Structural Control in Honor of Takuji Kobori

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ABSTRACT :

In recent years, considerable attention has been paid to research and development of structural control devices, with particular emphasis on alleviation of wind and seismic response of building and bridges. Serious efforts have been undertaken in the last two decades to develop the structural control concept into a workable technology. Full-scale implementation of active, hybrid, and semiactive control systems have been accomplished in several structures all over the world. Those control systems employ controllable force devices integrated with sensors, controllers and real-time information processing. This paper includes introduce the commonly seen control devices used in active/hybrid and semiactive control systems and review the recent implementation in full-scale structures.

KEYWORDS: Structural control, active/hybrid control systems, semiactive control systems, full-scale control impelemntation.

1. INTRODUCTION

Supplemental passive, active, hybrid, and semiactive damping strategies offer attractive means to protect structures against natural hazards. Passive supplemental damping strategies, including base isolation systems, viscoelastic dampers, and tuned mass dampers, are well understood and are widely accepted by the engineering community as a means for mitigating the effects of dynamic loading on structures. In general, such systems are characterized by their capability to enhance energy dissipation in the structural systems in which they are installed. However, these passive-device methods are unable to adapt to structural changes and to varying usage patterns and loading conditions.

Active, hybrid and semi-active control systems are a natural evolution of passive control technologies, and have been investigated by a number of researchers for more than two decades (Soong 1990; Spencer and Sain 1997; Soong and Spencer 2002; Spencer 2002). Those control systems are force delivery devices integrated with real-time processing evaluators/controllers and sensors within the structure. For example, the first full-scale application of active control to a building was accomplished using two active mass dampers by the Kajima Corporation in 1989 (Kobori et al. 1991).

To increase the overall reliability and efficiency of the controlled structure, the control system employs a combination of passive and active devices, namely a hybrid control strategy (Faravelli and Spencer 2003). Because multiple control devices are operating, hybrid control systems can alleviate some of the restrictions and limitations that exist when each system is acting alone. Thus higher levels of performance may be achievable. To date, there have been over 40 buildings and about 10 bridges that have employed feedback control strategies in full-scale implementations. The vast majority of these have been hybrid control systems.

Despite the impediments that exist to wider application of control to civil engineering structures, the future appears quite bright. Semiactive control strategies are particularly promising in addressing many of the challenges to this technology, offering the reliability of passive devices, yet maintaining the versatility and adaptability of full active systems, without requiring the associated large power sources and can operate on battery power (Spencer and Nagarajaiah 2003). Studies have shown that appropriately implemented semiactive damping systems perform significantly better than passive devices and have the potential to achieve, or even surpass, the performance of fully active systems, thus allowing for the possibility of effective response reduction during a wide array of dynamic loading conditions (Spencer and Sain 1997).

2. Active/hybrid Control Systems

An active structural control basically consists of (a) sensors located about the structure to measure either external excitations, or structural response variables, or both; (b) devices to process the measured information and to compute necessary control force needed based on a given control algorithm; and (c) actuators, usually powered by external sources, to produce the required force. The control configuration is defined as feedback control while only the structural response variables are measured. A feedforward control results when the control forces are regulated only by the measured excitation. In the case where the information on both the response quantities and excitation are utilized for control design, the term feedback-feedforward control is used.

A hybrid control system generally refers to a combined passive and active control system, which is able to increase the overall reliability and efficiency of the controlled structure potentially. Most common active/hybrid control systems always employ AMD and hybrid mass damper (HMD) that are derived from tuned mass damper (TMD) with active capability. Systems of these types have been implemented in a number of tall buildings in recent years in Japan. The AMD system is the pioneer in the implementation of the full-scale building. Due to the design constraints in severe space limitation, the HMD system is substituted to install in building systems. Both systems generate forces from the control actuator to increase the efficiency and the robustness to changes in the dynamic characteristics of the structure. The energy and force required to operate a typical HMD are far less than those associated with a fully AMD system of comparable performance.

To compare with passive control systems, active/hybrid control systems have a number of distinctive features to be addressed: (a) enhanced effectiveness in response control; (b) relatively insensitivity to site conditions and ground motion; (c) applicability to multi-hazard mitigation situations; and (d) selectivity of control objectives. The flexibility of active/hybrid control systems takes the advantages of either reduction on the vibration for human comfort or mitigation on the severe dynamic loading for structural safety; the multiple functionalities of these systems are able to resist the strong wind and earthquakes for different purposes.

