recorded on October 10, 1989, is used as an uncontrolled reference.



■ Figure 6
Top view of AMD

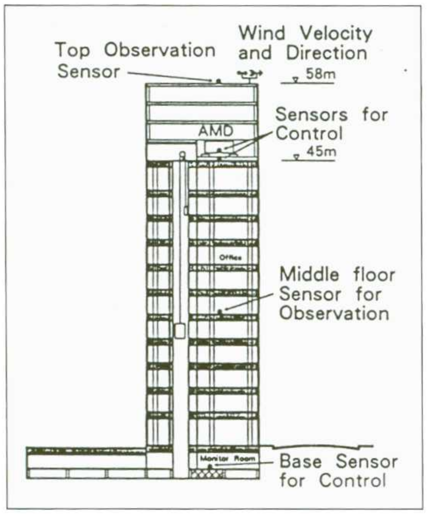


■ Figure 7
Acceleration transfer function at sixth floor

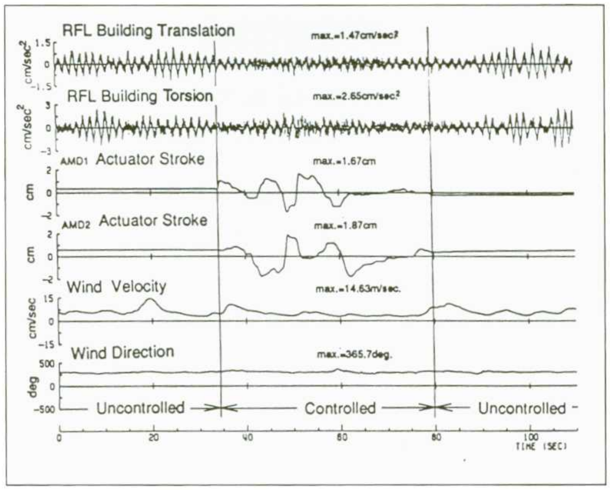
Summarizing the observation results for both control systems, a rough root-mean-square performance comparison of AMD and ABS is shown in table 1. Note that the AMD system has a better reduction of displacement response and a lesser reduction of accelerations. This implies a more comfortable response using the ABS and lesser base shear using the AMD. The maximum actuator movement is an indicator of the required input energy. It is very large for the AMD system and is quite small for the ABS, indicating substantially less energy needed by the ABS. Comparing the response transfer functions shown in figures 5 and 7, it is noted that the AMD reduces the structural response primarily in the lower modes while the ABS system reduces the structural response in all modes, as can be observed in figure 5. The ABS appeared to perform better in redistributing earthquake energy in higher modes and suppress their influence

	AMD	ABS
RMS Reduction of Peak Response.		
- Displacement	56%	29%
- Acceleration	22%	26%
Maximum Actuator Movement (cm)	10.51	0.194

■ Table 1
Comparison of AMD and ABS



■ **Figure 8**
Sendagaya INTES building

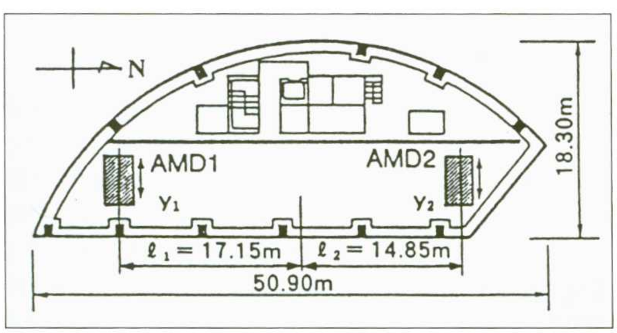


■ **Figure 10**
Response time histories (March 29, 1993)

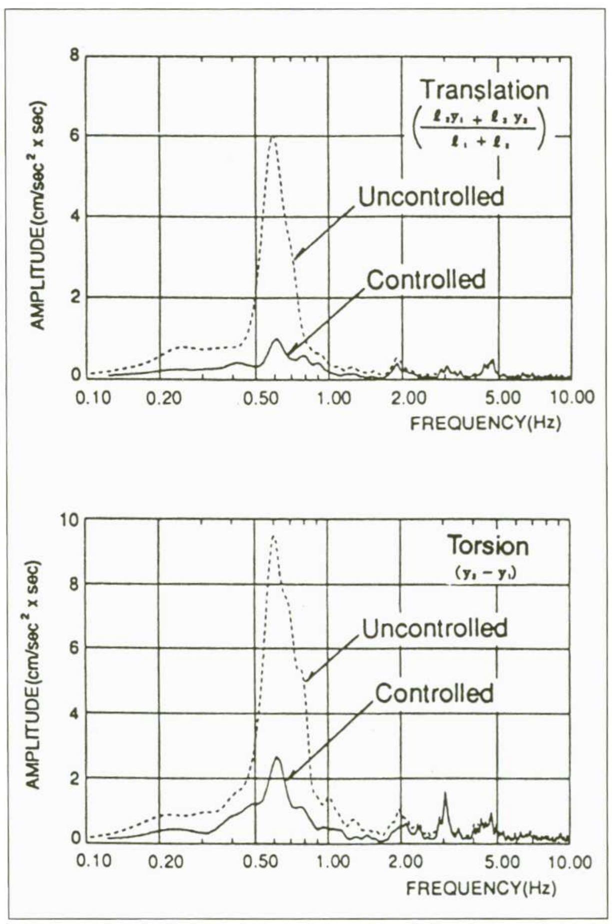
Stage 5

Sendagaya INTES Building

An active tuned mass damper system was installed in the Sendagaya INTES building in Tokyo in 1991. As shown in figure 8, the AMD was installed atop the 11th floor and consists of two masses to control transverse and torsional motions of the structure while hydraulic actuators provide the active control capabilities. The top view of the control system is shown in figure 9 where ice thermal storage tanks are used as mass blocks so that no extra mass is



