SEMI-ACTIVE CONTROL OF STRUCTURAL SYSTEMS

Anil K. Agrawal
The City College of City University of New York, USA.

Young-Jin Cha
Massachusetts Institute of Technology, Cambridge, USA.

Zhou Xu
Weidlinger Associates, 375 Hudson St., New York, USA

Keywords: Structural Control, Semi-active Control System, Passive Control System, Active Control System, Energy-dissipation

Contents

Summary

Vibration response control of civil engineering structures subjected to natural hazards, e.g., earthquakes, wind, etc., using smart protective systems, classified as passive, semi-active and active control systems, has been investigated extensively during last two decades. Semi-active control systems possess reliability of passive systems and adaptability of semi-active systems, and have shown tremendous potentials in protecting infrastructures against natural hazards. This paper presents a detailed literature review on the state-of-the-art and the state-of-practice of semi-active control devices and control algorithms. A brief description of important semi-active control devices, such as semi-active stiffness dampers and semi-active variable dampers, controllable friction dampers and controllable fluid dampers, such as ER and MR dampers, and numerous control algorithms based on the state-of-the-art review has been presented. A comparative performance of these devices is illustrated through an example of application of various semi-active controllers in a six story building. A brief case study of applications of various semi-active devices in new and existing civil engineering structures is also presented. Finally, a brief discussion on future research issues and needs important for facilitating practical implementation of semi-active devices/control algorithms is presented.

1. Introduction

Significant progress has been made during last few decades in the research and development of structural control and seismic protective systems technologies to alleviate structural responses due to natural hazards such as earthquakes, strong winds, etc. As a result of this, numerous control algorithms and devices have been investigated by Soong (1990); Housner et al (1997); Soong and Spencer (2002). Depending on the extent of external power supply required for operation of the device, these control devices are generally classified into three broad categories: passive, active, and semi-active systems. A combination of two different control devices (e.g., passive and active, passive and semi-active) simultaneously to improve effectiveness and reliability of control systems is called “Hybrid Control System”. During last two decades, many of these control devices have been implemented in new and existing structures by Spencer and Nagarajaiah (2003).

A passive control system, the most basic and reliable control system, uses material’s yielding force, viscosity of fluid or friction force to dissipate energy which are defined by Soong and Dargush (1997); Constantinou et al (1998). Some of the commonly used passive control systems are passive energy dissipation devices, passive base-isolation system and passive tuned mass damper systems based on Soong and Spencer (2002); Spencer and Nagarajaiah (2003). Examples of passive energy dissipation devices include metallic yielding dampers developed by Skinner et al (1975); Kelly et al (1972), friction damper and viscous and viscoelastic dampers and have been used widely during recent years to protect structures from destructive effects of earthquakes by Pall and Marsh (1982); Makris and Constantinou (1991); Li and Reinhorn (1995).

Active control systems require large external power supply to generate desired / required control force based on a control algorithm utilizing measured response quantities/excitations to calculate appropriate control signal which is used to drive hydraulic actuators. The definition of active control system is defined by Soong (1990); Soong and Constantinou (1994). Typical active control algorithms to calculate feedback control forces are LQG/H2/H_∞ control investigated by Suhardjo et al (1990); Spencer et al (1993); Yang et al (1996), sliding mode control investigated by Yang et al (1994); Yang et al (1995), optimal polynomial control studied by Agrawal and Yang (1996); Yang et al (1996); Cha and Agrawal (2013a) and fuzzy logic and artificial neural network based control investigated by Nagarajaiah (1994); Battaini et al (1998); Symans and Kelly (1999). Active control system can adjust the control force according to the scale of external excitations and structural responses. Although active control systems have been found to be the most effective among three categories of structural control systems because of their ability to obtain desired level performance, they can also destabilize the structural system by adding energy because of limitations, such as system uncertainties, time lags, measurement errors, sensor/actuator malfunctions, etc. In addition, large power supply required by these systems may not be available during strong earthquakes. Active control systems also require regular maintenance by expert technicians.

A semi-active control system typically requires smaller external power source and utilizes the motion of the structure to develop control forces through parametric control of the device, e.g., opening and closing of orifice of a passive fluid damper investigated by Reid (1956); Dyke and Spencer (1997); Dyke et al (1996). The device can continue to function in passive mode in the event of power failure. Hence, semi-active control systems can achieve control effect similar to a fully active system and significantly better those of passive system, while eliminating the concern of causing any instability in the structural system. Similar to active control systems, control forces in semi-active control systems are based on the feedback from the structural responses measured by sensors. A schematic diagram of a typical semi-active control system is shown in Figure 1.