3. Semiactive Control Systems

As considered in the power consumption during critically seismic events, a semiactive control system not only improves the requirement of large power sources in the active/hybrid control system but shares the best features of both passive and active/hybrid control systems. The semiactive control system configures with all setups in the active/hybrid control system, but the control devices do not inject mechanical energy directly to the structure. Therefore, in contrast to active control devices, semiactive control devices can be still controlled to optimally reduce the responses of the system without the potential to destabilize the structural system.

One means of achieving a semiactive damping device is to use a controllable, electromechanical, variable-orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper. The concept of applying the variable-orifice dampers to control the motion of bridges under seismic excitation was first proposed in 1990 and widely applied to different types of structures latter including the implementation in a full-scale bridge by Patten et al. (1999). Conceived as a variable-stiffness device, Kobori et al. (1993) implemented a full scale variable orifice damper, using on-off mode, in a semiactive variable-stiffness (AVS) to investigate semiactive control of the Kajima Research Institute building. For the reason of hydraulic fluid compressibility, the prototype AVS cannot vary stiffness continuously between different stiffness states, but later Nagarajaiah (2000) porposed a variable-stiffness device (SAIVS) capable of varying the stiffness independently and continuously. The SAIVS successfully worked in a scaled structural model by varying the stiffness smoothly and producing a nonresonant system.

The advantages and effectiveness of the TMDs have been shown and applied in the active/hybrid control system, but researchers still attempted to convert those active control devices into semiactive ones. Therefore, a semiactive tuned mass damper (STMD), with variable stiffness, that has the distinct advantage of continuously retuning its frequency due to real time control thus making it robust to changes in building stiffness and damping, has been developed by Nagarajaiah (2000) using the SAIVS device. The other approach to semiactive devices is the variable-friction dampers which utilize forces generated by surface friction to dissipate vibratory energy in a structural system. The force at the frictional interface was adjusted by allowing slippage in controlled amounts for bracing systems of structures. Both of them were validated in the control effectiveness through experiments in early 2000's.

Most semiactive dampers are controllable-fluid dampers employing some electrically controlled valves or mechanical to achieve changes in device characteristics. Two fluids that are viable contenders for development of controllable dampers are: (1) electrorheological (ER) fluids and (2) magnetorheological (MR) fluids. However, only MR fluids have been shown to be tractable for civil engineering applications (Carlson and Spencer 1996; Spencer and Sain 1997; Spencer et al. 1997). The MR fluid devices can be readily controlled with a low power (e.g., less than 50 W), low voltage (e.g., 12-24V), current-driven power supply outputting only for 1-2 A. Through simulations and laboratory model experiments, MR dampers have been shown to significantly outperform comparable passive damping configurations, while requiring only a fraction of the input power needed by the active controller. Moreover, Yang et al. (2002) have developed and tested a 20-t MR damper suitable for full-scale application.

4. Full-scale Implementation

41. Active/hybrid Control Implementation

One successful example of the full-scale implementation on HMD system is the Sendagaya INTES building in Tokyo in 1991. As seen in Figure 1, the HMD was installed at top the 11th floor and consists of two masses to control transverse and torsional motions of the structure, while hydraulic actuators provide the active control capability. Those masses are supported by multi-stage rubber bearings intended for reducing the control energy consumed in the HMD and for insuring smooth mass movements. Many similar approaches have been implemented around Japan including multi-step pendulum HMDs in the Yokohama Landmark Tower in Yokohama and the DUOX HMD system in the Ando Nishikicho Building in Tokyo.

