Smart Damping Technologies for Dynamic Hazard Mitigation

by

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ABSTRACT

In recent years, considerable attention has been paid to research and development of structural control devices, with particular emphasis on alleviation of wind and seismic response of buildings and bridges. In both areas, serious efforts have been undertaken to develop the structural control concept into a workable technology. To date, full-scale active and hybrid control systems have been designed and installed in approximately 40 commercial buildings and 15 bridges (during construction). Yet the engineering community is reluctant to fully embrace this new technology. Demonstrated cost-effectiveness and reliability are key considerations for acceptance and successful implementation of structural control. Because of their low power requirements and fail-safe character, smart damping strategies appear quite attractive in this regard. The focus of this paper will be to review a number of smart damping approaches that have been proposed and implemented in full-scale structures.

1.0 INTRODUCTION

Passive supplemental damping strategies, including base isolation systems, viscoelastic dampers and tuned mass dampers, are well understood and are accepted by the engineering community as a means for mitigating the effects of dynamic loadings such as strong earthquakes and high winds. However, these passive-device methods are unable to adapt to structural changes and to varying usage patterns and loading conditions.

For more than two decades, researchers have investigated the possibility of using active control methods to improve upon passive approaches to reduce structural responses (Soong 1990; Spencer and Sain 1997; Housner *et al.* 1997; Soong and Spencer 2002). The first full-scale application of active control to a building was accomplished by the Kajima Corporation in 1989 (Kobori 1994). The Kyobashi Seiwa building is an 11-story (33.1 m) building with a total floor area of 423 m^2. An active mass driver (AMD) system was installed, consisting of two AMDs — the primary AMD is used for transverse motion and has a mass of 4 tons, while the secondary AMD has a mass 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 of the building. Since that time, active/hybrid structural control has been successfully applied in approximately 40 commercial buildings and 15 bridges (during construction).

Although extensive analytical and experimental structural control research has been conducted in both the U.S. and Japan in the last decade, with the exception of one experimental system installed on a bridge in Oklahoma (discussed later in this paper), none of these full-scale active control installations are located the U.S. Many possible reasons can be cited for this disparity. For example, the civil engineering profession and construction industry in the U.S. are conservative and generally reluctant to apply new technologies. The absence of verified and consensus-approved analysis, design and testing procedures represent additional impediments to the application of this technology. However, more notable is the lack of research and development expenditures by the U.S. construction industry. This situation is in sharp contrast to the Japanese construction industry, which invests heavily in the development and implementation of new

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technologies. Yet even in Japan, few new projects for implementation of active control systems are being initiated. This situation is partly due to the modest number of tall buildings and long-span bridges being planned for the near future and partly due to a number of serious challenges that remain before active control can gain general acceptance by the engineering and construction professions at large. These challenges include: (i) reducing capital cost and maintenance, (ii) eliminating reliance on external power, (iii) increasing system reliability and robustness, and (iv) gaining acceptance of nontraditional technology.

Despite the impediments that exist to wider application of control to civil engineering structures, the future appears quite bright. Smart damping (also known as semiactive control) strategies are particularly promising in addressing many of the challenges to this technology, offering the reliability of passive devices, yet maintaining the versatility and adaptability of fully active systems. The remainder of this paper discusses several smart damping strategies that have recently been proposed, both in the U.S. and in Japan, for control of civil engineering structures, as well as several applications of this technology. Such systems may facilitate near-term acceptance of control technology by practitioners as an important means for mitigating dynamic hazards.

2.0 SMART DAMPING DEVICES

Smart damping devices have received a great deal of attention in recent years because they 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 smart damping 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 that can be controlled to optimally reduce the responses of the system. Therefore, in contrast to active control devices, smart damping devices do not have the potential to destabilize (in the bounded input/bounded output sense) the structural system. Studies have shown that appropriately implemented smart damping systems perform significantly better than passive devices and have the potential to achieve, or even surpass, the performance of fully active systems, thus allowing for the possibility of effective response reduction during a wide array of dynamic loading conditions (Dyke *et al.* 1998; Spencer *et al.* 2000). Examples of such devices include variable-orifice fluid dampers, controllable friction devices, variable stiffness devices, adjustable tuned liquid dampers, and controllable fluid dampers (Spencer and Sain 1997). Of these classes of smart dampers, two have already been implemented in full-scale structures and will be discussed in the subsequent sections.

2.1 variable-orifice Dampers

One means of achieving a smart 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. 1, which typically operates on approximately 50 watts of power.