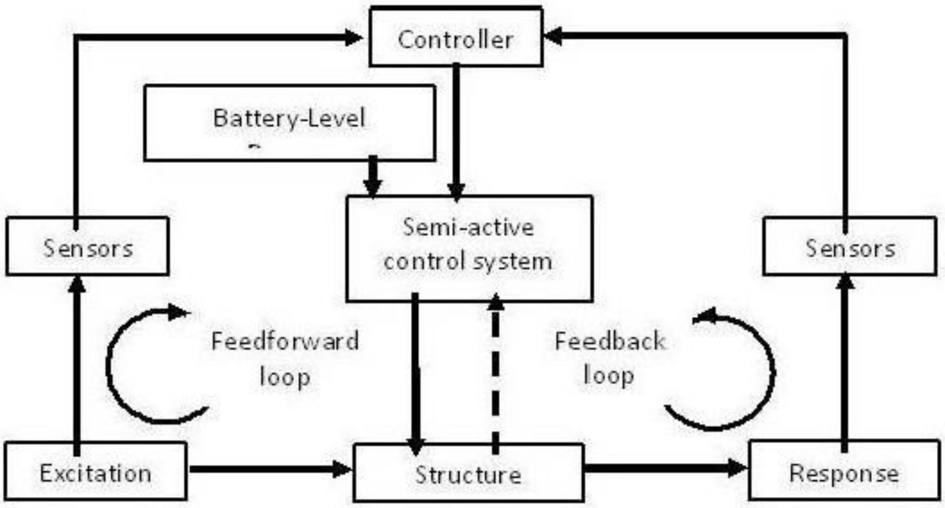

Figure 1. Schematic diagram of a semi-active control system.

Control mechanisms in all semi-active control devices are based on parametric control of device properties, such as size of the orifice in fluid viscous dampers, normal force in semi-active friction dampers, and current/voltage in magnetorheological (MR) dampers. Some of the studies were conducted by Dyke and Spencer (1997); Dyke et al (1996). Semi-active systems only require battery-level external power sources for operating the device. In numerical simulations utilizing different devices and controllers, semi-active control strategies can be realized by (i) directly applying friction-type restraints to passive devices, e.g., sequential controller developed by Stammers and Sireteanu (1998), modulated homogenous friction controller developed by Inaudi (1997); He et al (2003), visco-elastic fluid controller developed by Chen and Chen (2000), (ii) by applying semi-active dissipative restraints to active controllers, e.g., clipped optimal control developed by Dyke and Spencer (1997), and (iii) by applying friction type restraints to active controllers investigated by Xu et al (2006).

2. Semi-Active Control Systems: Devices

Majority of semi-active devices can be broadly classified into four types: (i) Hydraulic dampers (ii) Controllable friction dampers (iii) Controllable fluid dampers and (iv) Semi-active tuned mass dampers. A brief description of these devices is presented in the following.

2.1. Hydraulic Dampers

The hydraulic damper consists of a cylinder – piston system with a valve in the by-pass pipe connecting two sides of the cylinder as shown in Figure 2. It can be used both as passive and semi-active control device either by opening or closing the valve in the bypass of the cylinder, or by increasing / decreasing the size of the orifice in the cylinder bypass. The equivalent stiffness of the entire device, denoted by k_{hi}, is given as $k_{\mathrm{hi}} = k_{\mathrm{f}} k_{\mathrm{b}} (k_{\mathrm{f}} + k_{\mathrm{b}})^{-1}$, where k_{b} and k_{f} are stiffness of the bracing and stiffness of the compressed oil (because of bulk modulus of the fluid), respectively.

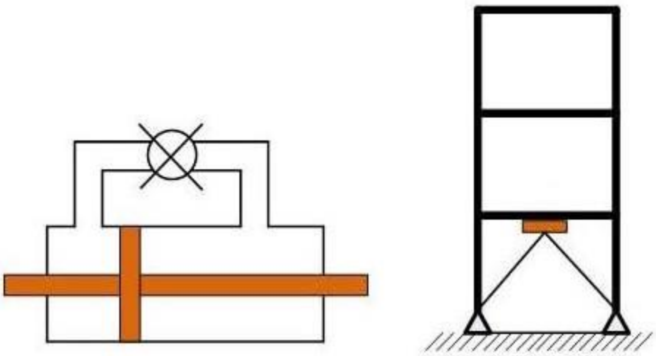

Figure 2. Schematic diagram of the hydraulic damper and building model

The damper provides stiffness to the structure because of bulk modulus of the fluid in the cylinder when the valve is closed, and provides damping to the structure because of head loss during the movement of the fluid when the valve is open. In actual application, when the valve is either always open or closed, the hydraulic damper is operated in passive mode. In this mode, the device adds constant stiffness k_{hi} to the story unit when the valve is closed and adds small damping to the structures when the valve is open. In semi-active control mode, the damper can either be operated to add variable stiffness (i.e., semi-active stiffness damper) or variable damping (semi-active variable damper) developed by Yang et al (2007).