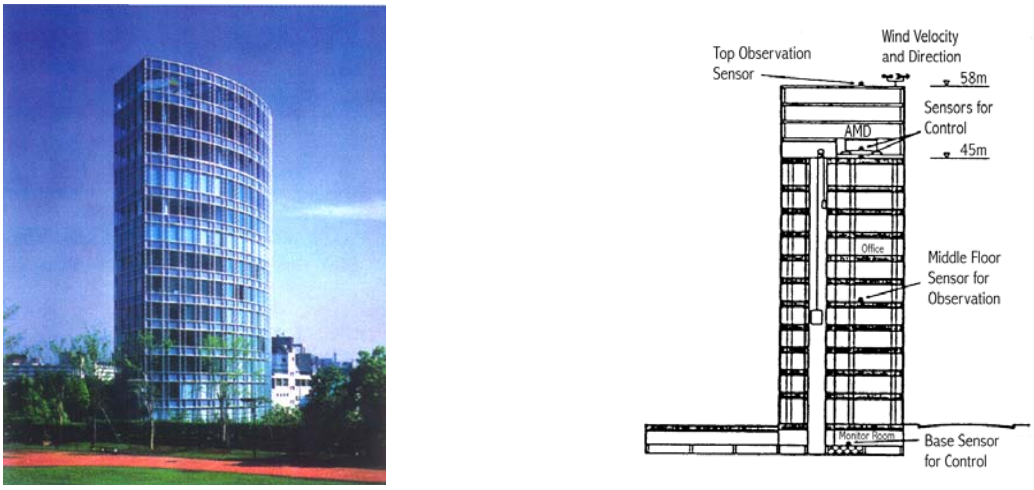

Figure1. Sendagaya INTES Building with hybrid mass dampers.

As for the AMD application, the Kyobashi Seiwa Building in 1989, the first full-scale implementation of active control technology (Kobori et al. 1991), is an 11-sotry building with a total floor area of 423 m^2, shown in Figure 2. The control system comprises two AMDs where primary AMD is used for transverse motion and has a weight of 4 ton, while the secondary AMD has a weight of 1 ton and is employed to reduce torsional motion. The role of the active system is to reduce building vibration under strong winds and moderate earthquake excitations and consequently to increase comfort of occupants in the building. Similarly, China applied a constrained AMD into the Nanjing Communication tower. Several constraints for the AMD system include a ring-shaped floor area for the physical size, steel supports for the floor with Teflon bearings for free access to the floor area, ±750 mm movement allowed from the rest position to maximum. Lack of sufficient lateral space made the use of mechanical springs impractical for restoring forces. Thus the active control actuator provided restoring force as well as the damping control forces.

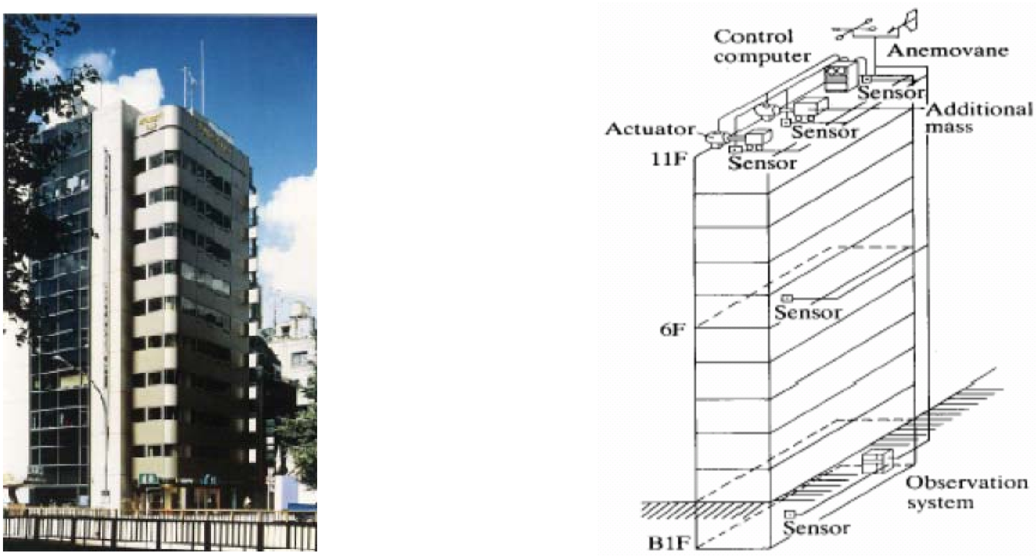

Figure 2. Kyobashi Seiwa Building and AMD.

