1

Introduction

1.1 GENERAL

Over the last 25 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 buildings and bridges. Serious efforts have been undertaken to develop the structural control concept into a workable technology, and today we have many such devices installed in a wide variety of structures (Soong and Spencer, 2000).

By and large, structural control systems can be grouped into three broad areas: (a) base isolation, (b) passive energy dissipation, and (c) active, hybrid, and semi-active control. Of the three, base isolation can now be considered a more mature technology with application as compared with the other two (ATC 17-1, 1993).

Passive energy dissipation systems encompass a range of materials and devices for enhancing damping, stiffness, and strength, and can be used both for seismic hazard mitigation and for rehabilitation of aging or deficient structures (Soong and Dargush, 1997; Constantinou *et al.*, 1998; Hanson and Soong, 2001). In general, such systems are characterized by their capability to enhance energy dissipation in the structural systems in which they are installed. These devices generally operate on principles such as frictional sliding, yielding of metals, phase transformation in metals, deformation of viscoelastic solids or fluids, and fluid orificing.

Active, hybrid, and semi-active structural control systems are a natural evolution of passive control technologies. The possible use of active control systems and some combinations of passive and active systems as a means of

Active, Hybrid, and Semi-active Structural Control – A Design and Implementation Handbook
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structural protection against seismic loads has received considerable attention in recent years. Active, hybrid, and semi-active control systems are force delivery devices integrated with real-time processing evaluators/controllers and sensors within the structure. They act simultaneously with the hazardous excitation to provide enhanced structural behavior for improved service and safety. Research to date has also reached the stage where active systems have been installed in full-scale structures for seismic hazard mitigation.

It is useful to distinguish among several types of active control systems currently being used in practice. A purely active structural control system has the basic configuration as shown schematically in Figure 1.1(a) (Soong, 1990). It 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 forces needed based on a given control algorithm; and (c) actuators, usually powered by external sources, to produce the required forces.

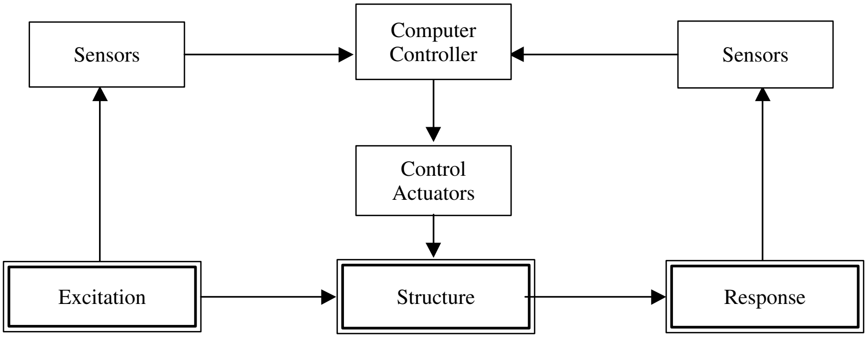
When only the structural response variables are measured, the control configuration is referred to as feedback control since the structural response is continually monitored and this information is used to make continual corrections to the applied control forces. A feedforward control results when the control forces are regulated only by the measured excitation, which can be achieved, for earthquake inputs, by measuring accelerations at the structural base. 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 (Suhardjo *et al.*, 1990).

The term hybrid control generally refers to a combined passive and active control system as depicted in Figure 1.1(b). A portion of the control objective is accomplished by the passive system, implying in a properly designed hybrid system that less power and resources are required.

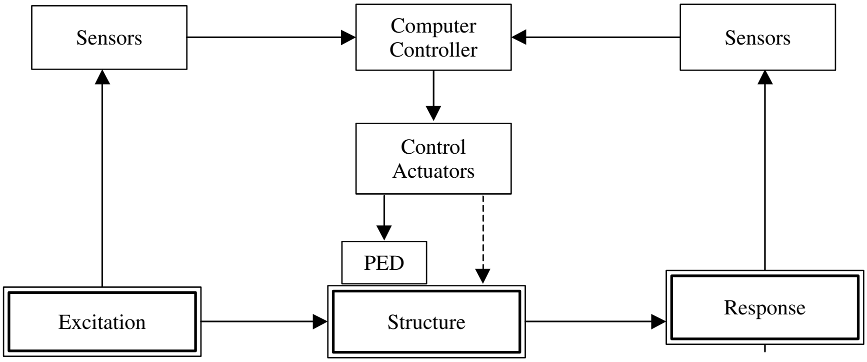
Similar control resource savings can be achieved using the semi-active control scheme sketched in Figure 1.1(c), where the control devices do not add mechanical energy directly to the structure; hence bounded-input/bounded-output stability is guaranteed. Semi-active control devices are often viewed as controllable passive devices.

A side benefit of hybrid and semi-active control systems is that, in the case of a power failure, the passive components of the control still offer some degree of protection, unlike a fully active control system.

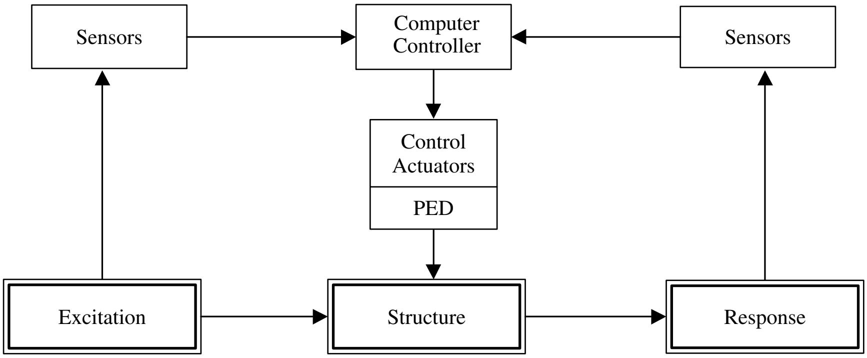
This book addresses active systems, which include hybrid and semi-active systems. It is useful to begin by outlining the basic principles involved in such systems.



(a) Structure with Active Control



(b) Structure with Hybrid Control



(c) Structure with Semi-Active Control

Figure 1.1 Structure with various active control schemes (PED: passive energy dissipation)

1.2 BASIC PRINCIPLES

In what follows, basic principles of active control are illustrated using a simple single-degree-of-freedom (SDOF) structural model. Consider the lateral motion of the SDOF model consisting of a mass m, supported by springs with the total linear elastic stiffness k, and a damper with damping coefficient c. This SDOF system is then subjected to an earthquake load where $\ddot{x}_g(t)$ is ground acceleration. The excited model responds with a lateral displacement $x(t)$ relative to the ground which satisfies the equation of motion

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{x}_g \tag{1.1}$$

To see the effect of applying an active control force to the linear structure, equation (1.1) in this case becomes

$$m\ddot{x} + c\dot{x} + kx = -mu(t) - m\ddot{x}_g \tag{1.2}$$

where $u(t)$ is the applied control force.

