Controlling Buildings: A New Frontier in Feedback

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The protection of civil structures, including their material contents and human occupants, is without doubt a worldwide priority of the most serious current importance. Such protection may range from reliable operation and comfort, on the one hand, to survivability on the other. Examples of such structures leap to one's mind, and include buildings, offshore rigs, towers, roads, bridges, and pipelines. In like manner, events that cause the need for such protective measures are earthquakes, winds, waves, traffic, lightning, and—today, regrettably—deliberate acts. Indications are that control methods will be able to make a genuine contribution to this problem area, which is of great economic and social importance. In this article, we review the rapid recent developments which have been occurring in the area of controlled civil structures, including full-scale implementations, actuator types and characteristics, and trends toward the incorporation of more modern algorithms and technologies.

Introduction

One of the exciting new application areas for feedback system design has to do with the protection of civil engineering structures from dynamic loadings such as strong earthquakes, high wind, extreme waves, heavy traffic, and highway loading. Buildings and other physical structures, including highway infrastructures, have traditionally relied on their strength and ability to dissipate energy to survive under severe dynamic loading. In recent years, worldwide attention has been directed toward the use of control and automation to mitigate the effects of these dynamic loads on these structures [1-3]. In fact, several buildings in Japan, including a 70-story hotel and a 52-story office complex, are currently employing active control strategies for motion control. Active systems are also used temporarily in construction of bridges or large span structures (e.g., lifelines, roofs) where no other means can provide adequate protection.

Fig. 1 provides a schematic diagram of the structural control problem. The basic task is to determine a control strategy that uses the measured structural responses to calculate an appropriate control signal to send to the actuator that will enhance structural safety and serviceability. To better understand the problem, consider control of the tall building depicted in Fig. 2 using an active mass damper (AMD) system. For this control system, a small auxiliary mass, which is usually less than 1% of the total mass of the structure, is installed on one of the upper floors of the building, and an actuator is connected between the auxiliary mass and the structure. Responses and loads at key locations on the building are measured and sent to the control computer. The computer processes the responses according to the control algorithm and sends an appropriate signal to the AMD actuator. The actuator then reacts against the auxiliary mass, applying inertial control forces to the structure to reduce the structural responses in the desired manner. A wealth of structural control studies have been conducted since Yao [4] first introduced the concept of active control of civil engineering structures. These include, for example, H_2 / H_∞ control [5-8], sliding mode control [9-12], saturation control [13, 14], reliability-based control [15-21], fuzzy control [22-26], neural control [27, 28], modeling and identification [29-32], nonlinear control [33-37], implementation issues [38-43], and benchmark studies [44, 45].

The first full-scale application of active control to a building was accomplished by the Kajima Corporation in 1989 [46, 47]. The Kyobashi Seiwa building shown in Fig. 3 is an 11-story (33.1 m) building in Tokyo, Japan, having a total floor area of 423 m^2. A control system was installed, consisting of two AMDs—the primary AMD is used for transverse motion and has a mass of four tons, while the secondary AMD has a mass of one ton and is employed to reduce torsional motion. The role of the active sys-

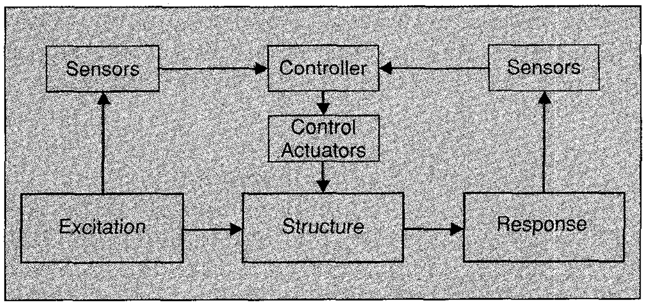

Fig. 1. Schematic diagram of the structural control problem.

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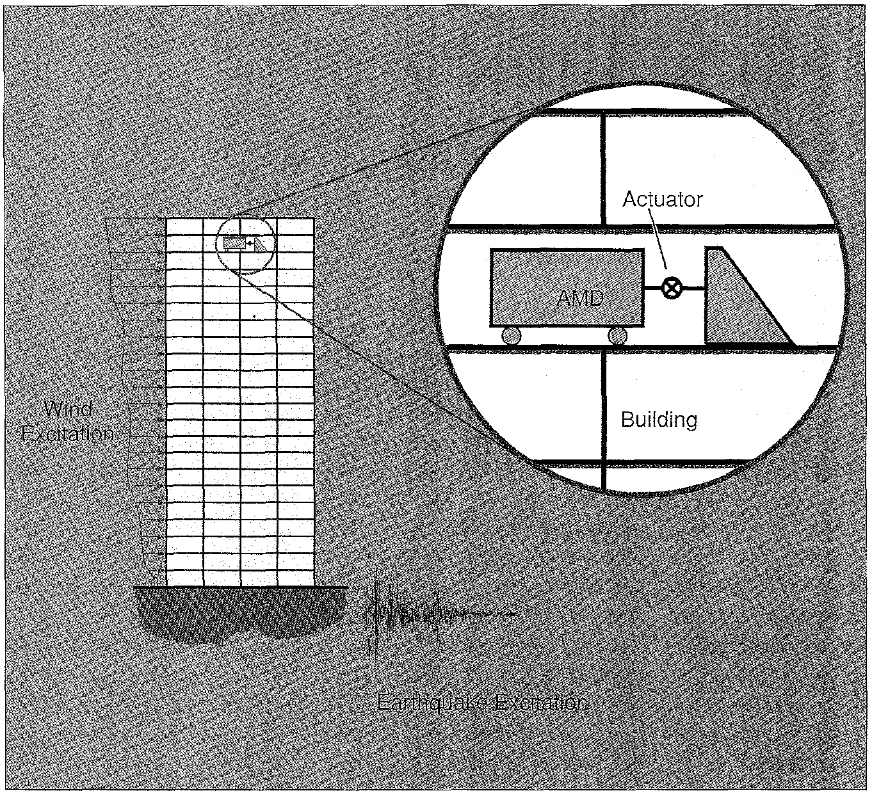

Fig. 2. Concept of the AMD control system.

tem is to reduce building vibration under strong winds and moderate earthquake excitations and consequently to increase the comfort of occupants of the building.

Although nearly a decade has passed since construction of the Kyobashi Seiwa building, a number of serious challenges remain to be resolved before feedback control technology can gain general acceptance by the engineering and construction professions at large. These challenges include: (i) reduction of capital cost and maintenance, (ii) eliminating reliance on external power, (iii) increasing system reliability and robustness, and (iv) gaining acceptance of nontraditional technology. Hybrid and semi-active control strategies are particularly promising in addressing a number of the challenges to this technology. The next section discusses some of the hybrid control systems, which are more mature. The subsequent section considers recently proposed semi-active control strategies, employing devices that have the possibility to provide the reliability and low power requirements of passive devices, yet maintain the versatility and adaptability of fully active systems. The final section more closely examines a specific semi-active damper, based on the magnetorheological technology, that has substantial promise for civil engineering applications.

Hybrid Control Systems

Hybrid control strategies have been investigated by many researchers to exploit their potential to increase the overall reliability and efficiency of the controlled structure [48]. A hybrid control system is typically defined as one that employs a combination of passive and active devices. 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. Additionally, the resulting hybrid control system can be more reliable than a fully active system, although it is also often somewhat more complicated. To date, there have been more than 20 buildings and 10 bridges (during erection) that have employed feedback control strategies in full-scale implementations (see Tables 1 and 2). The vast majority of these have been hybrid control systems. Research in the area of hybrid control systems has focused primarily on two classifications of systems: (i) hybrid mass damper systems and (ii) hybrid base isolation.