4.2 Semiactive Control Implementation

The first implementation with the semiactive control devices in a full-scale building is the Kajima Technical Research Institute, shown in Figure 3 (Kobori et al. 1998; Kurata et al. 1999, 2000, 2002). The AVS is a hydraulic device with a bypass valve used to switch the device between the on-off positions to engage and disengage the bracing system. The building's stiffness is varied based on the nature of the earthquake to produce a nonresonant system. The observed responses during severak eartguakes indicate the effectiveness of the AVS system in reducing the structural responses. Also Kobori summarized nine buildings incorporated with semiactive dampers in Japan in 2003. In the United States, the first full-scale implementation of semiactive control was conducted on the Walnut Creek Bridge on interstate highway I-35 to demonstrate variable-damper technology, shown in Figure 4. This experiment constitutes the only full-scale implementation of semiactive control in the United States.

Figure 3. Kajima Technical Research Institute with AVS system.

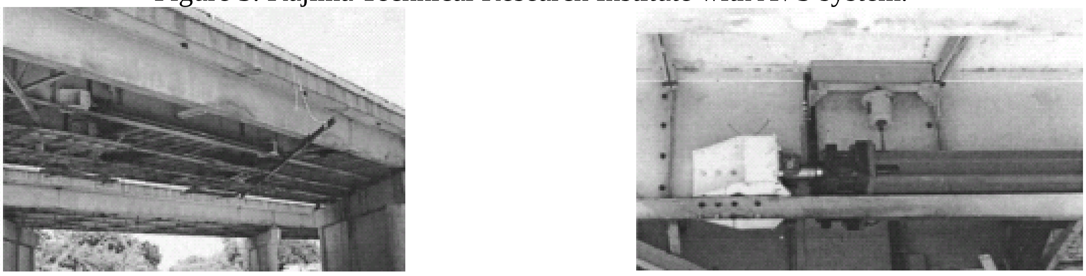

Figure 4. First full-scale implementation of smart damping in the U.S. and SAVA-II variable-orifice damper

The Kajima Shizuoka Building, shown in Figure 5, implemented a smart damping system inside the walls on both sides of the building. Each damper was designed with a flow control valve, a check valve, and an accumulator, and can develop a maximum damping force of 1,000 kN against earthquake disasters. A number of responses under the selected control schemes have been recorded from several seismic events that both story shear forces and story drifts are seen to be greatly reduced with control activated. In the case of the shear forces, they are confined within their elastic-limit values; without control, they would enter the plastic range.

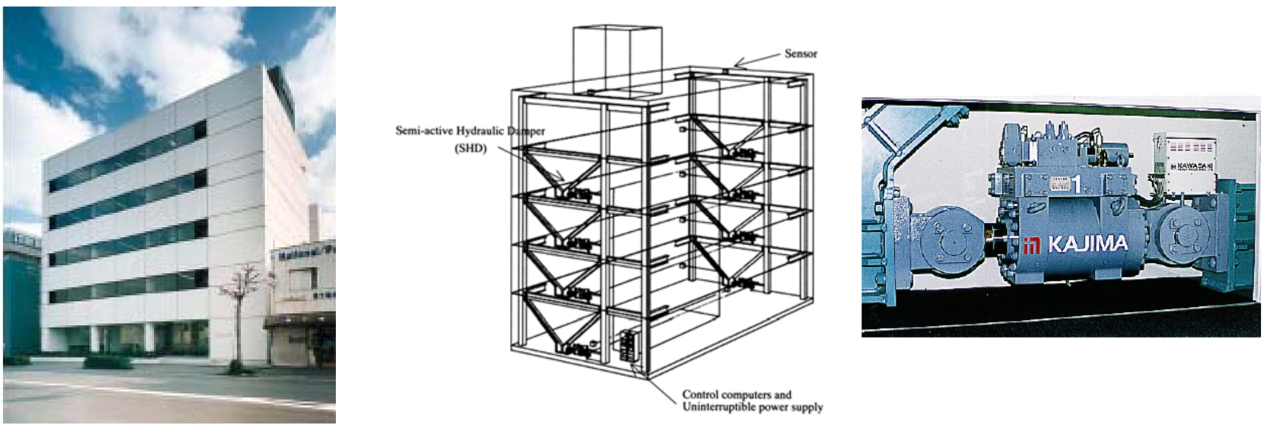

Figure 5. Kajima Shizuoka Building and semi-active hydraulic dampers

MR dampers appeared in the full-scale implementation at the first time in 2001. As shown in Figure 6, the civil engineering applications is the Nihon-Kagaku-Miraikan, the Tokyo National Museum of Emerging Science and Innovation having two 30-t MR fluid dampers installed between the third and fifth floors. The dampers were built by Sanwa Tekki using the Lord Corporation MR fluid. Retrofitted with stay-cable dampers, the Dongting Lake Bridge in Hunan, China constitutes the first full-scale implementation of MR dampers for bridge structures. To mitigate cable vibration, two Lord SD-1005 MR dampers are mounted on each cable that 312 MR dampers on 156 stayed cable, shown in Figure 7.