Suppose that the feedback configuration is used in which the control force $u(t)$ is designed to be

$$u(t) = \Gamma x/m \tag{1.3}$$

and equation (1.2) becomes

$$m\ddot{x} + c\dot{x} + kx + \Gamma x = -m\ddot{x}_g \tag{1.4}$$

It is seen that the effect of feedback control is to modify the structural properties so that it can respond more favorably to the ground motion. The form of Γx is governed by the control law chosen for a given application, which can change as a function of the excitation. In comparison with passive systems, several advantages associated with active control systems can be cited; among them are (a) enhanced effectiveness in the response control where the degree of effectiveness is, by and large, only limited by the capacity of the control systems; (b) relative insensitivity to site conditions and ground motion; (c) applicability to multi-hazard mitigation situations, where an active system can be used, for example, for motion control against both strong wind and earthquakes; and (d) selectivity of control objectives; e.g. one may emphasize human comfort over other aspects of structural motion during noncritical times, whereas increased structural safety may be the objective during severe dynamic loading.

While this description of active control is conceptually in the domain of familiar optimal control theory used in electrical engineering, mechanical engineering, and aerospace engineering, structural control for civil engineering applications has a number of distinctive features, largely due to implementation issues, that set it apart from the general field of feedback control. In particular, when addressing civil engineering structures, there is considerable uncertainty, including nonlinearity associated with both physical properties and disturbances such as earthquakes and wind, where the scale of the forces involved can be quite large, there are only a limited number of sensors and actuators, the dynamics of the actuators can be quite complex, the actuators are typically very large, and the systems must be fail-safe (Soong, 1990; Suhardjo *et al.*, 1990; Housner *et al.*, 1994, 1997; Kobori, 1994; Dyke *et al.*, 1995).

1.3 STATE-OF-THE-PRACTICE

The rapid growth of research interest and development of active, hybrid and semi-active structural control systems is in part due to several coordinated research efforts, largely in Japan and the US, marked by a series of milestones listed in Table 1.1. Indeed, the most challenging aspect of active control research in civil engineering is the fact that it is an integration of a number of diverse disciplines, some of which are not within the domain of traditional civil engineering. These include computer science, data processing, control theory, material science, sensing technology, as well as stochastic processes, structural dynamics, and wind and earthquake engineering. These coordinated

Table 1.1 Active structural control research – milestones

Year	Event
1989	US Panel on Structural Control Research (US-NSF)
1990	Japan Panel on Structural Response Control (Japan-SCJ)
1991	Five-Year Research Initiative on Structural Control (US-NSF)
1993	European Association for Control of Structures
1994	International Association for Structural Control
1994	First World Conference on Structural Control (Pasadena, California, USA)
1996	First European Conference on Structural Control (Barcelona, Spain)
1998	China Panel for Structural Control
1998	Korean Panel for Structural Control
1998	Second World Conference on Structural Control (Kyoto, Japan)
2000	Second European Conference on Structural Control (Paris, France)
2002	Third World Conference on Structural Control (Como, Italy)
2004	Third European Conference on Structural Control (Vienna, Austria)
2006	Fourth World Conference on Structural Control (San Diego, California, USA)

efforts have facilitated collaborative research efforts among researchers from diverse backgrounds and accelerated the research-to-implementation process as seen today.

As alluded to earlier, the development of active, hybrid, and semi-active control systems has reached the stage of full-scale applications to actual structures. From 1989 to 2003, the number of these installations in building structures and towers totalled 49 (Figure 1.2). However, 43 of them are found in Japan. In addition, approximately 15 bridge towers have employed active systems during erection (Fujino, 1993; Spencer and Sain, 1997). Most of these full-scale systems have been subjected to actual wind forces and ground motions and their observed performances provide invaluable information in terms of (a) validating analytical and simulation procedures used to predict actual system performance, (b) verifying complex electronic–digital–servohydraulic systems under actual loading conditions, and (c) verifying capability of these systems to operate or shut down under prescribed conditions.

Described below are several of these systems together, in some cases, with their observed performances. Also addressed are several practical issues in connection with actual structural applications of these systems.

1.3.1 Hybrid Mass Damper Systems

The hybrid mass damper (HMD) is the most common control device employed in full-scale civil engineering applications. An HMD is a

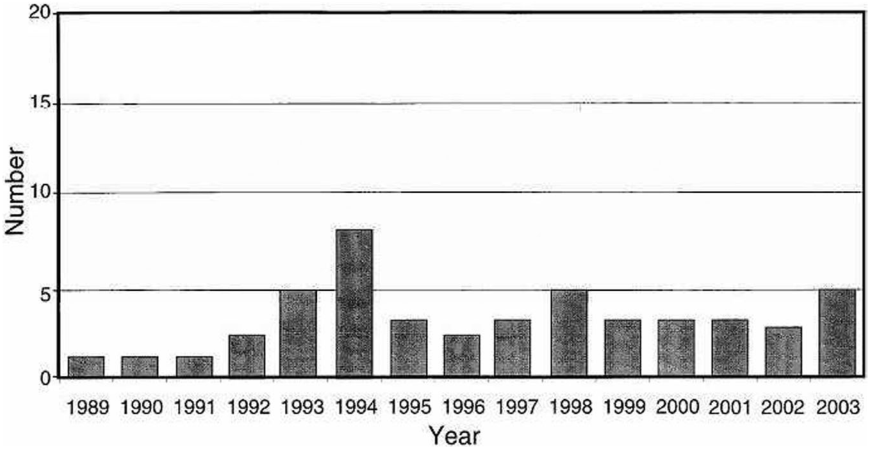


Figure 1.2 Number of installations – active, hybrid and semi-active systems

combination of a passive tuned mass damper (TMD) and an active control actuator. The ability of this device to reduce structural responses relies mainly on the natural motion of the TMD. The forces from the control actuator are employed to increase efficiency of the HMD and to increase its robustness to changes in the dynamic characteristics of the structure. The energy and forces required to operate a typical HMD are far less than those associated with a fully active mass damper system of comparable performance.

An example of such an application is the HMD system installed in the Sendagaya INTES building in Tokyo in 1991. As shown in Figure 1.3, the HMD 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 1.4, where ice thermal storage tanks are used as mass blocks so that no extra mass was introduced. The masses are supported by multi-stage rubber bearings intended for reducing the control energy consumed in the HMD and for insuring smooth mass movements (Higashino and Aizawa, 1993; Soong *et al.*, 1994).