Hybrid Mass Damper

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

Many researchers have made significant contributions toward development of HMDs that are compact, efficient and practically implementable. A number of innovative, long-period devices have been reported. For example, Tanida et al. [49] developed an arch-shaped HMD that has been employed in a variety of applications, including bridge tower construction, building response reduction, and ship roll stabilization. An arch-shaped hybrid mass damper (see Fig. 4) was used during erection of the bridge

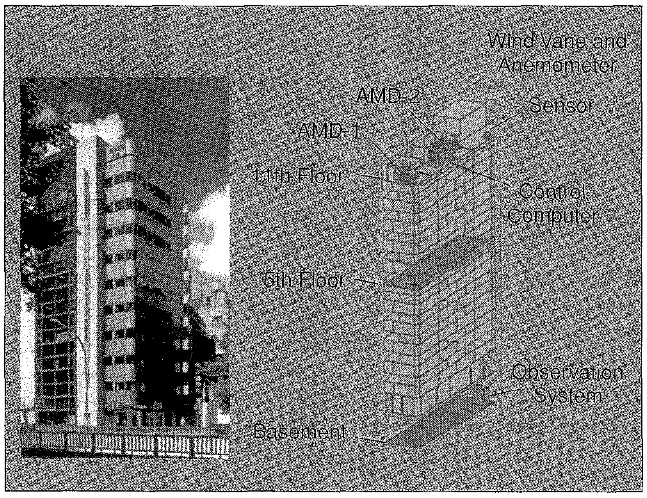

Fig. 3. Kyobashi Seiwa building with AMD installation.

tower (height = 119m) of the Rainbow suspension bridge in Tokyo to reduce large-amplitude vortex-induced vibration expected to occur at a wind speed of 7m/s [49, 50]. The mass ratio for the hybrid damper used for the Rainbow bridge tower was 0.14% of the first modal mass of the structure, whereas a comparable passive TMD would require a 1% mass ratio to achieve a similar level of performance. Fig. 5b shows an extension of the arch-shaped HMD, the V-shaped HMD [51], which has the advantage of having an easily adjustable fundamental period. Three of these devices were installed in the Shinjuku Park Tower, the largest building in Japan, in terms of square footage (see Fig. 5a).

Two multi-step pendulum HMDs each having a mass of 170 tons [52] have been developed and installed in the Yokohama Landmark Tower, Fig. 6, the tallest building in Japan. The process of constructing the Landmark Tower provides yet another interesting and attractive application of active control, which is associated with the way in which construction cranes were used during its erection. Active control of the position of the crane was carried out by two fans (see Fig. 7). These fans prevented excessive displacement and rotation of the building panels while hoisting and installing them, even under strong winds. Moreover, the overall efficiency of the crane work was significantly improved, and resulted in reduced construction time for the Tower.

The DUOX HMD [46, 53], which attains high control efficiency with a small actuator force, has also been proposed and employed in two buildings (see Fig. 8). Devices similar to the DUOX HMD were also studied by Iemura and Izuno [54]. Otsuka et al. [55] conducted experiments in which a roller-pendulum based HMD was applied to control a tower experiencing seismic excitation. Information regarding similar full-scale

Table 1. Summary of Actively Controlled Buildings/Towers

Full-Scale Structure	Location	Year Completed	Scale of Building	Control System Employed	AMD/HMD		Actuation Mechanism
					No.	Mass (Tons)	
Kyobashi Seiwa	Tokyo, Japan	1989	33m, 400 ton, 11 stories	AMD	2	5	Hydraulic
Kajima Research Institute KaTRI No. 21 Building	Tokyo, Japan	1990	12m, 400 ton, 3 stories	Active Variable Stiffness System (6 devices)	--	--	Hydraulic
Sendagaya INTES	Tokyo, Japan	1992	58m, 3280 ton, 11 stories	AMD	2	72	Hydraulic
Applause Tower	Osaka, Japan	1992	161m, 13943 ton, 34 stories	HMD	1	480	Hydraulic
Kansai Int. Airport Control Tower	Osaka, Japan	1992	86m, 2570 ton, 7 stories	HMD	2	10	Servo motor
Osaka Resort City 2000	Osaka, Japan	1992	200m, 56980 ton, 50 stories	HMD	2	200	Servo motor
Yokohama Land Mark Tower	Yokohama, Kanagawa, Japan	1993	296m, 260610 ton, 70 stories	HMD	2	340	Servo motor
Long Term Credit Bank	Tokyo, Japan	1993	129m, 40000 ton, 21 stories	HMD	1	195	Hydraulic
Ando Nishikicho	Tokyo, Japan	1993	54m, 2600 ton, 14 stories	HMD (DUOX)	1	22	Servo motor
Hotel Nikko Kanazawa	Kanazawa, Ishikawa, Japan	1994	131m, 27000 ton, 29 stories	HMD	2	100	Hydraulic
Hiroshima Riehga Royal Hotel	Hiroshima, Japan	1994	150m, 83000 ton, 35 stories	HMD	1	80	Servo motor
Penta-Ocean Exp. Building		1994	6 stories	HMD			
Shinjuku Park Tower	Tokyo, Japan	1994	227m, 130000 ton, 52 stories	HMD	3	330	Servo motor

Table 1. Summary of Actively Controlled Buildings/Towers (continued)

Full-Scale Structure	Location	Year Completed	Scale of Building	Control System Employed	AMD/HMD		Actuation Mechanism
					No.	Mass (Tons)	
MHI Yokohama Building	Yokohama, Kanagawa, Japan	1994	152m, 61800 ton, 34 stories	HMD	1	60	Servo motor
Hamamatsu ACT Tower	Hamamatsu, Shizuoka, Japan	1994	212m, 107500 ton, 46 stories	HMD	2	180	Servo motor
Riverside Sumida	Tokyo, Japan	1994	134m, 52000 ton, 33 stories	AMD	2	30	Servo motor
Hikarigaoka J-City	Tokyo, Japan	1994	110m, 29300 ton, 26 stories	HMD	2	44	Servo motor
Miyazaki Phoenix Hotel Ocean 45	Miyazaki, Japan	1994	154m, 83650 ton, 43 stories	HMD	2	240	Servo motor
Osaka WTC Building	Osaka, Japan	1994	252m, 80000 ton, 52 stories	HMD	2	100	Servo motor
Dowa Kasai Phoenix Tower	Osaka, Japan	1995	145m, 26000 ton, 28 stories	HMD (DUOX)	2	84	Servo motor
Rinku Gate Tower North Building	Osaka, Japan	1995	255m, 75000 ton, 56 stories	HMD	2	160	Servo motor
Hirobe Miyake Building	Tokyo, Japan	1995	31m, 273 ton, 9 stories	HMD	1	2.1	Servo motor
Plaza Ichihara	Chiba, Japan	1995	61m, 5760 ton, 12 stories	HMD	2	14	Servo motor
TC Tower	Kao Hsung, Taiwan	1996	85 stories	HMD	2	350	Servo motor
Nanjing Tower	Nanjing, China	1997/98	310m	AMD	1	60	Hydraulic

structural control implementations employing HMDs have been well documented (e.g., see [47, 51, 57-69]).

The active/hybrid mass damper is also effective for retrofit applications. Fig. 9 depicts the Nanjing Tower, a 340-meter high television transmission and observation tower recently constructed in Nanjing, China. The tower has two observation decks, the uppermost being at 240 m. During storms, excessive vibration occurs and accelerations at this upper deck can exceed human comfort limit of 0.15 m/sec^2. Cheng et al. [56] proposed to use an HMD system, combining a control actuator with a passive tuned liquid damper to control wind-induced vibration of the tower. Because the structure already existed, numerous physical constraints had to be accommodated in the control system design process. Wu and Yang [73] considered continuous sliding mode control of the Nanjing Tower. The design chosen to be implemented in the Nanjing Tower to bring the structural responses to within acceptable limits is an innovative active mass damper system reported in Cao et al. [71] and Riley et al. [72]. This design, employing a 60-ton ring-shaped mass on sliding friction bearings, was shown to adequately reduce the structural response via a nonlinear control policy, while not violating the constraints. This research was conducted as part of the U.S.-People's Republic of China cooperative program through the National Science Foundation.