2.1.1. Semi-Active Stiffness Dampers

Generally a hydraulic damper is connected to a bracing or replaces x-bracing in selected location of each story in order to add stiffness. As a variable stiffness device, two distinctive control modes can be operated on the damper. The first control mode is to pulse the valve open and close quickly at appropriate time instants, referred to as resetting control. In this mode, the valve is generally closed and the damper acts as a stiffness element, except during the resetting period (i.e., when the valve is opened and then closed quickly). Through such operations, energy from the vibrating system is dissipated after being transferred to the motion of oil. The hydraulic damper controlled through the resetting control approach is generally termed as resetting semi-active stiffness damper (RSASD) developed by Thai et al (1995); Jabbari (1997). The second control mode, referred to as switching control, is to open and close the valve in certain time interval according to certain control logic.

The performance of a full-scale RSASD device has been investigated on a large scale building model at the National Center of Earthquake Engineering Research (NCREE), Taiwan. The large scale RSASD installed in the first story of a 3-story large scale building model. Instead of the hydraulic fluid, the pressurized gas has been used in the full-scale model of RSASD for an easy adjustment of the stiffness of the RSASD by changing the gas pressure.

It has been observed that the theoretical stiffness of the RSASD is linearly related to the gas pressure. It also has been observed from experimental results that the full-scale RSASD is significantly effective in reducing the peak drifts, root mean square values and inter-story drifts of the building subjected to near-field earthquakes. However, it is less effective in reducing peak floor accelerations. The RSASD device has strong advantage in its schematic simplicity in comparison with other semi-active control devices such as MR dampers since the device consists of a hydraulic cylinder and a valve, which are standard mechanical components available readily and inexpensively. Moreover, the control law is also quite simple and decentralized, i.e., it utilizes displacement and velocity across the damper only) and is robust with respect to structural uncertainties. Consequently, the system reliability and total cost of the RSASD compare favorably with any other semi-active control system.

The performance of switching type semi-active dampers, widely known as active variable stiffness (AVS), has been investigated extensively by Yamada and Kobori (2006). This AVS system can change structure's stiffness and reduce its response by preventing resonant response against earthquake loads by utilizing a small power source. This AVS system has been operational in three-story building in Tokyo during last ten years. The building has been subjected to over 30 earthquakes during this period. From the analysis of recoded data, it has been demonstrated that the AVS system is highly reliable and easily maintainable.

2.1.2. Semi-Active Variable Dampers

Hydraulic dampers are sometimes used as semi-active fluid viscous dampers to add variable damping to the structure by increasing or decreasing the size of the orifice in the bypass valve with respect to a nominal value of the orifice. Therefore, the damping force increases with a decrease in the size of orifice until the pressure in the servovalve reaches a specified value after which the damping force becomes constant. During motion across the damper device, the fluid within the damper is forced to pass through small orifices at high speeds. The output force is modulated by the bypass control servovalve that connects the two sides of the cylinder. The servovalve as pressure relief device opens when the oil pressure through the valve exceeds a specified value. Energy dissipation in this device occurs because of head loss when oil flows from one side of cylinder to the other side of cylinder through the orifice (i.e., from low to high velocity through the orifice and from high to low velocity from the orifice to other side of the cylinder).

The semi-active fluid viscous dampers for structure control using shaking table test or through applications to existing structures have been investigatged by Yang et al (1995); Kawashima et al (1992); Symans et al (1994); Kurata et al (1994). A 200 kN prototype semi-active damper with a stroke of ±13 cm, a length of about 1.2 m, and valve operation power 50 W, was tested by Symans and Constantinou (1999). Two servovalves independently control the fluid flow for relative piston head motion to the left or right. The semi-active device behaves essentially as an adjustable force device with hysteretic-type damping. However, the device dissipates very little energy in the event of power failure without having fail-safe mode of operation. This type of semi-active damper has been used during reduced-scale shaking table tests of a seismically isolated single-span bridge structure with plan dimension of 7.6 m × 2 m, bridge piers of height of 1.6 m, weight of 390 kN and supported by four rubber bearings. The damper has been installed between the deck and one of the piers. It has been observed that the semi-active damper achieved approximately 46 % reduction in deck acceleration and 86 % reduction in the deck displacement.

Another semi-active fluid damper system consisting of a stainless steel piston rod, a bronze piston head, a piston rod make-up accumulator, thin silicone oil and an external bypass loop containing a servovalue has also been tested experimentally. This damper has been tested in two different configurations: (i) a two-stage damper utilizing a solenoid valve, and (ii) a variable damper utilizing a servovalve. The variable damper servovalve contains a spool position feedback system and is driven by an electric motor.