Sufficient data were obtained for evaluation of the HMD performance when the building was subjected to strong wind, with a peak instantaneous wind speed of 30.6 m/s. An example of the recorded time histories is shown in Figure 1.5, giving both the uncontrolled and controlled states. Their

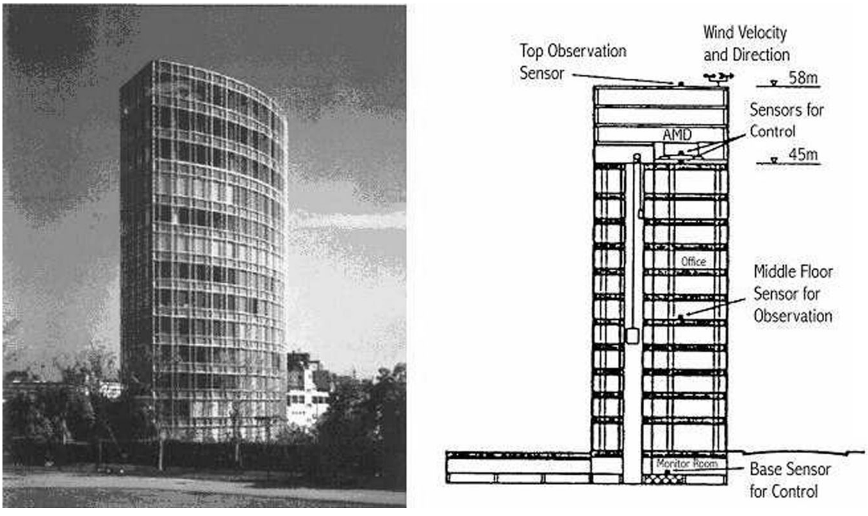


Figure 1.3 Sendagaya INTES building with hybrid mass dampers (Higashino and Aizawa, 1993)

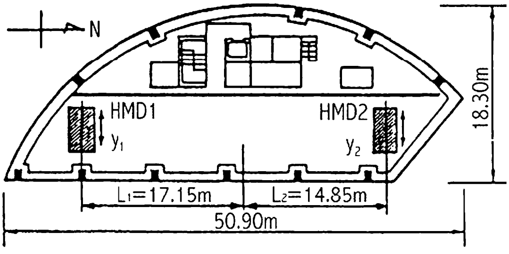


Figure 1.4 Top view of hybrid mass damper configuration (Higashino and Aizawa, 1993)

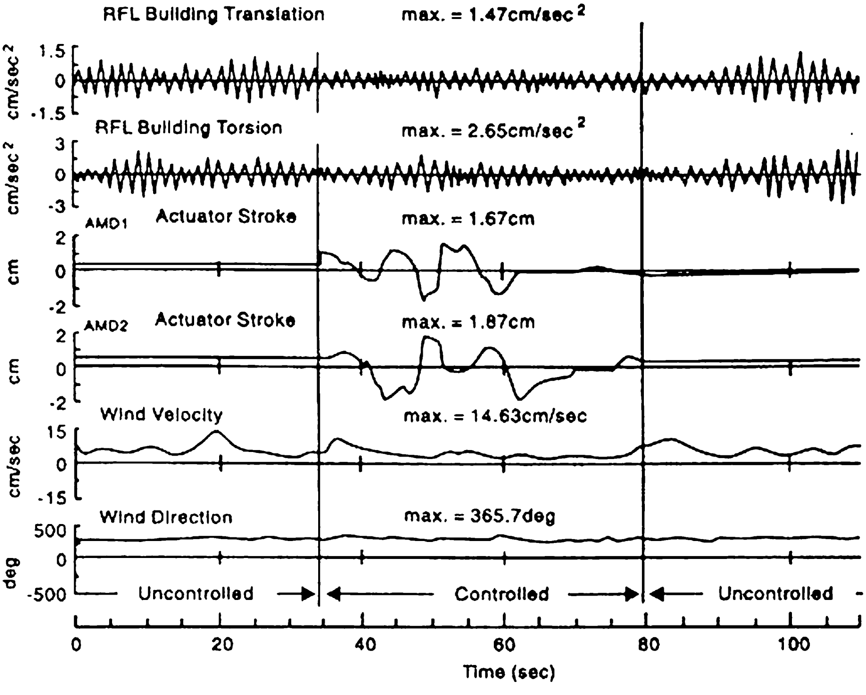


Figure 1.5 Response time histories (Higashino and Aizawa, 1993)

Fourier spectra using samples of 30-s duration are shown in Figure 1.6, again showing good performance in the low-frequency range. The response at the fundamental mode was reduced by 18% and 28% for translation and torsion, respectively.

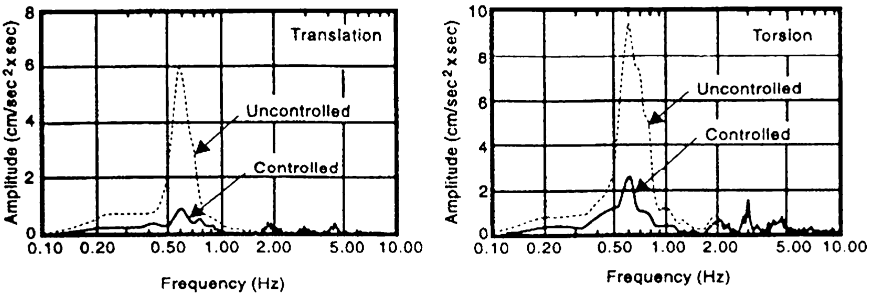


Figure 1.6 Response Fourier spectra (Higashino and Aizawa, 1993)

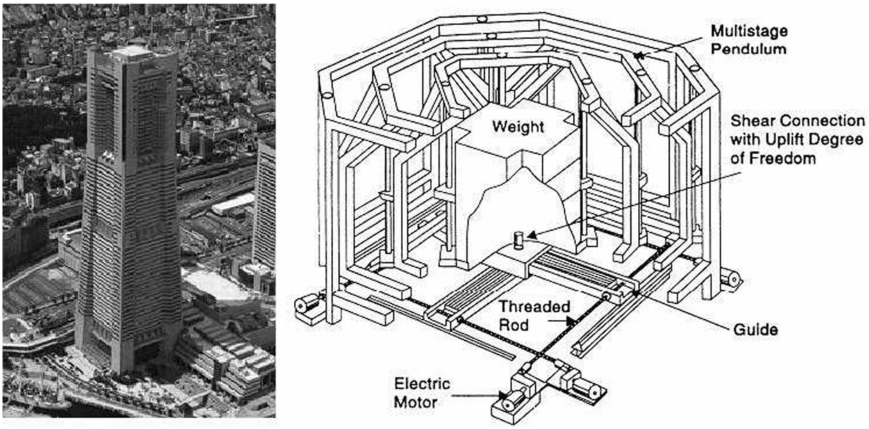


Figure 1.7 Yokohama Landmark Tower and HMD (Yamazaki *et al.*, 1992)

Variations of such an HMD configuration include multi-stage pendulum HMDs (as seen in Figure 1.7), which have been installed in, for example, the Yokohama Landmark Tower in Yokohama (Yamazaki *et al.*, 1992), the tallest building in Japan, and in the TC Tower in Kaohsiung, Taiwan. Additionally, the DUOX HMD system which, as shown schematically in Figure 1.8, consists of a TMD actively controlled by an auxiliary mass, has been installed in, for example, the Ando Nishikicho Building in Tokyo (Nishimura *et al.*, 1993).