A number of other interesting ideas employing the mass damper concept have been proposed. Seto [70, 74] investigated the possibility of using active or passive forces acting between two adjacent structures to reduce the seismic response of both structures. As viewed from actual construction, many modern buildings might be divided into two or more adjacent substructures with connecting elements. Mita and Feng [75], Mita and Kaneko [76], and Chai and Feng [77] presented studies of mega-sub control systems for tall buildings. The control system takes advantage of the mega-structure configuration by designing the sub-structures contained in the mega-structure to act as multi-degree-of-freedom tuned mass dampers. This approach implies that the sub-systems act as vibration absorbers, and hence no additional mass is required as would be the case with a more conventional design. Craig et al. [78] showed that hybrid control schemes, combining a simple active mass damper with the passive damping provided by cladding-structure interaction [79], doubled the reduction in peak response due to passive damping alone.

Researchers have investigated various control methods for HMDs. For example, Shing et al. [80], Kawatani et al. [81], Petti

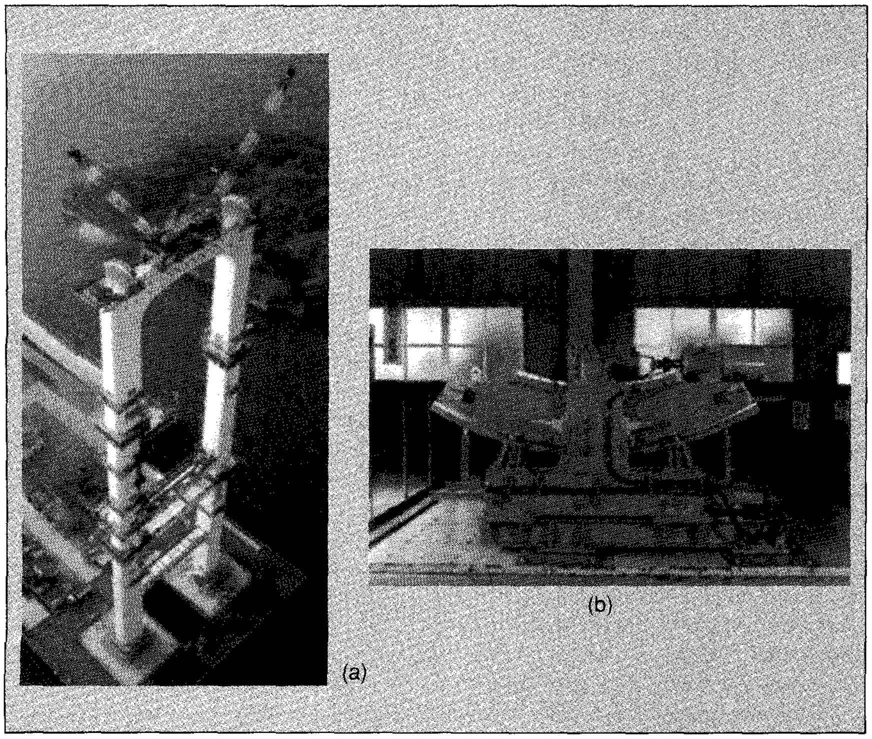

Fig. 4a. Rainbow Bridge Tower while under construction.Fig. 4b. HMD employed during tower erection.

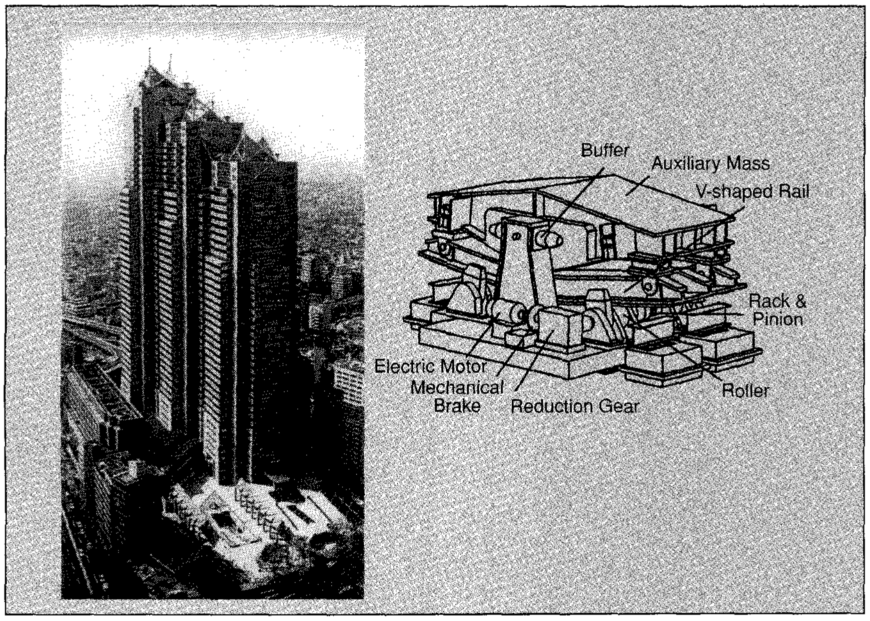

Fig. 5a. Shinjuku Park Tower. Fig. 5b. V-Shaped hybrid mass damper employed in the Shinjuku Park Tower.

et al. [82], Suhardjo et al. [5] and Spencer et al. [6] have considered optimal control methods for HMD controller design. Tamura et al. [83] proposed a gain scheduling technique in which the control gains vary with the excitation level to account for stroke and control force limitations. Similarly, Niiya et al. [84] proposed an ad hoc control algorithm for HMDs to account for the limitations on the stroke. Adhikari and Yamaguchi [11] and Nonami et al. [9] applied sliding mode theory to control structures with HMD systems.

Hybrid Base Isolation

Another class of hybrid control systems which has been investigated by a number of researchers is found in the active base isolation system, consisting of a passive base isolation system combined with a control actuator to supplement the effects of the base isolation system. Base isolation systems have been implemented on civil engineering structures worldwide for a number of years because of their simplicity, reliability, and effectiveness. Excellent review articles of base isolation systems are presented by Kelly [85, 86], Buckle and Mayes [87], and Soong and Constantinou [88]. However, base isolation systems are passive systems and are limited in their ability to adapt to changing demands for structural response reduction. With the addition of an active control device to a base isolated structure, a higher level of performance can potentially be achieved without a substantial increase in the cost [89], which is very appealing from a practical viewpoint. Since base isolation by itself can reduce the interstory drift and the absolute acceleration of the structure at the expense of large absolute base displacement, the combination with active control is able to achieve both low interstory drift and, at the same time, limit the maximum base displacement with a single set of control forces. A robust control for uncertain linear base-isolated structures was proposed by Kelly et al. [90] and more recently by Yoshida et al. [91], Schmitendorf et al. [92], and Yang et al. [93].

Several small-scale experiments have been performed to verify the effectiveness of this class of systems in reducing the structural responses. Reinhorn and Riley [94] performed analytical and experimental studies of a small-scale bridge with a sliding hybrid isolation system in which a control actuator was employed between the sliding surface and the ground to supplement the base isolation system.

Also mentioned in this context is another type of *hybrid* base isolation system which employs a semi-active, friction-controllable fluid bearing in the isolation system. Feng et al. [95] employed such bearings in a hybrid base isolation system in which the pressure in the fluid could be varied to control the amount of friction at the isolation surface. Yang et al. [10, 96] investigated the use of continuous sliding mode control and variable structure system for a base isolated structure with friction-controllable bearings.

Because base isolation systems often exhibit nonlinear behavior, researchers have developed various nonlinear control strategies including fuzzy control [22], neural network based control [27, 28], and robust nonlinear control [97]. In addition, Inaudi et al. [98] studied the use of frequency domain shaping techniques in designing controllers.

Semi-Active Control Systems

Control strategies based on semi-active devices appear to combine the best features of both passive and active control systems and to offer the greatest likelihood for near-term acceptance of control technology as a viable means of protecting civil engineering structural systems against earthquake and wind loading. The attention received 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.