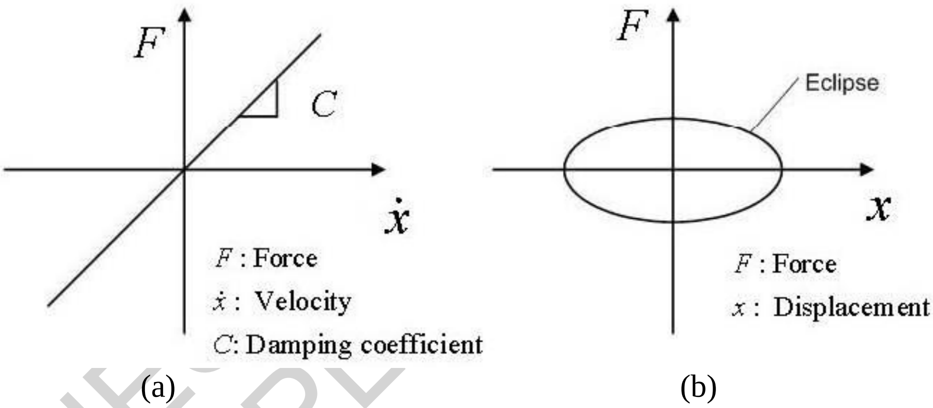

Figure 3. Behavior of linear viscous dashpot as described (a) in the force-velocity plane and (b) in the force-displacement plane

For this semi-active device, a simple analytical model was proposed consisting of a linear viscous dashpot with a voltage dependent damping coefficient, $C(V)$ The damper force F, is expressed by

$$F = C(V)\dot{x} \tag{1}$$

where $\dot{x}$ is the velocity across the damper, and V is the command voltage. Based on experiments for both sinusoidal and constant velocity cyclic testing over a frequency range from 0.25 to 4 Hz, the relationship between the semi-active damper command signal and the damping coefficient is obtained by Symans and Constantinou (1999) and shown in Figure 3. It is observed from the testing results that the damping coefficient can be estimated by fitting a linear curve through the experimental data for semi-active damper with command voltage levels between 0.75 and 2.25 V. The behavior of semi-active viscous dampers in the force-velocity plane is idealized in Figure 3(a) and the corresponding elliptical hysteresis curve (in the force displacement plane) is shown in Figure 3(b). Linear visco-elastic Maxwell models have been proposed by Symans and Constantinou (1995, 1997) for describing the damper behavior over a wider frequency range

-

-

-

Bibliography

[1]. Soong T.T. (1990). *Active Structural Control: Theory and Practice*, Longman, England and Wiley, New York, NY. [This presents active control theories and applications to structures]

[2]. Housner G.W., Bergman L.A., Caughey T.K., Chassiakos A.G., Claus R.O., Masri S.F., Skelton R.E., Soong T.T., Spencer Jr. B.F. Yao T.P. (1997). Structural control: Past, present, and future. *Journal of Engineering Mechanics*, ASCE 123(9), 897-971. [This presents overviews of structural control]

[3]. Soong T.T. Spencer Jr B.F. (2002). Supplemental energy dissipation: state-of-the-art and state-of-the practice. *Engineering Structures* 24, 243-259. [This presents supplemental energy dissipation based structural control]

[4].Spencer Jr B.F., Nagarajaiah S (2003). State of the Art of Structural Control. *Journal of Structural Engineering* 845-856. [This presents overviews of structural control]

[5]. Soong T.T., Dargush G.F. (1997). Passive energy dissipation systems in structural engineering. Wiley. [This presents overviews of structural control]

[6] Constantinou M.C., Soong T.T., Dargush G.F. (1998). Passive energy dissipation systems for structural design and retrofit. Buffalo, N.Y., Multidisciplinary Center for Earthquake Engineering Research, Monograph series, 299 (530 C66). [This presents overviews of structural control]

[7]. Skinner R.I., Kelly J.M., Heine A.J. (1975). Hysteresis dampers for earthquake-resistant structures, *Earthquake Engineering & Structural Dynamics* 3, 287-296. [This presents passive energy dissipating devices including metallic yielding dampers]

[8]. Kelly J.M., Skinner R.I., Heine A.J. (1972). Mechanisms of energy absorption in special devices for use in earthquake resistant structures. *Bull. N.Z. National Society of Earthquake Engineering* 5(3), 63-88. [This also presents passive energy dissipating devices including metallic yielding dampers]

[9]. Pall A.S., Marsh C. (1982). Response of Friction Damped Braced Frames, *Journal of the Structural Division* ASCE, 1208(ST6), 1313-1323. [This presents friction damper based control]

[10]. Makris N., Constantinou M.C. (1991). Fractional derivative Maxwell model for viscous damper. *Journal of Structural Engineering*, ASCE 117(9), 2708–2724. [This presents a fractional derivative Maxwell model for viscous damper]

[11]. Li C., Reinhorn A.M. (1995). Experimental and Analytical Investigation of Seismic Retrofit of Structures with Supplemental Damping, Part II-Friction Devices. Report NCEER-95-0009, NCEER, State Univ. of New York at Buffalo. [This presents experimental and analytical investigation of control]

[12]. Soong T.T., Constantinou M.C. (Eds.) (1994). *Passive and Active Structural vibration Control in Civil Engineering*. Springer-Verlag, Wien and New York. [This presents passive and active control in civil structures]

[13]. Suhardjo J., Spencer B.F., Sain M.K. (1990). Feedback–feedforward control of structures under seismic excitation. *Structural Safety* 8, 69–89. [This presents an example of active control]