1.3.2 Active Mass Damper Systems

Design constraints, such as severe space limitations, can preclude the use of an HMD system. Such is the case in the active mass damper or active

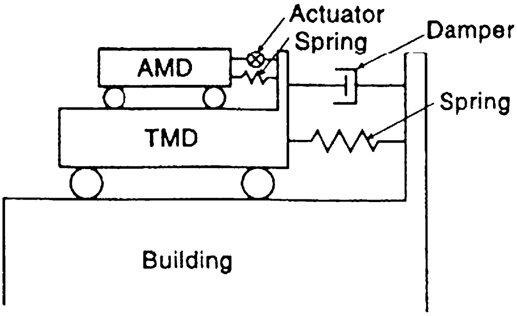


Figure 1.8 Principle of the DUOX system (Nishimura *et al.*, 1993)

mass driver (AMD) system designed and installed in the Kyobashi Seiwa Building in Tokyo. This building, the first full-scale implementation of active control technology, is an 11-story building with a total floor area of 423 m^2. As seen in Figure 1.9, the control system consists of two AMDs where the primary AMD is used for transverse motion and has a weight of 4 tons,

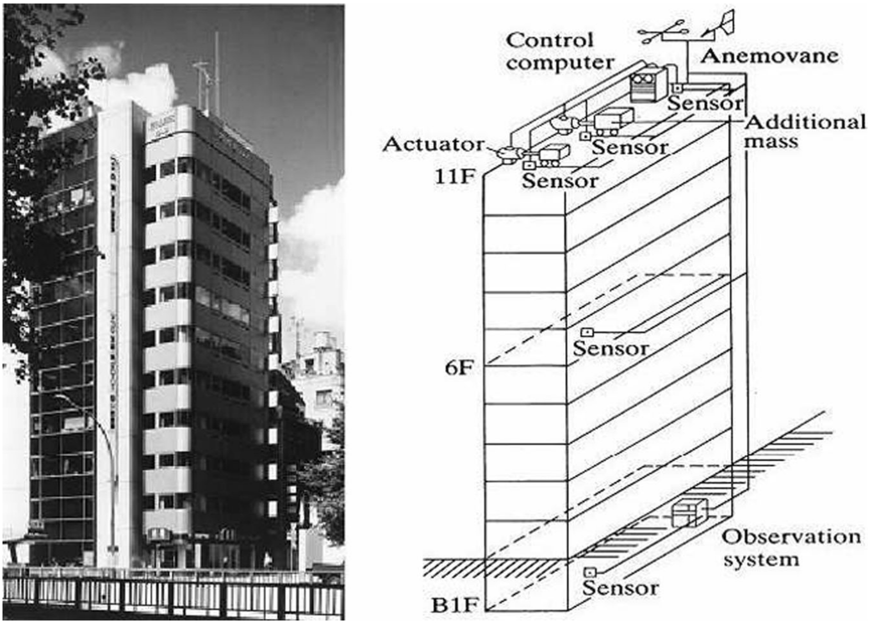


Figure 1.9 Kyobashi Seiwa Building and AMD (Kobori, 1994)

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 the comfort of occupants in the building (Kobori *et al.*, 1991a, 1991b; Kobori, 1994).

1.3.3 Semi-active Damper Systems

Control strategies based on semi-active devices combine the best features of both passive and active control systems. The close attention received in this area in recent years can be attributed to the fact that semi-active control devices offer the adaptability of active control devices without requiring the associated large power sources. In fact, many can operate on battery power, which is critical during seismic events when the main power source to the structure may fail. In addition, as stated earlier, semi-active control devices do not have the potential to destabilize (in the bounded input/bounded output sense) the structural system. Extensive studies have indicated that appropriately implemented semi-active systems perform significantly better than passive devices and have the potential to achieve the majority of the performance of fully active systems, thus allowing for the possibility of effective response reduction during a wide array of dynamic loading conditions.

One means of achieving a semi-active damping device is to use a controllable, electromechanical, variable-orifice valve to alter the resistance to flow of a conventional hydraulic fluid damper. A schematic of such a device is given in Figure 1.10. As described by Sack and Patten (1993), experiments were conducted in which a hydraulic actuator with a controllable orifice was

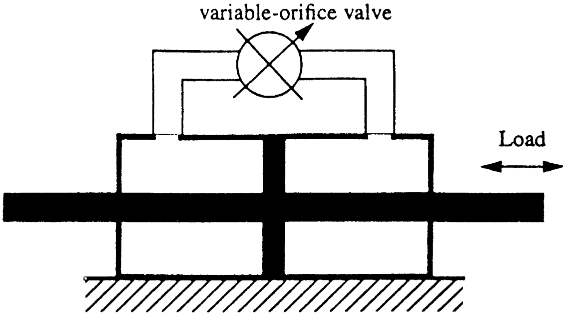


Figure 1.10 Schematic of variable-orifice damper

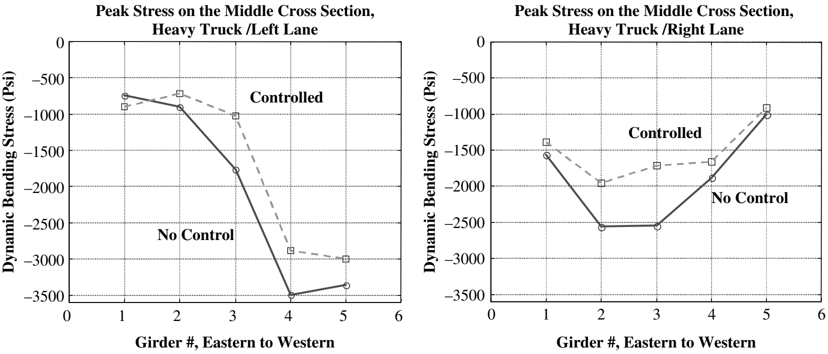


Figure 1.11 Comparison of peak stresses for heavy trucks (Patten *et al.*, 1999)

implemented in a single-lane model bridge to dissipate the energy induced by vehicle traffic (Figure 1.11), followed by a full-scale experiment conducted on a bridge on interstate highway I-35 to demonstrate this technology (Patten, 1998; Patten *et al.*, 1999; Kuehn *et al.*, 1999), as shown in Figure 1.12. This

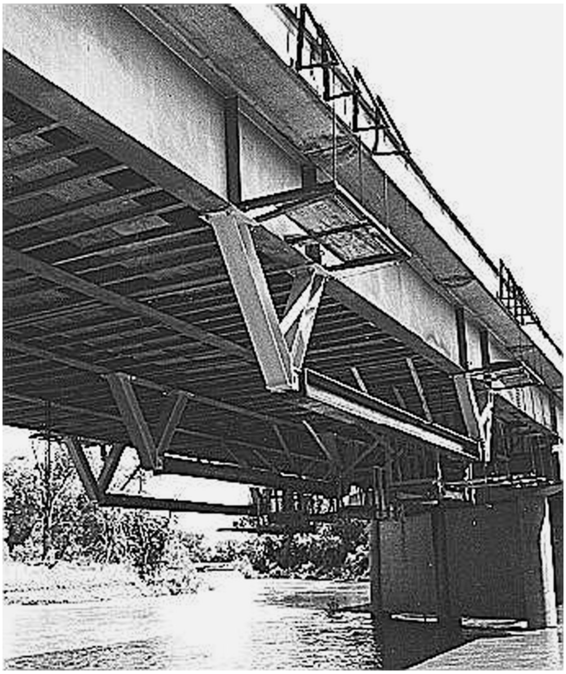


Figure 1.12 Highway I-35 bridge with semi-active dampers (Patten, 1998)

experiment constitutes the first full-scale implementation of active structural control in the US.