According to presently accepted definitions, a semi-active control device is one which cannot inject mechanical energy into the controlled structural system (i.e., including the structure and the control device), but has properties which can be controlled to optimally reduce the responses of the system. Therefore, in contrast to active control devices, semi-active control devices do not have the potential to destabilize (in the bounded input/bounded output sense) the structural system. Preliminary studies indicate 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 [99-101]. Examples of such devices will be discussed in this section, including variable-orifice fluid dampers, variable-stiffness devices, controllable friction devices, controllable tuned liquid dampers, controllable-fluid dampers, and controllable impact dampers.

Variable-Orifice Dampers

One means of achieving a variable-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 Fig. 10. The concept of applying this type of variable-damping device to control the motion of bridges experiencing seismic motion was first discussed by Feng and Shinozuka [102], Kawashima and Unjoh [103], and Kawashima et al. [104]. Subsequently, variable-orifice dampers have been studied by Symans et al. [105] and Symans and Constantinou [106] at the National Center for Earthquake Engineering Research in Buffalo, NY.

Sack and Patten [107] conducted experiments in which a hydraulic actuator with a controllable orifice was implemented in a single-lane model bridge to dissipate the energy induced by vehicle traffic (see also [108]). Fig. 11 shows a full-scale experiment

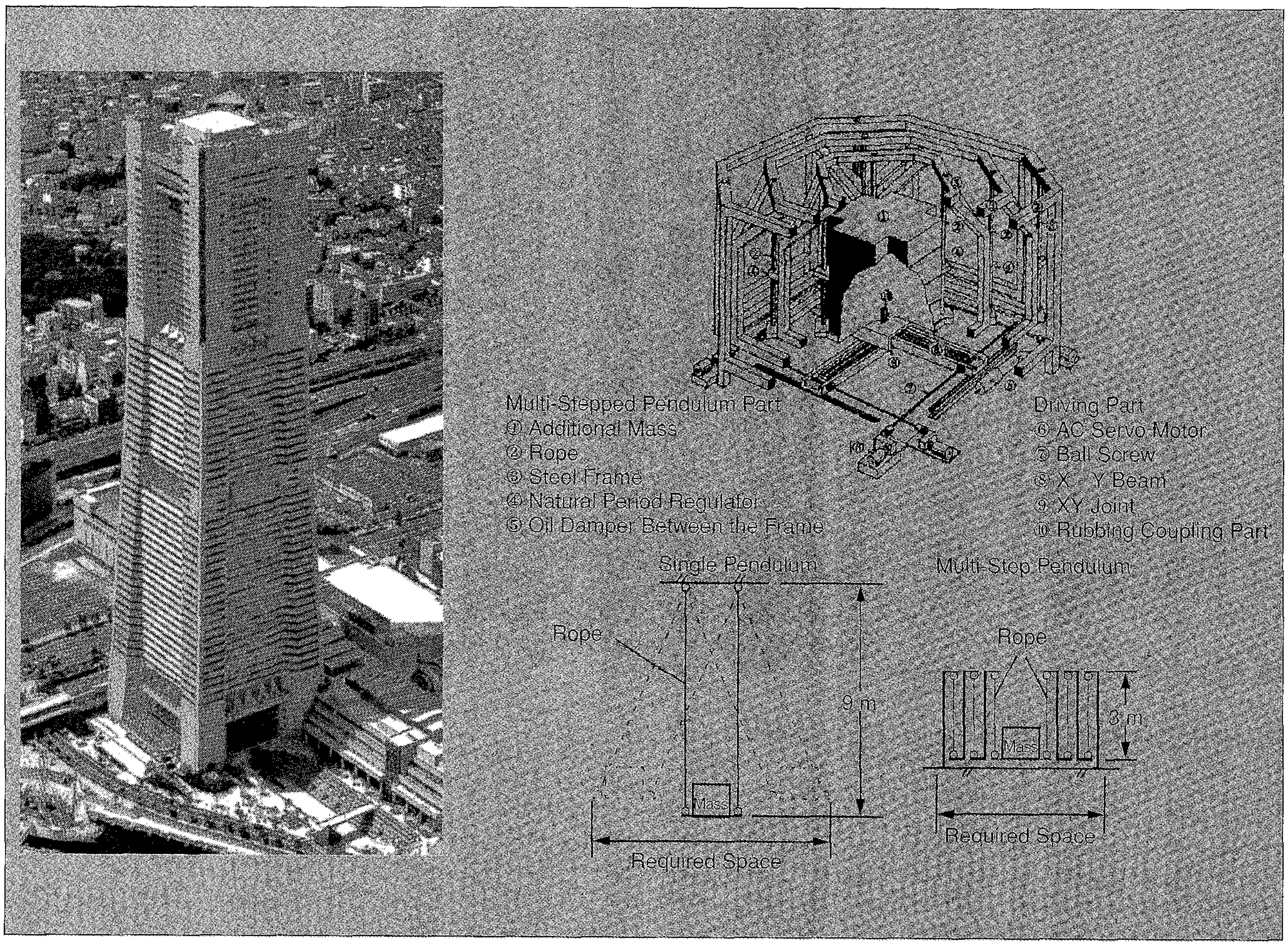

Fig. 6. Multi-step pendulum damper used in the Yokohama Landmark Tower.

being conducted by Sack and Patten on a bridge on interstate highway I-35 in Oklahoma to demonstrate this technology. This experiment constitutes the first full-scale implementation of structural control in the United States.

The effectiveness of variable-orifice dampers in controlling seismically excited buildings has been demonstrated through both simulation and small-scale experimental studies [109-117]. Kobori et al. [118] and Kamagata and Kobori [119] implemented a full-scale variable-orifice damper in an active variable-stiffness system to investigate adaptive control methods for an active variable-stiffness system at the Kobori Research Complex. The results of these analytical and experimental studies indicate that this device is effective in reducing structural responses.

Variable-Friction Dampers

Various semi-active devices have been proposed which utilize forces generated by surface friction to dissipate vibratory en-

Table 2. Summary of Bridge Towers Employing Active Control During Erection

Name of Bridge	Years Employed	Height, Weight	Frequency Range (Hz)	Moving Mass, Mass Ratio (%^{a})	Control Algorithm	Number of Controlled Modes
Rainbow Bridge Pylon I	1991 ~ 1992	119m 4800 tonf	0.26-0.95	6 ton x 2 0.6	Feedback control	3
Pylon 2	1991 ~ 1992	117m 4800 tonf	0.26-0.55	2 ton 0.14	DVFB^b	1
Tsurumi-Tsubasa Bridge^c	1992 ~ 1993	183m 3560 tonf	0.27-0.99	10 ton x 2 0.16	Optimal regulator DVFB	1
Hakucho Bridge Pylon 1	1992 ~ 1994	127.9m 2400 tonf	0.13-0.68	9 tonf 0.4	Sub-optimal feedback control	1
Pylon 2	1992 ~ 1994	131m 2500 tonf	0.13-0.68	4 ton x 2 0.36	DVFB	1
Akashi Kaikyo Bridge Pylons 1 & 2	1993 ~ 1995	293m 24,650 tonf	-0.127-	28 ton x 2 0.8	Optimal regulator DVFB	1
Meiko-Central Bridge^c Pylon 1	1994 ~ 1995	190m 6200 tonf	0.18-0.42	8 ton x 2 0.98-1.15	H_∞ Feedback control	1
Pylon 2	1994 ~ 1995	190 6200 tonf	0.16-0.25	0.17-0.38		1
1st Kurushima Bridge Pylon 1	1995 ~ 1997	112m 1600 tonf	0.23-1.67	6 ton x 2 0.15-2.05	Sub-optimal regulator control	3
Pylon 2	1995 ~ 1997	145m 2400 tonf	0.17-1.70	10 ton x 2 0.3-2.6	H_∞ Feedback control	3
2nd Kurushima Bridge Pylon 1	1994 ~ 1997	166m 4407 tonf	0.17-1.06	10 ton x 2 0.41	DVFB/H_∞	2
Pylon 2	1995 ~	1997143m 4000 tonf	0.20-1.45	10 ton x 2 0.54-1.01	Fuzzy control	More than 3
3rd Kurushima Bridge Pylon 1	1995 ~ 1996	179m 4500 tonf	0.13-0.76	11 ton x 2 0.3-2.4	Variable gain DVFB	1
Pylon 2	1994 ~ 1996	179m 4600 tonf	0.13-0.76	11 ton x 2 0.3-2.4	H_∞ output feedback control	1
Nakajima Bridge^c	1995 ~ 1996	71m 580 tonf	0.21-1.87	3.5 ton x 2 1.0-10.6	Fuzzy control	3

^{a}Percent of first modal mass.