[14]. Spencer B.F., Sain M.K., Won C-H., Barroso L.M. (1993). Analysis of Structural control Robustness, Reliability Methods, *Probabilistic Structural Mechanics: Advances in Structural Reliability Methods*, 504. [This presents an example of active control]

[15]. Yang J.N., Wu J.C., Reinhorn A.M., Riley M., Schmitendorf W.E., Jabbari F. (1996). Experimental verifications of H∞ and sliding mode control for seismically excited buildings. *Journal of structural engineering New York, N.Y.*, 122(1), 69-75. [This presents an example of active control]

[16]. Yang J.N., Li Z., Wu J.C., Hsu I.R. (1994). Control of sliding-isolated buildings using dynamic linearization. *Engineering Structures*, 16(6), 437-444. [This presents an example of sliding-isolated building control]

[17]. Yang J.N., Wu J.C., Kawashima K., Unjoh S. (1995). Hybrid control of seismic-excited bridge structures. *Earthquake Engineering and Structural Dynamics*, 24(11), 1437-1451. [This presents an hybrid control]

[18]. Agrawal A.K., Yang J.N. (1996). Optimal polynomial control of a duffing system, *Proceedings of Engineering Mechanics* 2, 890-893. [This presents an example of polynomial control]

[19]. Cha Y.J., Agrawal A.K., (2013a), Decentralized output feedback polynomial control of seismically excited structures using genetic algorithms, *Structural Control & Health Monitoring* 20(3): 241-258. [This presents an semi-active output feedback polynomial control]

[20]. Nagarajaiah S. (1994). Fuzzy controller for structures with hybrid isolation system. *Proc., 2nd World Conf. Structural Control*, Wiley, New York, TA2:67–76. [This presents an example of fuzzy logic control]

[21]. Battaini M., Casciati F., Faravelli L. (1998). Fuzzy control of structural vibration. An active mass system driven by fuzzy controller. *Earthquake Engrg. and Struct. Dyn.*, 27(11), 1267–1276. [This presents an example of fuzzy logic control]

[22]. Symans M.D., Kelly S.W. (1999). Fuzzy logic control of bridge structures using intelligent semi-active seismic isolation systems. *Earthquake Engrg. and Struct. Dyn.*, 28(1), 37–60. [This presents an example of fuzzy logic control]

[23]. Reid T.J. (1956). Free Vibrations and Hysteretic Damping. *J. Aero. Soc.*, 69, 283, 1956. [This presents an Reid control]

[24]. Dyke S.J., Spencer Jr. B.F. (1997). A Comparison of Semi-Active Control Strategies for the MR Damper. *Proceedings of Intelligent Information Systems Conference (IIS'97)*, Grand Bahama Island, Bahamas, December 8-10, 80-584. [This presents an MR damper implementation]

[25]. Dyke S.J., Spencer Jr. B.F., Sain M.K., Carlson J.D. (1996). Modeling and Control of Magnetorheological Dampers for Seismic Response Reduction. *Smart Materials and Structures*, 5: 565-575. [This presents an MR damper model]

[26]. Stammers C.W., Sireteanu T. (1998). Vibration Control of Machines by Use of Semi-active Dry Friction Damping. *Journal of Sound and Vibration* 209(4), 671-684. [This presents an sequential controller]

[27]. Inaudi J.A. (1997). Modulated homogeneous friction: A semi-active damping strategy. *Earthquake Engineering and Structural Dynamics* 26, 361–376. [This presents an modulated homogenous friction controller]

[28]. He W.L., Agrawal A.K., Yang J.N. (2003). Novel Semiactive Friction Controller for Linear Structures Against Earthquakes, *Journal of Structural Engineering* 129(7), 941-950. [This presents an modulated homogenous friction controller]

[29]. Chen C.C., Chen G.D. (2001). A high efficiency control logic for semi-active friction dampers. Proc., 2001 Structures Congress, May 21–23, Washington, D.C., (CD-ROM). [This presents a piezoelectric semi-active frictional damper using piezoelectric stack actuators]

[30]. Xu Z., Agrawal A.K., Yang J.N., Semi-active and passive control of the phase I linear base-isolated benchmark building model. *Structural Control and Health Monitoring* 13(2-3), 626-648, March/June 2006. [This presents an example of friction controller]

[31]. Yang J. N. Bobrow J., Jabbari F., Leavitt J., Cheng C. P., Lin P. Y. (2007). Full-scale experimental verification of resettable semi-active stiffness dampers, *Earthquake Engineering and Structural Dynamics* 36 1255-1273). [This paper presents resetting semi-active stiffness damper]

[32]. Thai K., Jabbari F., Bobrow J.E., (1995). Vibration Suppression through Parametric Control: A General Framework. *Proceedings of 1995 IMECE* ~International Mechanical Engineering Congress and Exposition, The Winter Annual Meeting of the ASME, San Francisco, CA. [This presents an resetting semi-active stiffness damper]