Conceived as a variable-stiffness device, a full-scale variable-orifice damper in a semi-active variable-stiffness system (SAVS) was implemented to investigate semi-active control at the Kobori Research Complex (Kobori *et al.*, 1993; Kamagata and Kobori, 1994). The overall system is shown in Figure 1.13 where SAVS devices were installed on both sides of the structure in the transverse direction. The results of these analytical and experimental studies indicate that this device is effective in reducing structural responses.

More recently, a semi-active damper system was installed in the Kajima Shizuoka Building in Shizuoka, Japan. As seen in Figure 1.14, semi-active hydraulic dampers are installed inside the walls on both sides of the building to enable it to be used as a disaster relief base in post-earthquake situations (Kobori, 1998; Kurata *et al.*, 1999). Each damper contains a flow control valve, a check valve, and an accumulator, and can develop a maximum damping force of 1000 kN. Figure 1.15 shows a sample of the response analysis results based on one of the selected control schemes and several earthquake

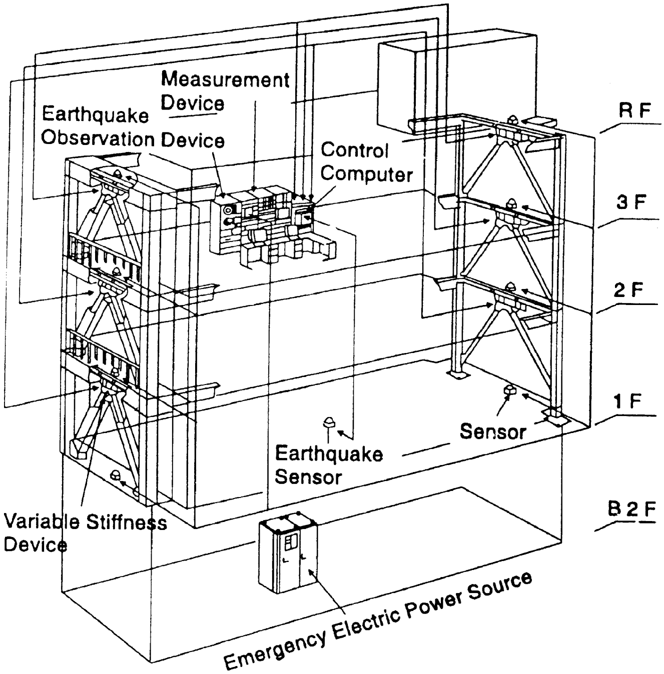


Figure 1.13 SAVS system configuration (Kurata *et al.*, 1999)

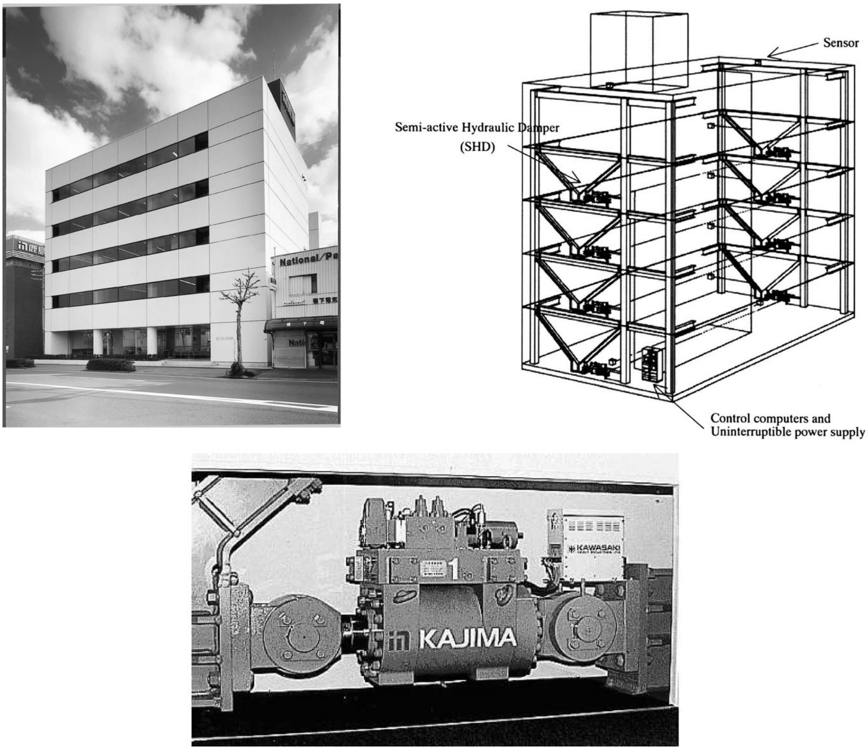
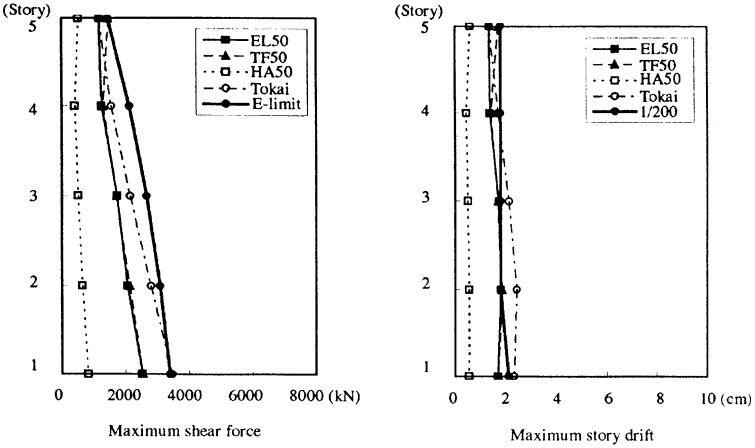


Figure 1.14 Kajima Shizuoka Building and semi-active hydraulic dampers (Kurata *et al.*, 1999)

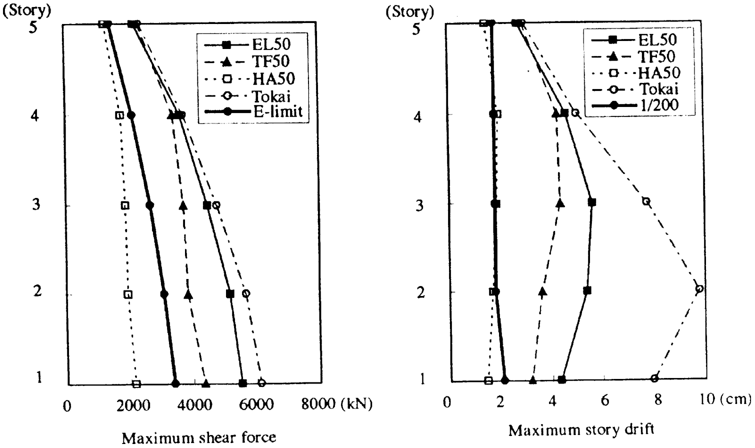
input motions with a scaled maximum velocity of 50 cm/s, together with a simulated Tokai wave. It is seen that both story shear forces and story drifts are greatly reduced with control activated. In the case of the shear forces, they are confined within their elastic-limit values (indicated by E-limit in Figure 1.15) while, without control, they would enter the plastic range.