^{b}Direct velocity feedback.

^{c}Cable-stayed bridge. Others are suspension bridges.

ergy in a structural system. Akbay and Aktan [120, 121] and Kannan et al. [122] proposed a variable-friction device that consists of a friction shaft that is rigidly connected to the structural bracing. The force at the frictional interface was adjusted by allowing slippage in controlled amounts. A similar device was considered at the University of British Columbia [123-125]. Through analytical studies, the ability of these semi-active devices to reduce the interstory drifts of a seismically excited structure was investigated [125]. In addition, a semi-active friction-controllable fluid bearing has been employed in parallel with a seismic isolation system in Feng et al. [95] and Yang et al. [96].

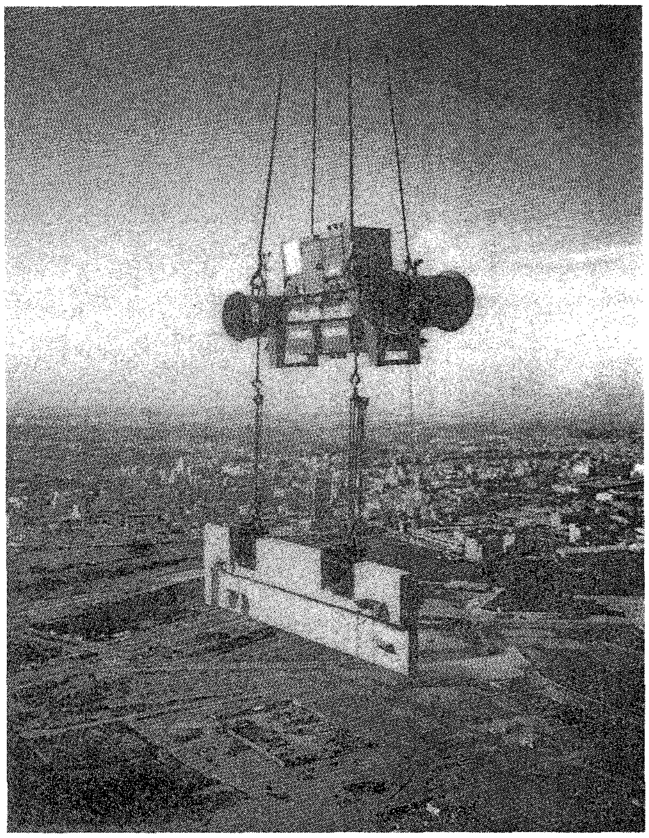

Fig. 7. Actively controlled crane used during construction of the Yokohama Landmark Tower.

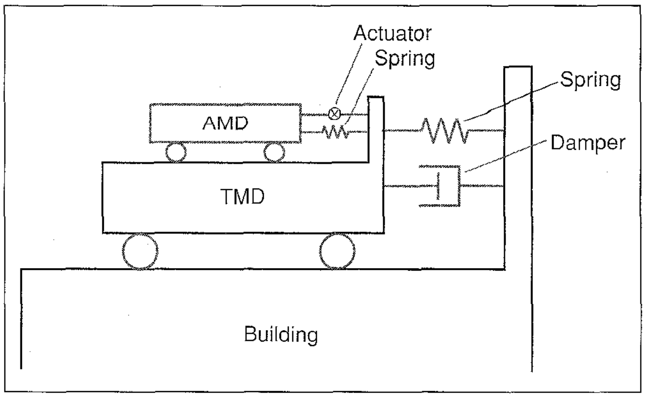

Fig. 8. Concept of the DUOX system.

Controllable Tuned Liquid Dampers

Another type of semi-active control device utilizes the motion of a sloshing fluid or a column of fluid to reduce the responses of a structure. These liquid dampers are based on the passive tuned sloshing dampers (TSD) and tuned liquid column dampers (TLCD). As in a tuned mass damper (TMD), the TSD uses the liquid in a sloshing tank to add damping to the structural system. Similarly, in a TLCD, the moving mass is a column of liquid which is driven by the vibrations of the structure. Because these passive systems have a fixed design, they are not very effective for a wide variety of loading conditions, and researchers are looking toward semi-active alternatives for these devices to improve their effectiveness in reducing structural responses [126]. Lou et al. [127] proposed a semi-active device based on the passive TSD, in which the length of the sloshing tank could be altered to change the properties of the device. Haroun et al. [128] and Abe et al. [129] presented a semi-active device based on a TLCD with a variable orifice.

Controllable-Fluid Dampers

All of the semi-active control devices discussed until now in this section have employed some electrically controlled valves or mechanisms. Such mechanical components can be problematic in terms of reliability and maintenance. Another class of semi-active devices uses controllable fluids. The advantage of controllable fluid dampers is simplicity; they contain no moving parts other than the piston.

Two fluids that are viable contenders for development of controllable dampers are: (i) electrorheological (ER) fluids and (ii) magnetorheological (MR) fluids. The essential characteristic of these fluids is their ability to reversibly change 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 magnetic (for MR fluids) field. Although the discovery of both ER and MR fluids dates back to the late 1940s [130-132], research programs have to date concentrated primarily on ER fluids. A number of ER fluid dampers (see Fig. 12) have recently been developed, modeled, and tested for civil engineering applications [133-138].

Recently developed MR fluids appear to be an attractive alternative to ER fluids for use in controllable fluid dampers [139-141] (see also: http://www.rheonetic.com/mrfluid/ and http://www.nd.edu/~quake/). MR fluids have an inherent ability to provide a simple and robust interface between electronic controls and mechanical components. Much of the current interest in MR fluids can be traced directly to the need for reliable, fast-acting valves necessary to enable semi-active vibration control systems [142-144]. MR fluid technology provides the means for enabling such a valve.

A typical magnetorheological fluid consists of 20-40% by volume of relatively pure, soft iron particles, e.g. carbonyl iron, suspended in an appropriate carrier liquid such as mineral oil, synthetic oil, water, or a glycol. MR fluids made from iron particles exhibit a yield strength of 50-100 kPa for an applied magnetic field of 150-250 kA/m (~2-3 kOe). MR fluids are not highly sensitive to contaminants or impurities such as are commonly encountered during manufacture and usage. Further, because the magnetic polarization mechanism is not affected by the surface chemistry of surfactants and additives, it is relatively straightforward to stabilize MR fluids against particle-liquid separation in