[33]. Jabbari F. (1997). Output feedback controllers for systems with structured uncertainty. *IEEE Transactions on Automatic Control* 42(5), 715-719. [This presents an resetting semi-active stiffness damper]

[34]. Yamada K., Kobori T. (2006). Control Algorithm for Estimating future responses of active variable stiffness structure. *Earthquake Engineering and Structural Dynamics*. Vol. 24(8). [This presents an active variable stiffness damper]

[35]. Yang J.N., Wu J.C., Kawashima K., Unjoh S. (1995). Hybrid control of seismic-excited bridge structures. *Earthquake Engineering and Structural Dynamics*, 24(11), 1437-1451. [This presents an example of semi-active fluid viscous damper]

[36]. Kawashima K., Unjoh S., Shimizu K. (1992). Experiments on Dynamics Characteristics of Variable Damper. *Proc. of the Japan National Symposium on Structural Response Control*, Tokyo, Japan, 121, 1085-1099. [This presents an example of semi-active fluid viscous damper]

[37]. Symans M.D., Constantinou M.C., Taylor D.P., Garjost K.D. (1994). Semi-Active Fluid Viscous Dampers for Seismic Response Control. *Proc. 1st World Conf. on Struct. Control*, Los Angeles, California, FA4:3–12, August. [This presents an experiment of semi-active fluid viscous damper]

[38]. Kurata N., Kobori T., Takahashi M., Niwa N., Kurino H. (1994). Shaking Table Experiment of Active Variable Damping System. *Proc. 1st World Conf. on Struct. Control*, Los Angeles, California, pp. TP2:108–117, August. [This presents an example of semi-active fluid viscous damper]

[39]. Symans M.D., Constantinou M.C., (1995). Development and experimental study of semi-active fluid damping devices for seismic protection of structures. *Report No. NCEER 95-0011, National Center for Earthquake Engineering Research*, Buffalo, NY. [This presents an linear visco-elastic Maxwell model]

[40]. Symans M.D., Constantinou M.C. (1999). Semi-active control systems for seismic protection of structures: a state-of-the-art review. *Engineering Structures* 21, 469-487. [This presents an fluid viscous damper model data]

[41]. Symens M.D., Constantinou M.C. (1997). Experimental testing and analytical modeling of semi-active fluid dampers for seismic protection. *Journal of Intelligent Material Systems and Structures* 8(8), 644–657. [This presents an experiment of semi-active fluid viscous damper]

[42]. Unsal M., Niezrecki C., Crane III, C.A. (2003). New semi-active piezoelectric-based friction damper. Proceedings of SPIE - The International Society for Optical Engineering 5052, 413-420.[This presents a typical semi-active frictional damper mechanism]

[43]. Xu Y.L., Qu W.L. Chen Z.H. (2001). Control of wind-excited truss tower using semiactive friction damper. *Journal of Structural Engineering* 861-868.[This presents a piezoelectric actuator consisting of a friction layer placed between an inner frame which has smaller transverse stiffness and an outer circular tube which has a larger transverse stiffness]

[44]. Buaka P., Masson P., Micheau P. (2004). Experimental validation of a semi-active friction control device. *Proceedings of SPIE* - The International Society for Optical Engineering, *Smart Structures and*

Materials 2004 - Smart Structures and Integrated Systems 5390, 347-358. [This presents piezoelectric stack actuators]

[45]. Agrawal A.K., Yang J.N. (2000). A semi-active electromagnetic friction damper for response control of structures. Advanced technology in structural engineering (CD-ROM), Proc., ASCE 2000 Structures Congress and Exposition, Chap. 2, Philadelphia. [A semi-active electromagnetic friction damper is presented]

[46]. Guglielmino E., Edge K.A. (2004). A controlled friction damper for vehicle applications. *Control Engineering Practice* 12(4), 431-443. [This presents a semi-active friction damper design based on hydraulic dampers has been presented for vehicles]

[47]. Yang G., Spencer Jr. B.F., Carlson J.D., Sain M.K. (2002). Large-scale MR fluid dampers: modeling and dynamic performance considerations. *Engineering Structures*, 24, 309–323. [This presents controllable fluid dampers such as MR and ER dampers' essential characteristics]

[48]. Shames I.H., Cozzarelli F.A. (1992). *Elastic and Inelastic Stress Analysis*. Prentice Hall, Englewood Cliffs, New Jersey, 120-122. [This presents an visco-plastic Bingham model]

[49]. Gavin H.P., Ortiz D.S., Hanson R.D. (1994). Testing and Modeling of a Prototype ER Damper for Seismic Structural Response Control. *Proceedings of the International Workshop on Structural Control*, USC Publication Number CE-9311, 166-180. [This presents an ER damper model]

[50]. Makris N. (1997). Rigidity-plasticity-viscosity: can electrorheological dampers protect base-isolated structures from near-source ground motions, *Earthquake Engineering and Structural Dynamics* 26, 571–591. [This presents an ER damper model]