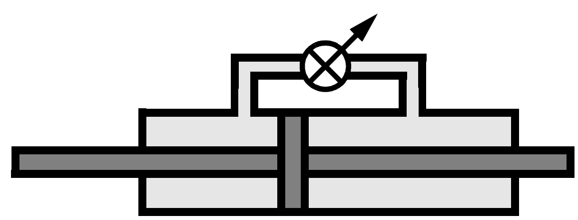


Figure 1. Schematic of Variable-Orifice Damper.

Sack and Patten (1993) 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. These studies were followed by a full-scale experiment conducted on a bridge on interstate highway I-35 to demonstrate this technology (Patten, 1998, 1999; Kuehn et al., 1999) shown in Figs. 2–3. Figure 4 shows the effectiveness of the SAVA system. This experiment constitutes the first full-scale implementation of structural control in the US.

Figure 2. First Full-Scale Implementation of Smart Damping in the US.

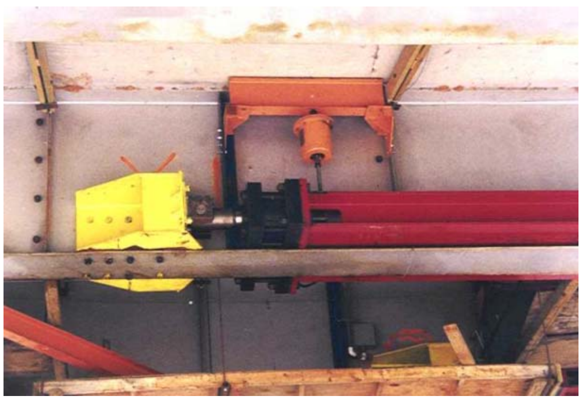


Figure 3. SAVA-II variable-orifice Damper.

Conceived as a variable-stiffness device, Kobori et al. (1993) and Kamagata and Kobori (1994) implemented a full-scale variable-orifice damper in a semiactive variable-stiffness system (SAVS) to investigate semiactive control at the Kajima Technical Research Institute. The overall system is shown in Fig. 5 where SAVS devices were installed on both sides of the structure in the longitudinal direction. The results of these analytical and experimental studies indicate that this device is effective in reducing structural responses.

More recently, a smart damping system was installed in the Kajima Shizuoka Building in Shizuoka, Japan. As seen in Fig. 6, semiactive 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

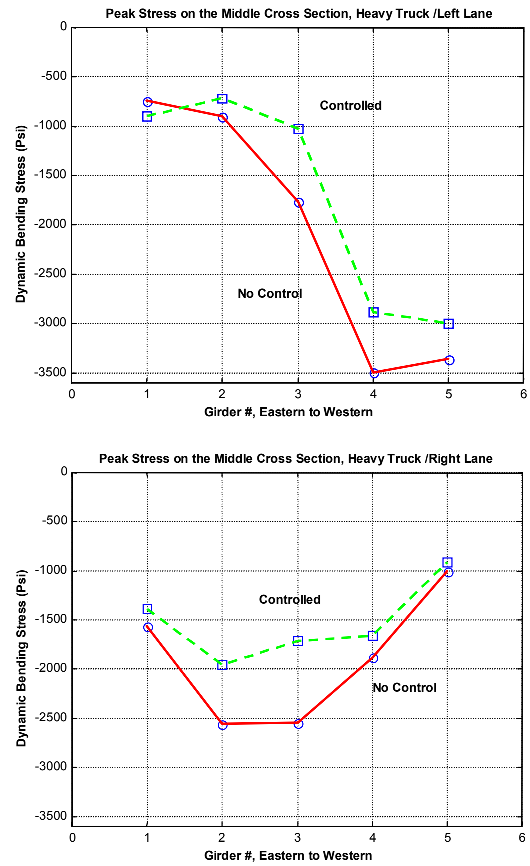


Figure 4. Comparison of Peak Stresses for Heavy Trucks.