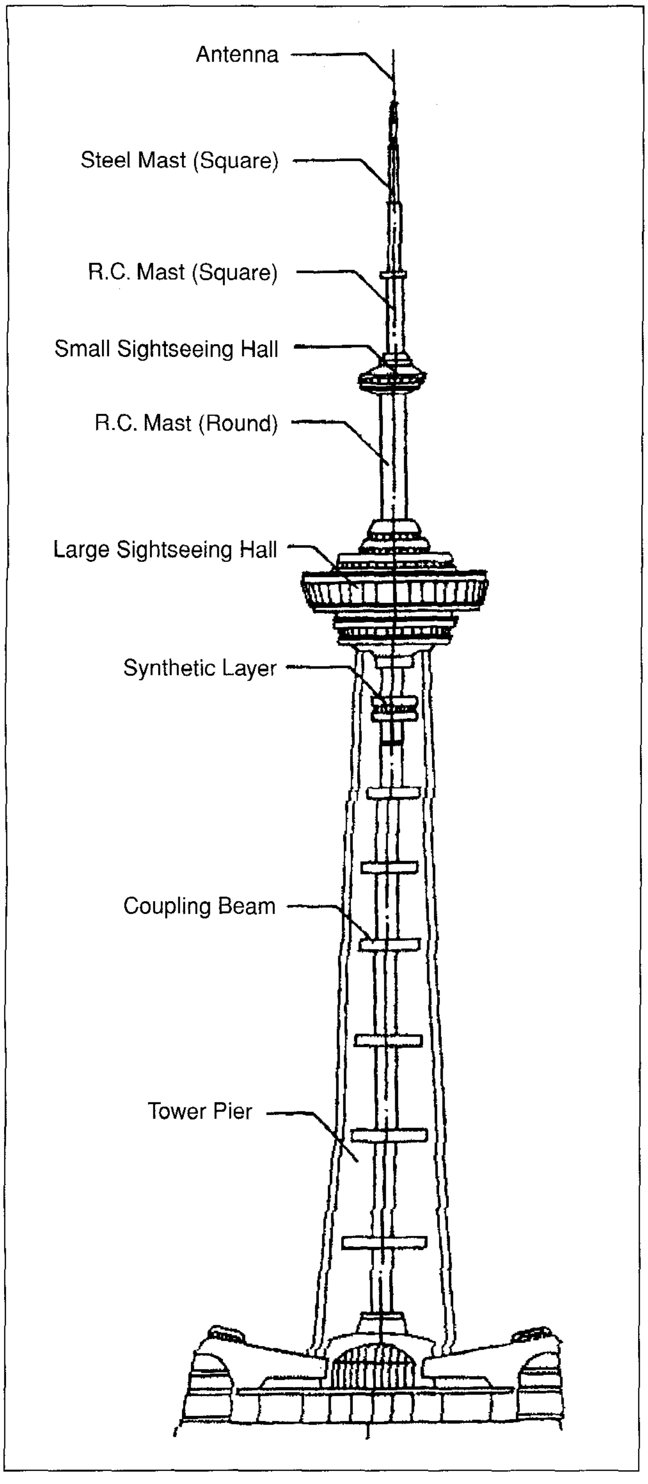

Fig. 9. Nanjing Tower elevation.

spite of the large density mismatch. Antiwear and lubricity additives can also be included in the formulation without affecting strength and power requirements [145, 146].

As a controllable fluid, the primary advantage of an MR fluid stems from the large, controlled yield stress it is able to achieve. Typically, the maximum yield stress of an MR fluid is an order of magnitude greater than that of the best ER fluid, while their viscosity is comparable. This has a profound impact on ultimate device size and dynamic range, because the minimum amount of active fluid in a controllable fluid device is proportional to the plastic viscosity and inversely proportional to the square of the maximum field induced yield stress [139, 141]. This means that for comparable mechanical performance the amount of active fluid needed in an MR fluid device will be about two orders of magnitude smaller than that of an ER device.

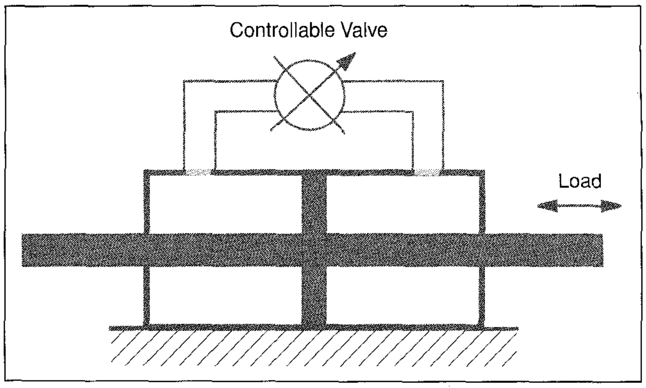

Fig. 10. Schematic of a variable-orifice damper.

From a practical application perspective, an advantage of MR fluids is the ancillary power supply needed to control the fluid. While the total energy and power requirements for comparably performing MR and ER devices are approximately equal [139, 141], only MR devices can be powered directly from common, low-voltage sources. Further, standard electrical connectors, wires, and feedthroughs can be reliably used, even in mechanically aggressive and dirty environments, without fear of dielectric breakdown. This aspect is particularly important in cost-sensitive applications.

Another advantage of MR fluids is their relative insensitivity to temperature extremes and contaminants. Carlson and Weiss [140] indicated that MR fluids can operate at temperatures from -40° to 150°C with only slight variations in the yield stress. This arises from the fact that the magnetic polarization of the particles, and therefore the yield stress of the MR fluid, is not strongly influenced by temperature variations. Similarly, contaminants (e.g., moisture) have little effect on the fluid's magnetic properties. A summary of the properties of both MR and ER fluids is given in Table 3.

The future of MR devices for civil engineering applications appears to be quite bright. Spencer et al. [147-149], Carlson and Spencer [150], and Dyke et al. [99-101] have conducted a number of pilot studies to assess the usefulness of MR dampers for seismic response reduction. Dyke et al. [99-101] have shown through simulations and laboratory experiments that the MR damper, used in conjunction with recently proposed acceleration feedback control strategies, significantly outperforms comparable passive configurations of the damper while using only a fraction of the power required by fully active devices. More details regarding the application of MR technology to control of civil engineering structures will be given in the next section.

Semi-Active Impact Dampers

Passive impact dampers have been around for many years and have been used very successfully to reduce vibration and noise in turbines and gear cases. Studies of multi-particle dampers under random excitation [151] have shown that significant vibration re-

Table 3. Summary of the Properties of Today's MR and ER Fluids [145, 146]

Property	MR Fluids	ER Fluids
Max. Yield Stress $\tau_{y(\text{field})}$	50-100 kPa	2-5 kPa
Maximum Field	~250 kA/m	~4 kV/mm
Plastic Viscosity, η_p	0.1-1.0 Pa-s	0.1-1.0 Pa-s
Operable Temp. Range	-40° to 150° C	+10° to 90° C
Stability	Unaffected by most impurities	Cannot tolerate impurities
Response Time	milliseconds	milliseconds
Density	3 to 4 g/cm^3	1 to 2 g/cm^3
$\eta_p / \tau^2_{y(\text{field})}$	10^{-10} - 10^{-11} s/Pa	10^{-7} - 10^{-8} s/Pa
Maximum Energy Density	0.1 Joules/cm^3	0.001 Joules/cm^3
Power Supply (typical)	2-25 V 1-2 A	2000-5000 V 1-10 mA

duction can be achieved in lightly damped systems with a relatively small multi-particle impact damper. Single particle dampers of the same total mass give greater vibration reduction in certain frequency bands but may have little or no effect in other frequency bands. To remedy this defect, semi-active control has been applied to impact dampers, such that only favorable impacts are permitted [152-154].

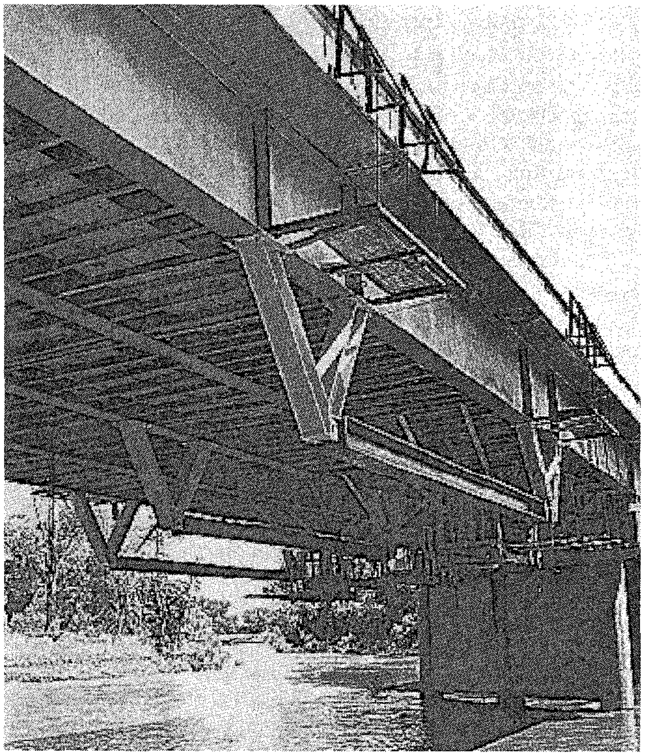

Fig. 11. Full-scale experiment on Interstate 35 in Oklahoma.