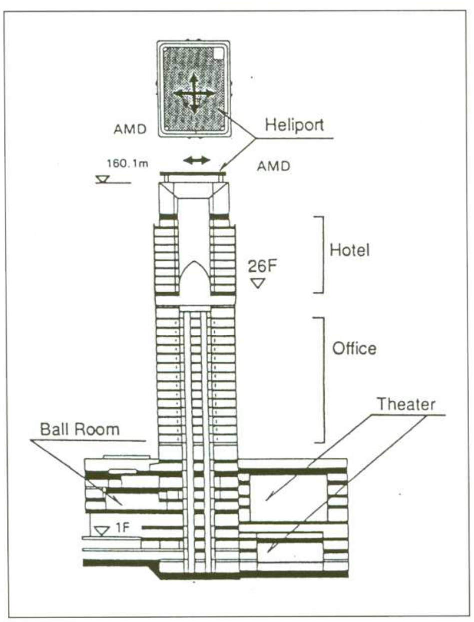
■ **Figure 9**
Top view of AMD



■ **Figure 11**
Response Fourier spectra (March 29, 1993)

introduced. The masses are supported by multi-stage rubber bearings intended for reducing the control energy consumed in the AMD and for insuring smooth mass movements (Higashino and Aizawa, 1993).

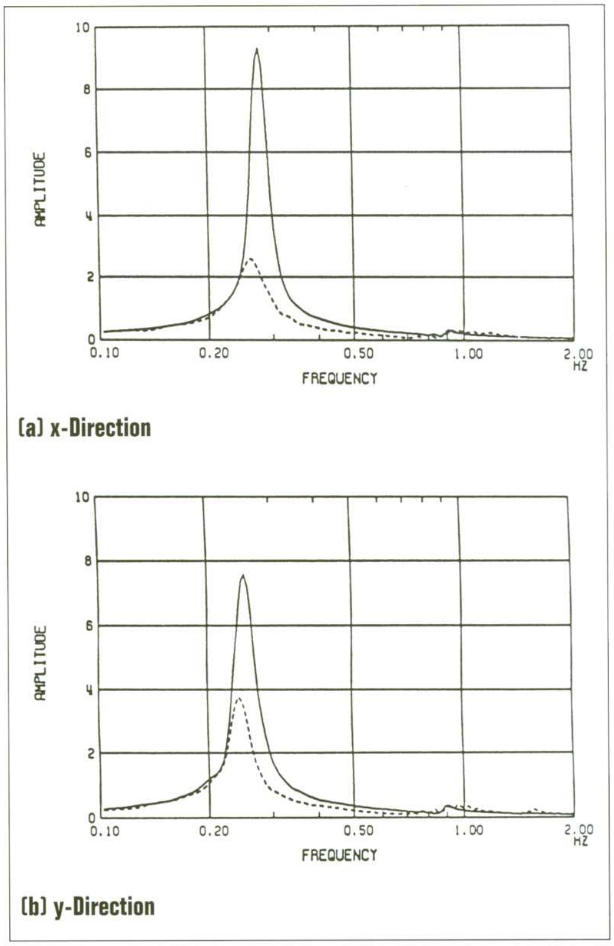
Sufficient data were obtained for evaluation of the AMD performance when the building was subjected to strong wind on March 29, 1993, with peak instantaneous wind speed of 30.6 m/second. An example of the recorded time histories is shown in figure 10, giving both the uncontrolled and controlled states. The Fourier spectra using samples of 30-second durations are shown in figure 11, again showing good performance in the low frequency range but not in the region exceeding 3 Hz. The response at the fundamental mode was reduced by 18% and 28% for translation and torsion, respectively. Similar performance characteristics were observed during a series of earthquakes recorded between May, 1992 and February, 1993.



■ Figure 12
Hankyu Chayamachi building

Hankyu Chayamachi Building

The 160-meter 34-story Hankyu Chayamachi building, as shown in figure 12, is located in Osaka, Japan, where an AMD system was installed



■ Figure 13
Acceleration Fourier spectra

in 1992 for the primary purpose of occupant comfort control. In this case, the heliport at the roof top is utilized as the moving mass of the AMD, which weighs 480 tons and is about 3.5% of the weight of the tower portion. The heliport is supported by six multi-stage rubber bearings. The natural period of rubber and heliport system was set to 3.6 seconds, slightly lower than that of the building (3.8 seconds). The AMD mechanism used here has the same architecture as that of Sendagaya INTES, namely, scheme of the digital controller, servomechanism and the hydraulic design, except that two actuators of 5-ton thrusts are attached in horizontal orthogonal directions. Torsional control is not considered here.

Acceleration Fourier spectra during a recent typhoon are shown in figure 13. Since the building in this case oscillated primarily in its fundamental mode, significant reductions in acceleration levels were observed.

Conclusion

An important observation to be made in the performance observation of these control systems is that efficient active control systems can be implemented with existing technology under practical constraints such as power requirements and stringent demand of reliability. Thus, significant strides have been made considering that serious implementational efforts began less than ten years ago.

The active mass dampers developed for Sendagaya INTES and Hankyu Chayamachi buildings were designed primarily for response control due to wind and moderate earthquakes. An outstanding issue that needs to be addressed is whether such systems, with limited control resources and practical constraints such as mass excursions, can be made effective under strong earthquakes One possible direction is to explore new control algorithms, such as nonlinear control laws, which may be more efficient under energy and other limitations. Reliability is another important consideration, particularly when an active control system designed for strong earthquakes must endure long dormant periods.

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