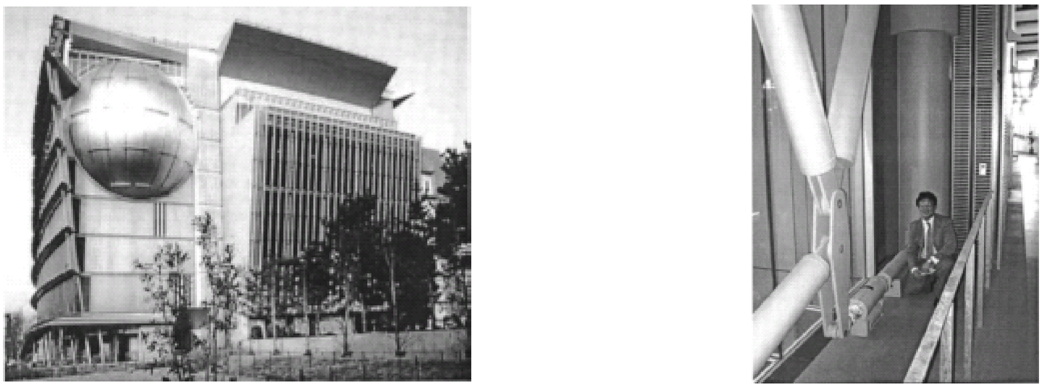

Figure 6. Tokyo National Museum of Emerging Science and Inoovation and 30-t MR fulid damper.

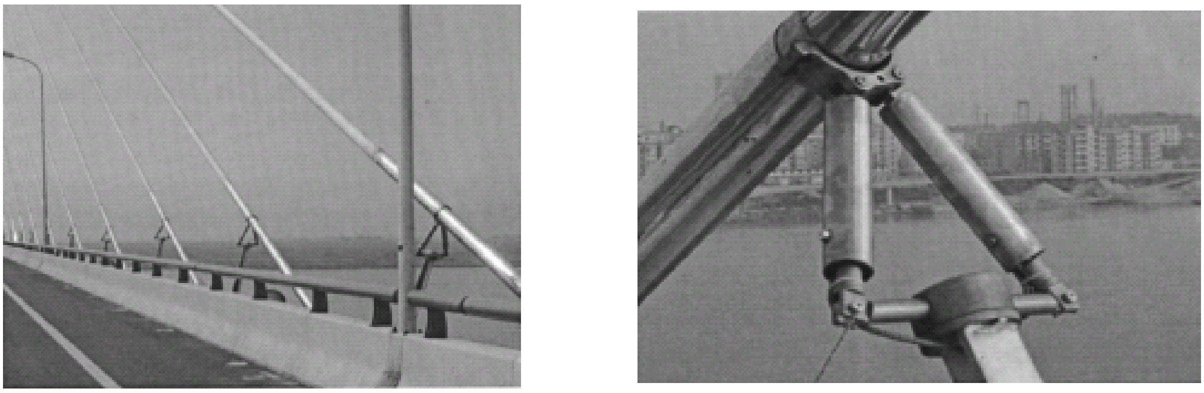

Figure 7. MR damper installed on the Dongting Lake Bridge in China.

4.3 Smart Control Implementation

Passive base isolation is also widely accepted for protection on structures against strong earthquakes. All three types of seismic isolation systems, which are very effective in protecting structures from strong earthquakes, are lead-rubber bearing system, high-damping bearing system, and friction-pendulum spherical sliding bearings. The passive base isolation systems have been concerned to protect structures against near-source, high-velocity, long period pulse earthquake. However, an alternative solution may be to use smart dampers, such as MR dampers (Yoshida et al. 1994; Spencer et al. 2000; Ramallo et al. 2002). In 2000, the world's first smart base isolation building was constructed at the Keio University School of Science and Technology in Japan. The office-and-laboratory building employs variable-orifice dampers in parallel with traditional damping mechanisms. In 2003, 40-t MR fluid dampers, shown in Figure 8, were installed in a residential building in Japan along with laminated rubber bearings, lead dampers, and oil dampers to provide the best seismic protection.