Semi-Active Control of Civil Engineering Structures

Magnetorheological dampers are one of the most promising realizations of semi-active technology for application to full-scale civil structures. This section summarizes the work in Spencer et al. [147-149], Dyke et al. [99-101], and Carlson and Spencer [150] to demonstrate the efficacy of MR dampers for seismic response reduction. Both scale-model and full-scale studies are presented.

Scale-Model Studies

Fig. 13 is a diagram of the three-story model building that was employed in the pilot MR damper studies conducted at the Structural Dynamics and Control / Earthquake Engineering Laboratory at the University of Notre Dame (see http://www.nd.edu/~quake/). The test structure used in this experiment is designed to be a scale model of the prototype building discussed in Chung et al. [38] and is subject to one-dimensional ground motion. A single magnetorheological (MR) damper is installed between the ground and the first floor, as shown in Fig. 13. The MR damper employed here, the Lord SD-1000 linear MR fluid damper, is a small, monotube damper designed for use in a semi-active suspension system in large on- and off-highway vehicle seats. The SD-1000 damper is capable of providing a wide dynamic range of force control for very modest input power levels. The damper is 3.8 cm in diameter, 21.5 cm long in the fully extended position, and has a ±2.5 cm stroke. An input power of four watts is required to operate the damper at its nominal maximum design current of one amp.

Because of the intrinsically nonlinear nature of all semi-active control devices, development of control strategies that are practically implementable and can fully utilize the capabilities of these unique devices is a challenging task. Various nonlinear control strategies have been developed to take advantage of the particular characteristics of the semi-active devices, including bang-bang control [138], clipped optimal control [99-101,108,112], bi-state control [108, 112], fuzzy control methods [155], modulated homogeneous friction [156] and adaptive non-

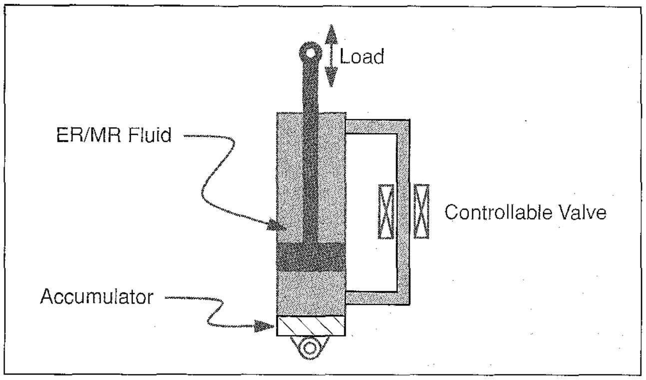

Fig. 12. Schematic controllable fluid damper.

linear control [119]. Caughey [157] proposed a variable stiffness algorithm that employed a semi-active implementation of the Reid spring [158] as a structural element which could provide large amounts of damping for a very small expenditure of control energy.

To evaluate the effectiveness of the semi-active control system employing the MR damper, acceleration feedback control strategies [99-101] based on H_2 performance measures were implemented on the laboratory structure. The three-story model structure was subjected to a scaled version of the N-S component of the 1940 El Centro earthquake, and the measured responses were recorded. Fig. 14 shows the uncontrolled (i.e., without the MR damper attached) and semi-actively controlled responses for the tested structure. The effectiveness of the proposed control strategy is clearly seen, with peak third-floor displacement being reduced by 74.5% and the peak third floor acceleration being reduced by 47.6%.

The semi-active control systems performed significantly better than two passive configurations that were simultaneously considered. A 24.3% reduction in the peak third-floor displacement and a 29.1% reduction in the maximum interstory displacement were achieved as compared to the best passive case. Moreover, these results were obtained while also achieving a modest reduction in the maximum acceleration over the comparable passive case. These results demonstrate the significant potential for the use of MR technology in dynamic hazard mitigation.

Table 4. Design Parameters for 20-Ton Seismic Damper

Stroke	±8 cm
$F_{\max} / F_{\min}$	10.1 @ 10 cm/s
Cylinder Bore (ID)	20.32 cm
Max. Input Power	<50 watts
Max. Force (nominal)	200,000 N
Effective Axial Pole Length	8.4 cm
Coils	3 x 1050 turns
Fluid $\eta_p / \tau^2_{y(\text{field})}$	2×10^{-10} s/Pa
Fluid η_p	1 Pa-s
Fluid $\tau_{y(\text{field})}$ Max	70 kPa
Gap	2 mm
Active Fluid Volume	~90 cm^3
Wire	16 gauge
Inductance (L)	6.6 henries
Coil Resistance (R)	3 x 7.3 ohms

Full-Scale Seismic MR Damper

To prove the scalability of MR fluid technology to devices of appropriate size for civil engineering applications, a full-scale, MR fluid damper has been designed and built [149, 150]. For the nominal design, a maximum damping force of 200,000 N (20-ton) and a dynamic range equal to ten were chosen. A schematic of the large-scale MR fluid damper is shown in Fig. 15. The damper uses a particularly simple geometry in which the outer cylindrical housing is part of the magnetic circuit. The effective fluid orifice is the entire annular space between the piston outside diameter and the inside of the damper cylinder housing. Movement of the piston causes fluid to flow through this entire annular region. The damper is double-ended, i.e., the piston is supported by a shaft on both ends. This arrangement has the advantage that a rod-volume compensator does not need to be incorporated into the damper, although a small pressurized accumulator is provided to accommodate thermal expansion of the fluid. The damper has an inside diameter of 20.3 cm and a stroke of ±8 cm. The electromagnetic coil is wound in three sections on the piston. This results in four effective valve regions as the fluid flows past the piston. The coils contain a total of about 1.5 km magnetic wire. The completed damper is approximately 1 m long and with a mass of 250 kg. The damper contains approximately five liters of MR fluid. The amount of fluid energized by the magnetic field at any given instant is approximately 90 cm^3.

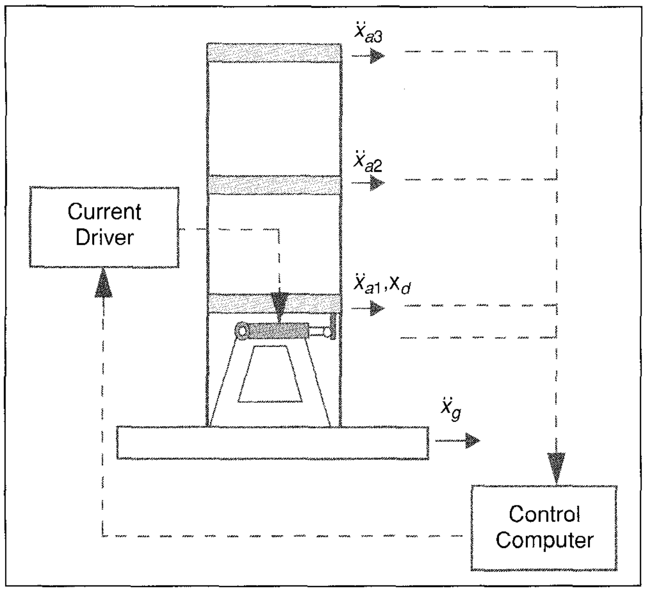

Fig. 13. Diagram of MR damper implementation.