[51]. Spencer Jr. B.F., Dyke S.J., Sain M.K., Carlson J.D. (1997). Phenomenological model of a magnetorheological damper. *Journal of Engineering Mechanics* 123(3), 230–238. [This presents an Bouc-Wen MR damper model]

[52]. Spencer B.F. Jr., Johnson E.A., Ramallo J.C. (2000). Smart isolation for seismic control. *JSME Int. J., Ser. C,* 43(3), 704–711. [This presents an smart base isolation systems using clipped optimal control]

[53]. Ramallo J.C., Johnson E.A., Spencer B.F. Jr. (2002). Smart base isolation systems. *J. Eng. Mech.,* 128(10), 1088–1099. [This presents an smart base isolation systems using clipped optimal control]

[54]. Gamota D.R., Filisko F.E(1991). Dynamic mechanical studies of electrorheological materials: Moderate frequencies. *Journal of Rheology*. 35(3), 399-425. [This presents an extension of the Bingham model]

[55]. Bass B.J., Christenson R.E. (2007). System Identification of a 200kN magneto-rheological fluid damper for structural control in large-scale smart structures. *Proceedings of the 2007 American control conference Marriott marquis hotel at Times Square*, New York City, USA, July 11-13. [This presents an hyperbolic tangent model]

[56]. Hrovat D., Barak P., Rabins M. (1983). Semi-active versus passive or active Tuned mass Dampers for structural Control. *Journal of Engineering Mechanics*, 109(3). 691-705. [This presents an semi-active tuned mass damper]

[57]. Abe M., Igusa T. (1996). Semi-active dynamic vibration absorbers for controlling transient response. Jornal of Sound and Vibration. 198(5), 547-569. [This presents an semi-active tuned mass damper]

[58]. Tsai H.C., Lin G.C. (1993). Optimum tuned mass dampers for minimizing steady-state response of support-excited and damped systems. *Earthquake Engineering and Structural Dynamics* 22, 957-973. [This presents an semi-active tuned mass damper]

[59]. Setareh M. (2001). Application of semi-active tuned mass dampers to base-excited systems. *Earthquake Engineering and Structural Dynamics* 30, 449-462. [This presents an semi-active tuned mass damper]

[60]. He W.L., Agrawal, A.K., Mahmoud, K.(2001), Control of seismically excited cable-stayed bridge using resetting semiactive stiffness dampers. *Journal of Bridge Engineering*, 6(6), 376-384. [This presents an modulated homogenous friction controller]

[61]. Yang J.N., Kim J.H., Agrawal A.K. (2000). Resetting semiactive stiffness damper for seismic response control. *Journal of Structural Engineering* 126(12), 1427–1433. [This presents a control algorithm for the resetting semi-active stiffness damper]

[62]. Karnopp D.C., Crosby M.J., Harwood R.A. (1974). Vibration control using semi-active force generators, American Society of Mechanical Engineers. *Journal of Engineering for Industry* 96(2), 619–626. [This presents an skyhook controller]

[63]. Liu Y., Waters T.P., Brennan M.J. (2005). A comparison of semi-active damping control strategies for vibration isolation of harmonic disturbances. *Journal of Sound and Vibration* 280, 21–39. [This presents an skyhook controller]

[64]. Alanoly J., Sankar S. (1987). A new concept in semi-active vibration isolation, American Society of Mechanical Engineers, *Journal of Mechanisms, Transmissions, and Automation in Design* 109, 242–247. [This presents an balance control algorithm]

[65]. Zadeh L.A. (1965). Fuzzy sets. *Information and Control* 8 (3): 338–353. [This presents an fuzzy logic control algorithm]

[66]. Choi K-.M., Cho S-W., Jung H-J., and Lee I-W. (2004). Semi-active fuzzy control for seismic response reduction using magnetorheological dampers. *Earthquake Engineering and Structural Dynamics* 33,723–736. [This presents an fuzzy logic control algorithm]

[67]. Cha Y.J., Agrawal, A.K. (2013b), Velocity-based semi-active turbo-Lyapunov control algorithm for seismically excited nonlinear smart structures, *Structural Control & Health Monitoring*, 20(6): 1043-1056. [This presents an turbo-Lyapunov control algorithm]

[68]. Brogan W.L. (1991). *Modern Control Theory*, Prentice Hall, Englewood Cliffs, New Jersey. [This presents a Lyapunov algorithm based control strategy]

[69]. McClamroch N.H., Gavin H.P. (1995). Closed loop structural control using electrorheological dampers. *Proc., Am. Control Conf.*, American Automatic Control Council, Washington, D.C., 4173–4177. [This presents a Lyapunov algorithm based control strategy]

[70]. Kurata N., Kobori T., Takahashi M., Niwa N., Midorikawa H. (1999). Actual Seismic Response Controlled Building with Semi-active Damper System. *Earthquake Engineering and Structural Dynamics* 28, 1427-1447. [This presents a Lyapunov algorithm based control strategy]

[71]. Yang J.N., Wu J.C., Agrawal A.K., Li Z. (1994). Sliding Mode control of seismic-excited linear and nonlinear civil engineering structures. *Techical Report NCEER-94-0017, National Center for Earthquake engineering research*, State University of New York, Buffalo. [This presents a sliding model control]

[72]. Jansen L.M., Dyke S.J. (2000). Semiactive control strategies for MR dampers: Comparative study. *Journal of Engineering Mechanics* 126(8), 795-803.[This presents a case study of semi-active control algorithms to civil structures and its mathematical formulations].