1.3.4 Semi-active Controllable Fluid Dampers

Another class of semi-active devices uses controllable fluids, schematically shown in Figure 1.16. In comparison with semi-active damper systems described above, an advantage of controllable fluid devices is that they contain no moving parts other than the piston, which makes them simple and potentially very reliable.



(a) With SAHD control



(b) Without control

Figure 1.15 Maximum Responses (El Centro, Taft, and Hachinohe waves with 50 cm/s and assumed Tokai waves) (Kurata *et al.*, 1999) (SAHD: semi-active hydraulic damper)

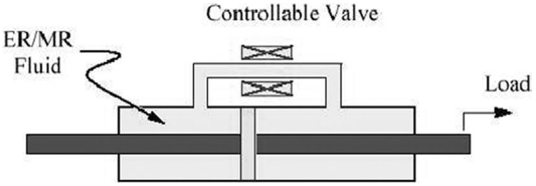


Figure 1.16 Schematic of a controllable fluid damper

Two fluids that are viable contenders for development of controllable dampers are: (a) electrorheological (ER) fluids and (b) magnetorheological (MR) fluids. The essential characteristic of these fluids is their ability to change reversibly from a free-flowing, linear viscous fluid to a semi-solid with a controllable yield strength in milliseconds when exposed to an electric (for ER fluids) or a magnetic (for MR fluids) field. In the absence of an applied field, these fluids flow freely and can be modeled as Newtonian. When the field is applied, a Bingham plastic model (Shames and Cozzarelli, 1992) is often used to describe the fluid behavior. In this model, the plastic viscosity is defined as the slope of the measured shear stress versus shear strain rate data. Thus, the total yield stress is given by

$$\tau = \tau_{\mathrm{y(field)}} \operatorname{sgn}(\dot{\gamma}) + \eta_{\mathrm{p}} \dot{\gamma} \tag{1.5}$$

where $\tau_{\mathrm{y(field)}}$ is the yield stress caused by the applied field, $\dot{\gamma}$ is the shear strain rate, and η_{p} is the plastic viscosity, defined as the slope of the measured shear stress versus the shear strain rate data.

Although the discovery of both ER and MR fluids dates back to the late 1940s (Winslow, 1948; Rabinow, 1948), for many years research programs concentrated primarily on ER fluids. Nevertheless, some obstacles remain in the development of commercially feasible damping devices using ER fluids. For example, the best ER fluids currently available have a yield stress of only 3.0–3.5 kPa and cannot tolerate common impurities (e.g. water) that might be introduced during manufacturing or use. In addition, safety, availability, and cost of the high-voltage (e.g. ∼4000 V) power supplies required to control the ER fluids need to be addressed.

Recently developed MR fluids appear to be an attractive alternative to ER fluids for use in controllable fluid dampers (Carlson, 1994; Carlson and Weiss, 1994; Carlson *et al.*, 1996). MR fluids typically consist of micron-sized, magnetically polarizable particles dispersed in a carrier medium such as mineral or silicone oil. It has been indicated by Carlson and Weiss (1994) that the achievable yield stress of an MR fluid is an order of magnitude greater than its ER counterpart and that MR fluids can operate at temperatures from −40 to 150°C with only modest variations in the yield stress. Moreover, MR fluids are not sensitive to impurities such as those commonly encountered during manufacturing and usage, and little particle/carrier fluid separation takes place in MR fluids under common flow conditions. The size, shape, and performance of a given device are determined by a combination of $\tau_{\mathrm{y(field)}}$ and η_{p}. The design equations for most controllable damper geometries indicate that minimizing the ratio $\eta_{\mathrm{p}}/\tau^2_{\mathrm{y(field)}}$ is desirable. This ratio for

MR fluids ($\approx 5 \times 10^{-11}$ s/Pa) is three orders of magnitude smaller than the corresponding ratio for today's best ER fluids. Thus, controllable devices using MR fluids have the potential of being much smaller than ER devices with similar capabilities. Further, the MR fluid can be readily controlled with a low power (e.g. less than 50 W), low voltage (e.g. ~12–24 V), and current-driven power supply outputting only ~1–2 A. Batteries can readily supply such power levels.

A number of pilot studies have been conducted to assess the usefulness of magnetorheological fluid dampers for seismic response reduction (Spencer *et al.*, 1996, 1997; Dyke, 1996; Dyke *et al.*, 1996a, 1996b). In Dyke (1996), Dyke *et al.* (1996a, 1996b), Baker *et al.* (1999), and Spencer *et al.* (1999), simulations and laboratory experiments have shown that the magnetorheological damper, used in conjunction with recently proposed acceleration feedback control strategies, significantly outperforms comparable passive configurations of the damper for seismic response reduction. In addition, the design of a full-scale, 20-ton magnetorheological damper has been reported (Carlson and Spencer, 1996; Spencer *et al.*, 1998) (see Figure 1.17), showing that this technology is scalable to devices appropriate for civil engineering

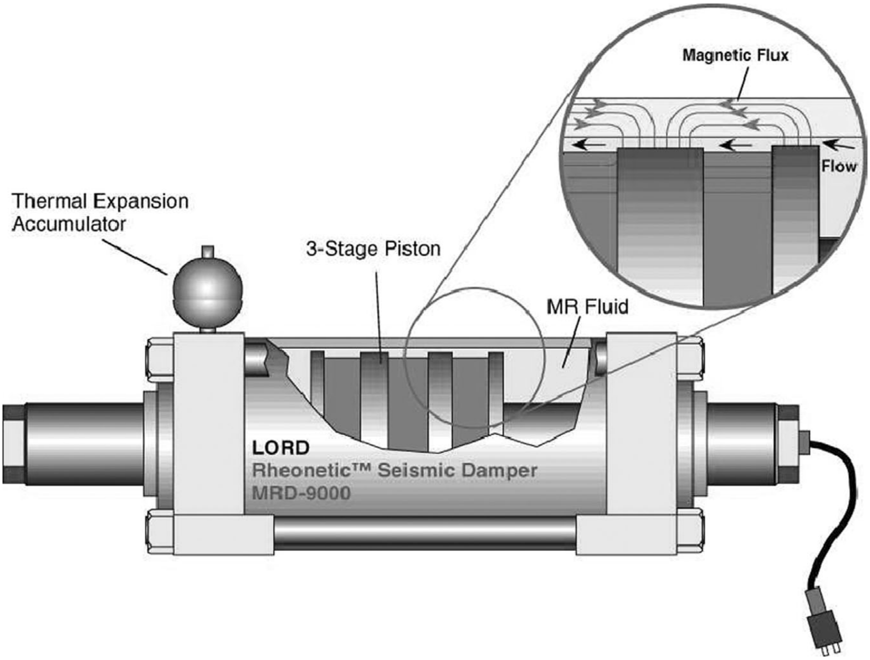


Figure 1.17 Full-scale 20-ton MR fluid damper (Dyke *et al.*, 1998)