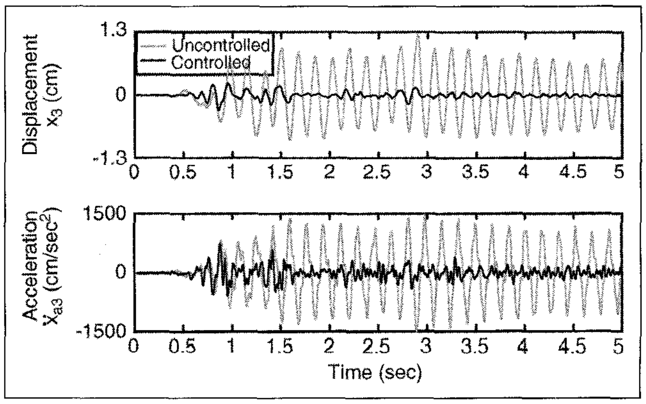

Fig. 14. Controlled and uncontrolled structural responses due to El Centro earthquake.

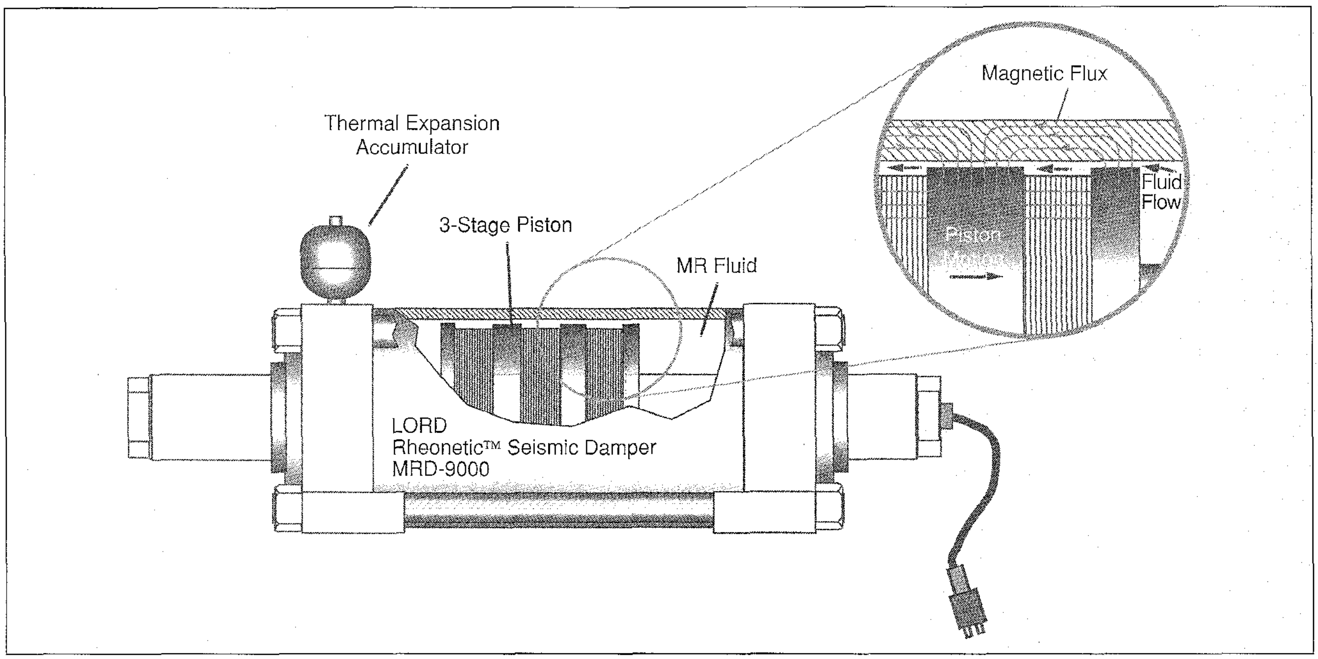

Fig. 15. Schematic of 20-ton MR fluid damper.

A summary of the parameters for the 20-ton damper are given in Table 4.

Fig. 16 shows the experimental setup at the University of Notre Dame for the 20-ton MR fluid damper. The damper was attached to a 7.5 cm thick plate that was grouted to a 2 m thick strong floor. The damper is driven by a 560 kN actuator configured with a 305 lpm servo-valve with a bandwidth of 80 Hz. A Schenck-Pegasus 5910 servo-hydraulic controller is employed in conjunction with a 200 MPa, 340 lpm hydraulic pump.

Fig. 17 shows the measured performance for the damper at 5 cm/sec (triangular displacement). The maximum force measured at full magnetic field strength is 201 kN at a piston velocity of 5 cm/sec, which is within 0.5% of the analytically predicted result [149]. Moreover, the dynamic range of the damper is well over the design specification of 10.

Because of their mechanical simplicity, low power requirements and high force capacity, magnetorheological (MR) dampers constitute a class of semi-active control devices that meshes well with the demands and constraints of civil infrastructure applications and will likely see increasing interest from the engineering community as a viable means for mitigating the devastating effects of severe dynamic loads on civil structures.

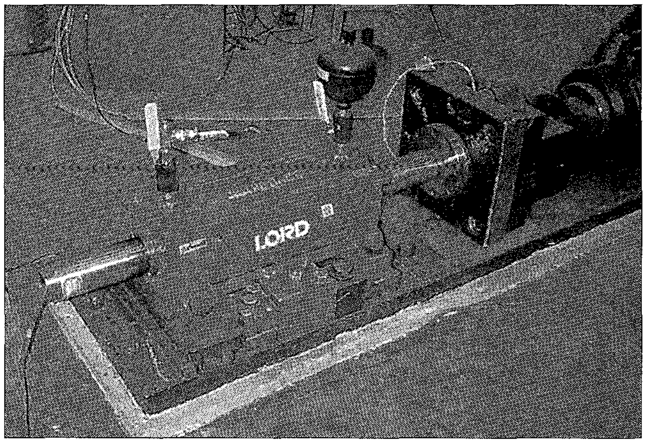

Fig. 16. Experimental setup for 20-ton MR fluid damper.

Conclusions

Protecting civil structures from natural and other types of unwanted dynamic influences is continuing to move steadily up the list of high-priority needs of the world community. The structures alone represent a huge investment of resources. Moreover, they are platforms that carry within them very expensive equipments, irreplaceable records, and priceless human cargo.

As our readers have seen over and over again, the traditional methods of dealing with these exigencies are being reconsidered, and are beginning to give way to the influence of more recent technologies. Of course, along with these technologies comes

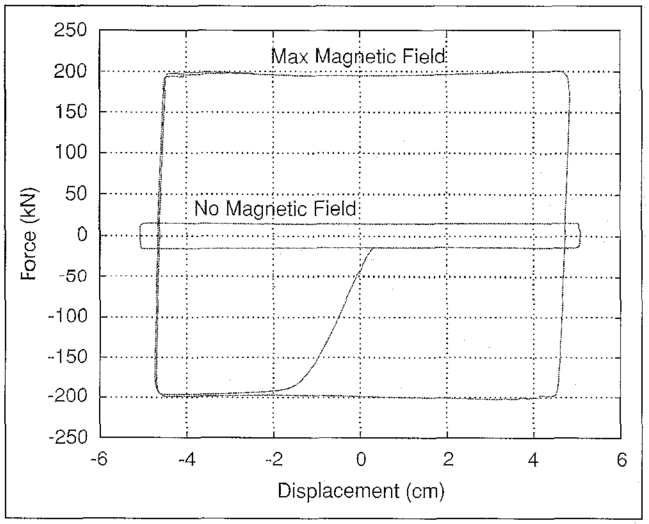

Fig. 17. Measured performance for 20-ton MR fluid damper at 5 cm/sec.

the possibility of more advanced design goals, more modern algorithms, and more state-of-the-art implementations.

Full-scale buildings are being controlled successfully; and attention is turning toward the features of a whole new family of actuators, especially those of semi-active type. Controllable fluid dampers provide a fascinating class of instances, with the magnetorheological fluids offering attractive properties.

It turns out that models for such devices lead one into issues of hybrid control and hysteresis, both of which are topics of considerable current interest in the controls community.

In summary, the modern thrust toward control of civil structures is providing a new opportunity for control engineers to make their work more understandable to the public, while at the same time making a genuine technical, economic, and social contribution.

And, there are hundreds of interesting ideas to ponder ... !

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