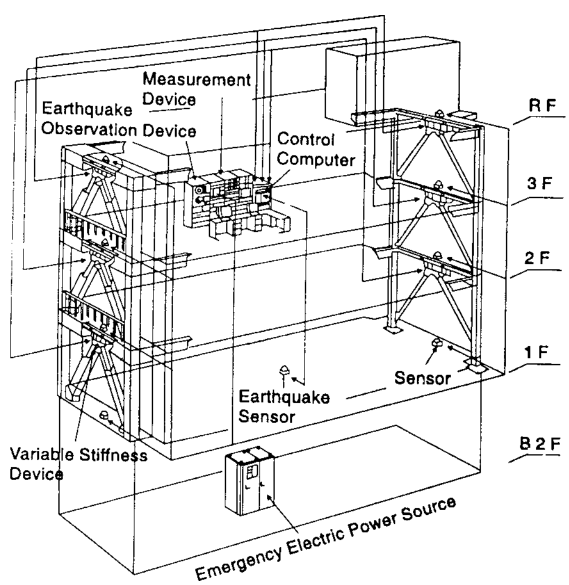


Figure 5. SAVS System Configuration.

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 (see Fig. 7). Figure 8 shows a sample of the response analysis results based on one of the selected control schemes and several earthquake input motions with the scaled maximum velocity of 50 cm/sec, together with a simulated Tokai wave. Both story shear forces and story drifts are seen to be greatly reduced with control activated. In the case of the shear forces, they are confined within their elastic-limit values (indicated by E-limit) while, without control, they would enter the plastic range.

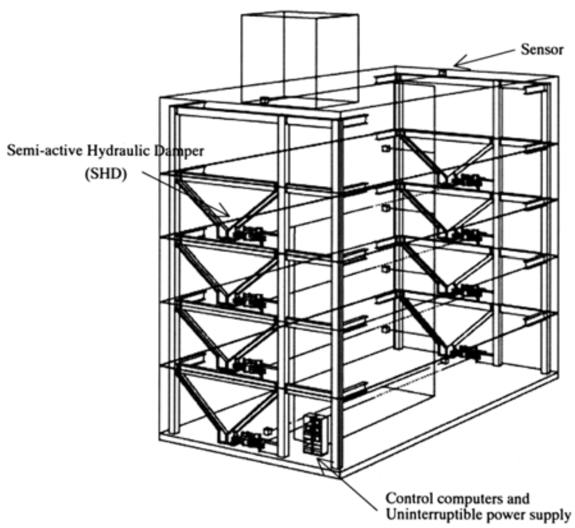


Figure 6. Kajima Shizuoka Building Configured with Semiactive Hydraulic Dampers.

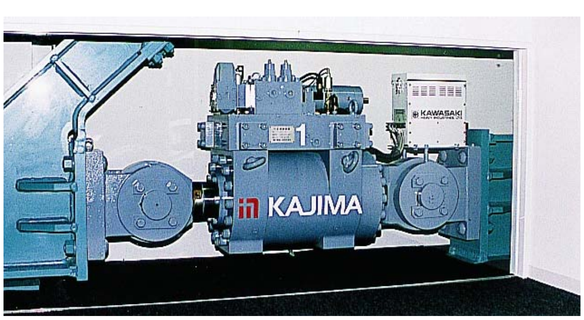
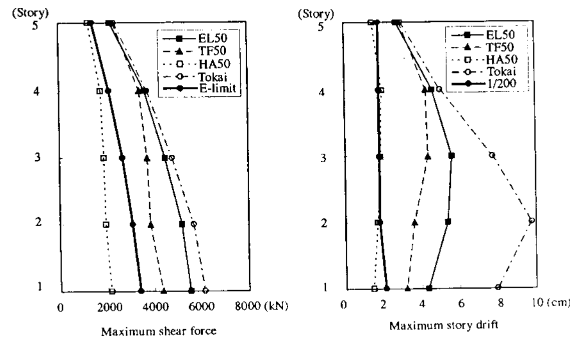


Figure 7. Shizuoka Building variable-orifice Damper.



(a) w/ control (b) w/o control

Figure 8. Maximum Responses (El Centro, Taft and Hachinohe Waves with 50 cm/sec. and Assumed Tokai Waves).

The use of the variable-orifice damper has blossomed in Japan. In the Tokyo Siodome area, 4 new buildings are currently under construction (Kobori 2002). One of these structures is the Kajima K-Building, 38-story building with 88 variable-orifice dampers and 2 hybrid mass dampers. In another area of Tokyo, the Kajima R-Building, a 54-story building with 356 variable-orifice dampers and 192 passive dampers distributed throughout, is under construction. When these projects are completed, a total of more than 700 variable-orifice dampers will be installed in building structures in Japan.

2.2 Controllable Fluid Dampers

In comparison with variable-orifice damper systems, another class of relatively new smart damping devices uses controllable fluids, schematically shown in Fig. 9. In comparison with smart damping 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.