[73]. Kobori T., Takahashi M., Nasu T., Niwa N., Ogasawara, K., (1993). Seismic Response Controlled Structure with Active Variable Stiffness System. Earthquake Engineering & Structural Dynamics. 22(11). 925-941. [This presents full-scale semi-active variable-stiffness system application]

[74]. Cha Y.J., Zhang J., Agrawal AK., Dong B., Friedman A., Dyke S.J., Ricles J. (2013a). Comparative studies of semiactive control strategies for MR dampers: pure simulation and real-time hybrid tests. *Journal of Structural Engineering*, *139*(7), 1237-1248. [This presents performance validation of semi-active controllers using large-scale MR dampers]

[75]. Cha Y.J., Agrawal A.K., Friedman A., Phillips B., Ahn R., Dong B., Christenson R. (2014). Performance Validations of Semiactive Controllers on Large-Scale Moment-Resisting Frame Equipped with 200-kN MR Damper Using Real-Time Hybrid Simulations. *Journal of Structural Engineering*. [This presents performance validation of semi-active controllers using large-scale MR dampers]

[76]. Cha Y.J., Agrawal A.K., Dyke S.J. (2013b). Time delay effects on large-scale MR damper based semi-active control strategies. *Smart Materials and Structures*, *22*(1), 015011. [This presents time-delay effects of the semi-active controllers]

[77]. Cha, Y. J., Agrawal, A. K. (2014). Robustness studies of sensor faults and noises for semi-active control strategies using large-scale magnetorheological dampers. *Journal of Vibration and Control*, 1077546314535947. [This presents sensor fault effects of the semi-active controllers]

[78]. He W.L. (2003), Smart energy dissipation systems for protection of civil infrastructures from near-field earthquakes. Ph.D. Dissertation, The City University of New York.

Biographical Sketches

Anil K. Agrawal is Professor of Civil Engineering at the City College of the City University of New York, New York. He received his Ph.D. in Civil Engineering from the University of California, Irvine, in August 1997 and joined the City College of New York in September 1998. He has published more than 50 Journal papers and 100 conference papers. He is currently the member of executive committee on U.S. Panel of International Association of Structural Control and Monitoring, Chair of the ASCE Committee on Structural Control and Sensing, and Chief Editor of the ASCE Journal of Bridge Engineering.

Young-Jin Cha received his M.S. degree in Civil Engineering from Yonsei University, Seoul Korea in 2004 and his Ph.D. degree in Structural Engineering from Texas A&M University, College Station, Texas in 2008. Currently he is an Assistant Professor at University of Manitoba. Previously he served as a postdoctoral position at Massachusetts Institute of Technology. He has published more than 25 Journal papers and 28 conference papers. He have served as A scholarly peer reviewer at *Journal of Bridge Engineering*, *Journal of Structural Engineering*, ASCE, *Structural Control & Health Monitoring*, A*dvances in Structural Engineering*, *Earthquake Spectra*, *Journal of Engineering Mechanics*, *Structures Congress*, ASCE, and ISET Journal of Earthquake Technology. He is also a member of American Society of Civil Engineers, ASCE, Association of Civil Engineering Doctoral Students (AceDoc), The New York Academy of Sciences (Post-doctoral fellowship member), Structural Engineers Association of Texas (SeAoT), and Earthquake Engineering Society of Korea (EESK), and he served as a chief manager of Structures & Bridge Engineering Lab. At Department of Civil Engineering at Yonsei University, and president of Graduate Student Association of Civil Engineering at Yonsei University. His main scientific interests are structural control, real-time hybrid simulation, structural health monitoring, damage detection, time-frequency decomposition, digital signal & image processing, artificial intelligence based multi-objective optimization and performance-based design (artificial neural networks, genetic algorithms, and time series analyses).

Zhou Xu is a licensed professional engineer (PE) and LEED Accredited Professional (LEED®AP) currently working for the Weidlinger Associates INC, New York. He is also a committee member of Structural Control Committee of ASCE, and full member of ASCE & AISC. He received his PhD from the Department of Civil Engineering, the City University of New Year in Jan 2007. His research interests include design & assessment of seismic protective systems for near-field earthquakes, optimal design & analysis of high-rise and special structures. He has published his research findings on the Journal of Structural Engineering, Journal of Earthquake Engineering, Engineering Structures and Journal of Structural Control & Health Monitoring, etc.