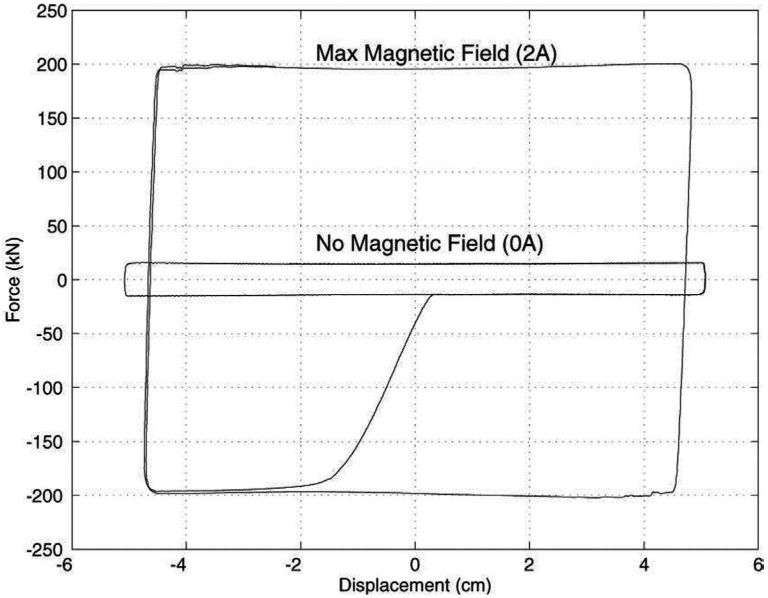


Figure 1.18 Force–displacement loops at maximum and zero magnetic fields (Dyke *et al.*, 1998)

applications. At design velocities, the dynamic range of forces produced by this device is over 10 (see Figure 1.18), and the total power required by the device is only 20–50 W.

Full-scale implementation of MR fluid dampers has taken place. In 2001, two 30-ton MR fluid dampers were installed between the 3rd and 5th floors of the Tokyo Natural Museum of Engineering Science and Innovation Building. In 2002, MR dampers were used to retrofit a cable-stayed bridge crossing the Dongting Lake in China to mitigate rain–wind-induced vibration of the cables (Figure 1.19). Two MR fluid dampers were installed on each cable. *In situ* test results under severe rain–wind weather conditions have shown a significant reduction in both in-plane and out-of-plane cable vibrations (Spencer, 2002).

1.4 IMPLEMENTATION-RELATED ISSUES

It is seen from Figure 1.1 that, whether an active control system is purely active, hybrid, or semi-active, the ‘active’ loop of the system consists of the same basic elements. They comprise sensors, a digital controller, control

Figure 1.19 Damper configuration (Spencer, 2002)

algorithms, and control force generation devices as an integral system. While much work has been done on the theoretical development of control algorithms, implementation of these control strategies to real structures requires resolution of a host of practice-based important issues. These include custom-designed overall system configuration, software/hardware integration, custom-designed system status monitoring, automatic operations of force generators, multi-protection fail-safe measures, and control performance verification.

The focus of this book is on these implementation-related issues. Many of them present challenges. For example, in practical application, digital controllers are better suited than analog for real-time control because of their flexibility and reliability. Their major tasks are to perform the calculation of required control forces and implement fail-safe protection features. However, their inherent discrete-time nature gives us the first challenge when implementing the designed continuous-time control algorithm. In an ideal situation, a simple digital controller can be designed based on a continuous-time control theory, without consideration of many problems and imperfections that are present in a typical structural control system. Unfortunately, such a controller is likely to perform poorly if it is implemented in a realistic structural system.

On the other hand, active control force generation devices and sensors are commonly analog hardware. The second challenge is how to deal with these two different systems through the help of a digital computer. The design and analysis of general civil engineering structures are essentially carried out on a case-by-case basis, in the same way as active control design and implementation. Therefore, the commonly used commercial control packages are obviously not applicable in general. Therefore, custom design is always required not only for control algorithm analysis but also for the development of an integrated control system.

Although a number of control problems are theoretically solvable, necessary knowledge about a practical control system is required in order to translate theoretical developments into practice. Issues associated with successful implementation of an integrated system are complex and interdisciplinary in nature. Based on the implementation experience gained from previous scaled-down and full-scale experimental verifications and other related disciplines, there are many issues involved that need to be addressed clearly and investigated theoretically. It is not only necessary to consider individual control components in detail, but the integrated system also has to be validated appropriately.

Furthermore, integrated verification and validation of a complete control system with proposed control algorithms prior to their implementation to real structures have always been a time-consuming and costly process. The investment in experimental hardware and inherent inaccuracies in experimental set-up or modeling is usually a major obstacle in structural control implementation.

1.4.1 An Overview

Although both passive and active control systems have been implemented to control wind- or earthquake-induced vibration of buildings around the world (Spencer and Sain, 1997; Soong and Spencer, 2000), there are still some practical and important issues to be considered, such as the limited number of sensors and controllers, modeling errors, spillover effects, discrete-time implementation, time delay, and control–structure interaction. In these areas, there are only a few detailed references that can be cited. However, several experimental studies have been conducted in order to provide better solutions for implementation (Wu *et al.*, 1995; Riley, 1996).

With a view toward implementation, Chung (1988) and Chung *et al.* (1988, 1989) have applied linear quadratic regulator theory to an SDOF/3DOF model with an active tendon device and considered that the phase-shift compensation method compensated for the time delay effect. A six-story scaled-down model structure was tested and verified through shaking table tests in the laboratory prior to full-scale implementation of an active bracing system (Reinhorn *et al.* 1989, 1992, 1993; Soong *et al.*, 1991). Direct three-velocity feedback control was implemented. The experiences gained through the development of the active control system are invaluable, especially on the documentation of the implementation issues. Control results for structures under real earthquake excitations also show that imperfect compensation for time delay may cause frequency shift and possible instability.

Other implementational issues regarding the effects of control–structure interaction and actuator dynamics have been conducted by Dyke (1996) and Dyke *et al.* (1995, 1996a, 1996b) while applying acceleration feedback strategies. In these experiments, computational time delays are negligible because the controller was implemented using a relatively modern DSP (digital signal processor) chip. Additionally, the identified system model explicitly included actuator dynamics and control–structure interaction, ensuring that the control design would accommodate these dynamics. Several other experiments using this approach were also conducted to verify acceleration feedback techniques (Quast *et al.*, 1995; Battaini and Dyke, 1998; Battaini *et al.*, 2000). Some implementation details were addressed.

Quast *et al.* (1995) specifically address how to deal with implementation of the controller on a digital computer when the system and sensor information are continuous-time signals. In such a situation, the method of 'emulation' is often adopted. In digital control, it is common to design a continuous-time controller and then convert the resulting system to its discrete-time equivalent. This technique is commonly used by practicing engineers in the control industry (Franklin *et al.*, 1997). In this case, a combination of samplers, digital filters, and hold devices emulates the operation of a continuous-time controller which produces satisfactory control performance. Generally, the sampling rate should be about 20 times the highest frequency of the controller (Quast *et al.*, 1995) to prevent warping in the conversion process. Moreover, there are many practical considerations that need to be considered in order to successfully implement the emulation system, including factors such as computational time delay and sampling period.