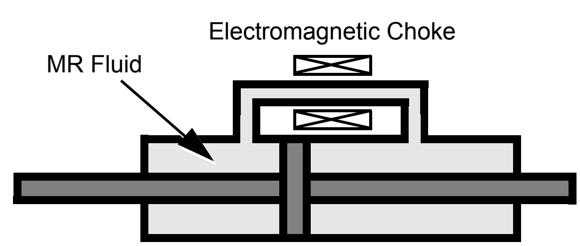


Figure 9. Schematic of MR Damper.

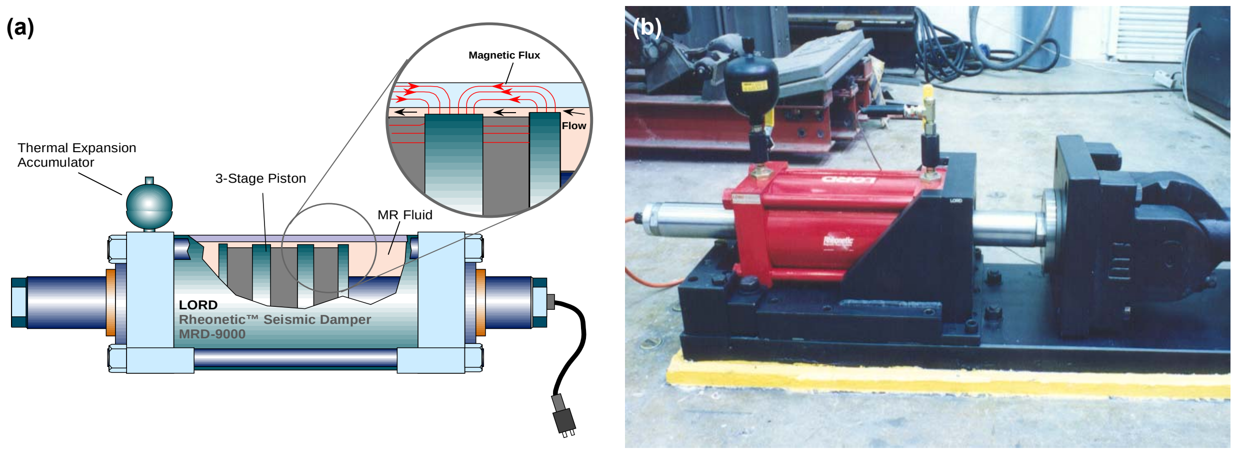


Figure 10. (a) Schematic of 20-ton MR fluid damper; (b) Experimental setup.

The essential characteristics of controllable 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 electrorheological (ER) fluids) or magnetic (for magnetorheological (MR) fluids) field.

In the case of magnetorheological fluids, they typically consist of micron-sized, magnetically polarizable particles dispersed in a carrier medium such as mineral or silicone oil. When a magnetic field is applied to the fluid, particle chains form, and the fluid becomes a semi-solid and exhibits viscoplastic behavior. Transition to rheological equilibrium can be achieved in a few milliseconds, allowing construction of devices with high bandwidth. Additionally, Carlson and Weiss (1994) indicated that high yield stress of a magnetorheological fluid can be achieved and that magnetorheological fluids can operate at temperatures from –40^{o}C to 150^{o}C with only slight variations in the yield stress. Moreover, magnetorheological fluids are not sensitive to impurities such as are commonly encountered during manufacturing and usage, and little particle/carrier fluid separation takes place in magnetorheological fluids under common flow conditions. Further, a wider choice of additives (surfactants, dispersants, friction modifiers, antiwear agents, etc.) can generally be used with magnetorheological fluids to enhance stability, seal life, bearing life, and so on, since electrochemistry does not affect the magnetopolarization mechanism. The magnetorheological fluid can be readily controlled with a low voltage (e.g., 12-24 V), current-driven power supply outputting only 1-2 amps.

Carlson and Spencer (1996) and Spencer et al. (1997, 1998) and Yang *et al.* (2002) report on the design of a full-scale, 20-ton magnetorheological damper (see Fig. 10–11) showing that this technology is scalable to devices appropriate for civil engineering applications. At design velocities, the dynamic range of forces produced by this device is over 10 (see Fig. 11), and the total power required by the device is only 20-50 W.