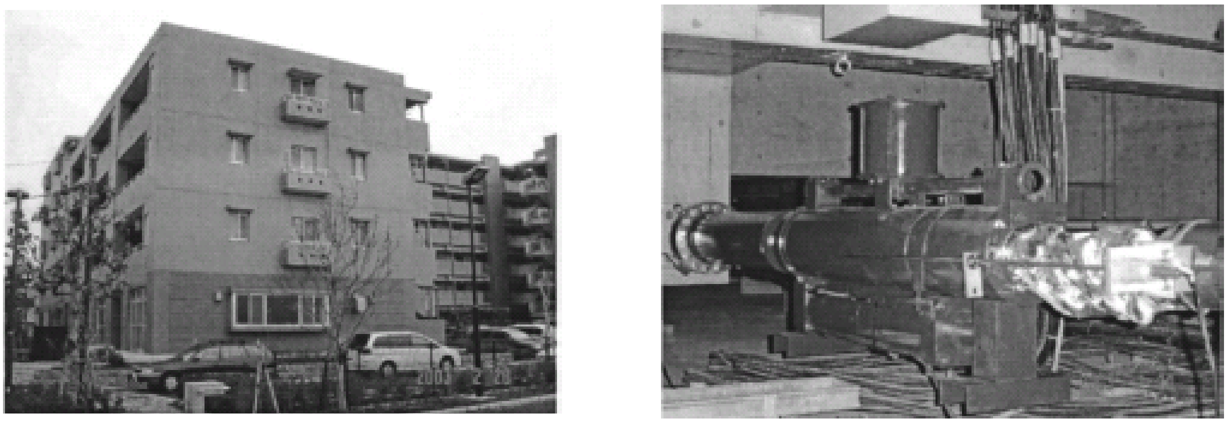

Figure 8. Smart isolation system installed with MR damper in a building.

4. Conclusions

Structural control technology offers many new ways to protect structures from natural and other types of hazards. In the context of earthquake engineering, one of the goals for active control application was the desire that, through active control, conventional structures can be protected against infrequent, but highly damaging earthquakes. The active control devices currently deployed in structures and towers were designed primarily for performance enhancement against wind and moderate earthquakes and, in many cases, only for occupant comfort. An upgrade of current active systems to this higher level of structural protection is necessary, since only then can the unique capability of active control systems be realized. Therefore, collaboration on a global scale is essential and must be nurtured and reinforced.

The deployment of active control systems would add economy and flexibility to structural design and construction. An active structure is defined as one consisting of two types of load resisting members, capability to support static design loads and to resist extraordinary dynamic loads. The integration is done in an optimal fashion and produces a structure that is adaptive to changing environmental loads and usage. Note that an active structure is conceptually and physically different from a structure that is actively controlled. In the case of a structure with active control, a conventionally designed structure is supplemented by an active control device that is activated whenever necessary in order to enhance structural performance under extraordinary loads. Thus, the structure and the active control system are individually designed and optimized. An active structure, on the other hand, is one whose active and passive components are integrated and simultaneously optimized to produce a new breed of structural systems. Among many possible consequences, one can envision greater flexibilities which may lead to longer, taller, slender or more open structures and structural forms.

To combine the best features of both passive and active control systems and offer a viable means of protecting civil engineering structural systems against earthquakes and wind loading, the semiactive structural control technology is gradually accepted for structural design and retrofit in real implementations. The semiactive control systems always provide the reliability and fail-safe character of passive devices, yet possess the adaptability of fully active devices. Because of their mechanical simplicity, low power requirements and high force capacity, MR dampers constitute a class of smart damping devices that mesh well with the demands and constraints of civil infrastructure applications and are seeing increased interest from the engineering community.

A number of aspects of the semiactive and smart damping control problem merit additional attention. One particularly important area is system integration. Structural systems are complex combinations of individual structural components. Integration of semiactive and smart damping control strategies directly into the basic design of these complex systems can offer the optimal combination of performance enhancement versus construction costs and long-term effects, particularly in the case of resisting earthquake loadings. Because of the intrinsically nonlinear nature of semiactive and smart damping control devices, development of output feedback control strategies that are practically implementable and can fully utilize the capabilities of these unique devices is another important and challenging task. Once the advantages of semiactive and smart damping control systems are fully recognized, a primary task is the development of prototype design standards or specifications complementary to existing standards.