Apart from approximation errors caused by implementing the equivalent discrete-time controller, the time delay has always been a major issue in active control applications. In general, the total time delay in a control system can be divided into two parts. The first source is referred to as a fixed (or computational) delay due to on-line data acquisition, filtering, manipulation of digital data inside the digital control processor (DCP), calculation of required control force, and signal transmission from the computer to the actuator. This time delay is general negligibly small for a simple experimental set-up, being on the order of a few hundred microseconds. However, it will be increased depending on the number of acquisition channels and the designed modules inside the microcode for real implementation. The second source is due to the dynamics of the actuator. In reality, electromechanical actuators have dynamics associated with them that result in a time lag in the generation of control forces. This time lag may be modeled as a time delay. Alternatively, one may explicitly include the actuator dynamics in the model of the structure (Dyke *et al.*, 1995). When these dynamics are modeled as a time delay, the effects on the performance of active control systems has been investigated by many researchers (Abdel-Rohman, 1987; Agrawal *et al.*, 1993; Hou and Iwan, 1992; Inaudi and Kelly, 1994; Sain *et al.*, 1992; Yang *et al.*, 1990; Zhang *et al.*, 1993; Quast *et al.*, 1995; Battaini and Dyke, 1998; Battaini *et al.*, 2000) and various methodologies to deal with this problem have also been available in the literature (Chung *et al.*, 1989; McGreevy *et al.*, 1987; Lin *et al.*, 1996). Agrawal and Yang (1997) conducted a state-of-the-art literature survey on the effect of the fixed time delay and also presented an approach to determine the critical time delay of multiple-degree-of-freedom systems numerically. Furthermore, five methods of compensating for the fixed time delay were presented and investigated by Agrawal and Yang (2000), but these apply to continuous-time systems only.

By considering the discrete-time nature and the effect of time delay, it is more feasible and realistic to consider control design in a direct discrete-time approach. Chung *et al.* (1995) and Lin *et al.* (1993a) adopted the discrete-time approach in the control derivation and also incorporated a time delay to derive direct output feedback optimal control gains. An SDOF/3DOF analytical model with an active tendon device was simulated and the results demonstrated the applicability of this approach in practical implementation. Another simulation based on the hybrid/active mass damper (HMD/AMD) device was conducted by Chu *et al.* (2002). The control algorithm was formulated in discrete-time format, which also follows the trend to use digital computers for on-line calculation of control forces. Time delay and sampling period are considered at the very beginning of the controller design, and no approximation and estimation are made on the control system.

Based on full-scale implementation experiences gained, a real structural implementation of a control system was considered for the Nanjing Tower in China in order to reduce its excessive vibration during wind storms. Cheng *et al.* (1994) proposed to use an HMD system. Wu and Yang (1998) considered the continuous sliding mode control strategy. An AMD system was finally chosen to bring the structural response to within acceptable limits. Control analysis and design for this implementational effort were reported in Cao (1997) and Cao *et al.* (1998). Preliminary implementation issues were also reported in Reinhorn *et al.* (1998). The fail-safe protection is also an extremely important aspect of a strucural control system (Casciati and Faravelli, 1991). A study on fault tolerance was considered in Battaini and Dyke (1998).

1.5 ORGANIZATION

The focus of this book is to document necessary knowledge needed to successfully implement an active, hybrid, or semi-active control system on a structure. The controller has the main role to synthesize the sensed information to produce the control signal which is transferred to the force generation in the ideal case. Many control algorithms were developed and designed for implementations. However, the controller has many more functions:

(a) detect imperfections, delays, malfunctions, and deterioration of the sensing system;

(b) detect imperfections, delays, malfunctions, and deterioration of the force generation system and power supply;

(c) detect imperfections, delays, malfunctions, and deterioration of the structural system being controlled;

(d) compensate the system on fail-safe in the presence of the above;

(e) transfer information between analog and digital electronics of all components.

Substantial progress in the control design has been made in the past two decades, as indicated in previous sections. Moreover, substantial progress was made in the implementation of the above components and functions (Soong and Spencer, 2002).

This book presents through a case study the detailed functions of the components, their construction, and interactions. The components involved in sensing, control calculation, and force generation are shown using a combination of analog and digital electronics and electro-servo-hydraulics. Although the presentation shows specific components fitting the above architecture, the functions, solutions, and component structures can be implemented using more modern packages, digital microelectronics, or electrical/magnetic/optical power sources using some schematics and performance objectives.

Moreover, the book presents the principles and requirements for prototype software built on logic, which implements control design while providing the functions of detection, compensation, and fail-safe as related to the hardware. The book also presents the concept of pre-implementation simulation for quality control and specifies the components and the qualifications procedures. It shows the control principles, the components' functions and specifications, the performance evaluation, and system requirements. The case study presented herein shows all components involved, a physical implementation, and verification. It should be noted that all parts and components can be replaced or could be replaced in the future with integrated circuitries and functions, but the specifications indicated in this book would apply equally well.

Dedicated to control design professionals and manufacturers, this book illustrates to owners and designers of structures the level of complexity and reliability that can be obtained using pre-implementation qualifications and simulations.

Chapter 2 gives a general description of the active control hardware functions. They can be divided into two major categories: the analog control system and the digital control system. Commonly used hardware and their generic features are introduced. Advantages and limitations on the selection of different devices are also compared. Some basic electronic components and circuitry are introduced to provide customized options while designing an active control system. The important fail-safe features are also included.

Software issues associated with active control applications are described in Chapter 3. The required knowledge and control software developing issues involved in the digital control system are addressed in order to translate the theoretical development into practice. The basic design morphology of a complete control system is introduced. Both traditional and advanced control algorithms are applicable. The modular design approach allows straightforward inclusion of their effects at appropriate times. The compatibility between control hardware and software of the integrated control system is also evaluated.

In Chapter 4, the required theoretical development and practical implementation techniques in active structural control are derived in both continuous-time and discrete-time approaches. The effects of sampling period and time delay are examined and are considered in the derivation. This chapter provides the analytical background for any system implemented in the digital control hardware. A numerical scheme that performs pre-implementation simulation and estimates the maximum system response is developed. In considering the limited numbers of sensors and controllers, a discrete-time optimal direct output feedback control algorithm is developed in order to provide the required control gains for practical applications.

A real-time structural simulator (RTSS), discussed in Chapter 5, provides an alternative to conducting a real-time integrated testing platform before a proposed control algorithm is applied to a reduced-scale shaking table test or a full-scale on-site structural test. The RTSS emulates the response of a discrete-time theoretical structural model in real-time, and interacts with the active control force. The compatibility between control hardware and software of the whole system is also evaluated. It provides a pre-implementation testing base to verify the accuracy of system identification results and can be used to conduct reliability analysis of the integrated system with parameter uncertainty or measurement noise.

Based on the proposed general implementation-related guidelines, a real structural implementation case study is adopted to demonstrate the detailed description of each major component in an active control system and conduct the real-time integrated performance test. Some specific hardware are used to illustrate the detailed hardware functions that are designed based on the general guidelines provided in Chapter 2. The core of the control system, the control software, is developed including the appropriate modules that are necessary for the case study model. The designed real-time functions, especially the multiple fail-safe protection functions, are verified through the real-time structural simulator to ensure and validate their performance before practical implementation.

Chapter 6 summarizes the important findings and results, and gives recommendations for future work that can be done based on this monograph in order to further verify the integrated procedures.