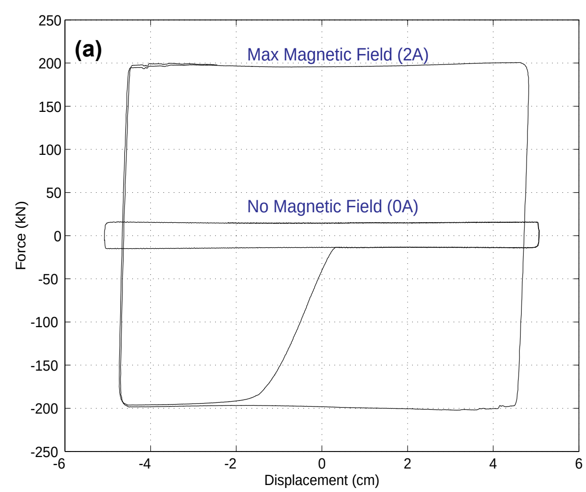


Figure 11. Measured force-displacement loops at 5.4 cm/sec.

Recently, Sunakoda, *et al.* (2001) have also presented encouraging results regarding design, construction, and commercial manufacturing of large scale MR dampers.

In 2001, the first full-scale implementation of MR dampers for civil engineering applications was achieved. The Nihon-Kagaku-Miraikan, the Tokyo National Museum of Emerging Science and Innovation shown in Fig. 12, has two 30-ton, MR Fluid dampers installed between the 3rd and 5th floors. The dampers were built by Sanwa Tekki using the Lord Corporation MR fluid.

Currently being retrofitted with stay-cable dampers, the Dongting Lake Bridge in Hunan, China will constitute the first full-scale implementation of MR dampers for bridge structures. Long steel cables, such as are used in cable-stayed bridges and other structures, are prone to vibration induced by the structure to which they are connected and by weather conditions, particularly wind combined with rain, that may cause cable galloping. The extremely low damping inherent in such cables, typically on the order of a fraction of a percent, is insufficient to eliminate this vibration, causing reduced cable and connection life due to fatigue and/or breakdown of corrosion protection. Two Lord SD-1005 (www.rheonetic.com) MR dampers are being installed on each cable to mitigate cable vibration.

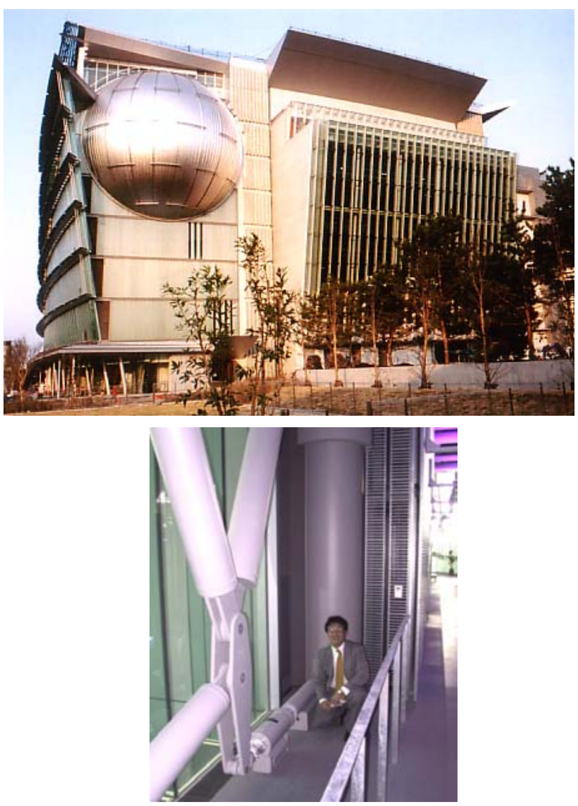


Figure 12. Nihon-Kagaku-Miraikan, Tokyo National Museum of Emerging Science and Innovation.

Figure 13. Dongting Lake Bridge, Hunan, China.

3.0 CONCLUSIONS

Although in their infancy, control strategies based on smart damping devices appear to combine the best features of both passive and active control systems and to offer a viable means of protecting civil engineering structural systems against earthquake and wind loading. In particular, they provide the reliability and fail-safe character of passive devices, yet possess the adaptability of fully active devices. Because of their mechanical simplicity, low power requirements and high force capacity, magnetorheological (MR) dampers constitute a class of smart damping devices that meshes well with the demands and constraints of civil infrastructure applications and will likely see increased interest from the engineering community.

ACKNOWLEDGMENT

The author gratefully acknowledges the support of this research by the National Science Foundation under grant CMS 99-00234 (Dr. S.C. Liu, Program Director) and the Lord Corporation.

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