REFERENCES

Carlson, J. D., and Spencer, B.F., Jr. (1996). "Magneto-rheological fluid dampers for semi-active seismic control." *Proc., 3rd Int. Conf. on Motion and Vibration Control*. **III**, 35-40.

Faravelli L., and Spencer, B. F., Jr., eds. (2003). *Proc., Sensors and Smart Structures Technology*, Wiley, New York.

Kobori, T. (2003). "Past, present and future in seismic response control in civil engineering structures." *Proc., 3rd World Conf. on Structural Control*, Wiley, New York, 9-14.

Kobori, T., Inou, Y., Seto, K., Iemura, H., and Nishitani, A., eds. (1998). *Proc., 2nd World Conf. on Structural Control*, Wiley, New York.

Kobori, T., Koshika, N., Yamada, N., and Ikeda, Y. (1991). "Seismic response controlled structure with active mass driver system. Part1: Design." *Earthquake Eng. Struct. Dyn.*, **20**, 133-139.

Kobori, T., Takahashi, M., Nasu, T., Niwa, N., and Ogasawara, K. (1993). "Seismic response controlled structure with active variable stiffness systems." *Earthquake Eng. Struct. Dyn.*, **22**, 925-941.

Kurata, N., Kobori, T., and Koshika, N. (2002). "Performance-based design with semiactive control technique." *Earthquake Eng. Struct. Dyn.*, **31**,445-458.

Kurata, N., Kobori, T., Takahashi, M., Ishibashi, T., Niwa, J., Tagami, J., and Midorikawa, H. (2000). "Forced vibration test of a building with semiactive damper system." *Earthquake Eng. Struct. Dyn.*, **29**, 629-645

Kurata, N., Kobori, T., Takahashi, M., Niwa, N., and Midorikawa, H. (1999). "Actual seismic response controlled building with semiactive damper system." *Earthquake Eng. Struct. Dyn.*, **28**, 1427-1447.

Nagarajaiah, S., and Varadarajan, N. (2000). "Novel semiactive variable stiffness tuned mass damper with real time tuning capability." *Proc., 13th Engineering Mechanics Conf.* (CD ROM), Reston, Va.

Patten. W., Sun, J., Li, G., Kuehn, J., and Song, G. (1999). "Field test of an intelligent stiffener for bridges at the I-35 Walnut Creek bridge." *Eathquake Eng. Struct. Dyn.*, **28**(2), 109-126.

Ramallo, J. C., Johnson, E. A., and Spencer, B. F., Jr. (2002). "Smart base isolation systems." *J. Eng. Mech.*, **128**(10), 1088-1099.

Soong, T. T. (1990). *Active structural control: Theory and practice*, Longman Scientific, Essex, U.K.

Soong, T. T., and Spencer, B. F. (2002). "Supplementary energy dissipation: State-of-the-art and state-of-the-practice." *Eng. Struct.*, **24**, 243-259.

Spencer, B. F., Jr. (2002). "Civil engineering applications of smart damping technology." *Proc. 5th Int. Conf. on Vibration Engineering*, Nanjing, China, 771-782.

Spencer, B. F., Jr., and Sain, M. K. (1997). "Controlling buildings: A new frontier in feedback." *IEEE Control Syst. Mag.*, **17**(6), 19-35.

Spencer, B. F., Jr., and Dyke, S. J., Sain, M. K., and Carlson, J. D. (1997). "Phenomenological model of a magnetorheological damper." *J. Eng. Mech.*, **123**(3), 230-238.

Spencer, B. F., Jr., Yang G., Carlson, J. D., and Sain, M. K. (1999). "'Smart' dampers for seismic protection of structures: A full-scale study." *Proc., 2nd World Conf. Structural Control*, Vol. **1**, Wiley, New York, 417-426.

Spencer, B. F., Jr. and Nagarajaiah S. (2003). "State of the art of structural control." *J. Struct. Eng.*, **113**(3), 845-856.

Yoshioka, H., Ramallo, J. C., and Spencer, B. F., Jr. (2002). "'Smart' base isolation strategies employing magnetorheological damper." *J. Struct. Eng.*, **128**(5), 540-551.