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A Review of semi-active control in smart structures

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Abstract

This study presents a brief review of a significant research performed in the area of semi-active control systems which is a type of smart structures. The main focus of the review has been derived from journal articles which has been published from1997 to the present. This paper reviews articles on semi active control of structures which include magneto rheological (MR) fluid dampers, semi active stiffness dampers, semi-active tuned liquid column dampers, and piezoelectric dampers. A review of hybrid control systems and control strategies will be presented in the companion paper.

Keywords: semi-active control; smart structures;

1. Introduction

Smart structure can sense its dynamic loading environment via sensors and modify its behavior in real time, so that it can withstand external dynamic forces, such as earthquake loading, wind or impact. In other words, A smart structure is an intelligent machine that can change and adapt to its environment dynamically. There has been increasing interest in the field of smart structures in the past twenty years.

This is definitely one of the most exciting areas of research in structural engineering. Many workers in the field are multidisciplinary, forward thinking and out-of-the-box researchers. The goal of this review paper is to review the significant research done in this area in recent years [1-5].

In an adaptive/smart structure, we design a predetermined number of members to be actively controlled members. Each such member has a sensor, a feedback control device and an actuator.

The sensor measures the displacements along the degrees of freedom.

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The feedback control device determines the appropriate correction to the uncontrolled response, and the actuator applies the required force. Such a system consists of three physical components: sensors, actuators and a computer. There is also the need for a control algorithm that will determine the magnitude of control forces at any given time. However, there are other strategies and physical systems. The common goal in them all is to minimize the vibrations in real time. All of them require an effective control algorithm [6-8].

Housner et al. presented a thorough review of the field of structural control up to 1996. The scope of the present review is limited primarily to journal articles published since 1997. A host of engineers are working in the area of smart structures including mechanical, electrical, materials and structural engineers. As such, the field of smart structures can be quite broad and multidisciplinary. It can also include the field of smart materials. In order to limit the scope of this review within the limitations of a review paper, it has been limited mostly to civil structures, with only mention of relevant papers on smart materials. This paper is dedicated to the review of papers published on semi-active control of structures [9-15].

2. Semi-active control of structures

The shortcoming of an active control system is its requirement for a considerable power source. A semi-active control system needs limited power and is normally operated by a battery.

2.1. Magnetorheological (MR) fluid dampers

One method of semi-active control is the use of MR fluid dampers. These dampers employ MR fluids which produce large damping forces in a piston-cylinder system that can be controlled by varying the current to the damper in real time. In the event of power loss, the MR fluid dampers act as passive dampers, thus maintaining some protection.

Jung et al. use MR dampers to control the vibrations of cable-stayed bridges subjected to earthquake loadings. The ASCE benchmark cable-stayed problem, which is based on the Cape Girardeau Bridge in Missouri, was the model for this study. The actual bridge is 633 m long and has two cable-stayed towers. Twenty-four MR fluid dampers, each with a 1000 kN capacity, were placed at four different locations between the deck and the piers and outer supports along the bridge. A clipped-optimal and an H_2/LQG control algorithms were used to control the MR dampers. After subjecting the bridge to three different earthquakes (1940 El Centro, California, 1985 Mexico City, and 1999 Gebze, Turkey), the authors conclude MR dampers are a viable option for controlling the vibration response of a bridge, with a "*reduction of* 69% *seen in all responses*".

Moon et al. carried out a finite element analysis of the benchmark Cape Girardeau cable-stayed bridge fitted with 24 MR dampers and controlled with SMC and LQG controllers. They subjected the bridge to the 1940 El Centro, 1985 Mexico City, and 1999 Gebze, Turkey, earthquakes and concluded that the SMC algorithm is more effective for the MR system and the MR system is comparable to active hydraulic actuator systems.

Hiemenz et al. use MR dampers in active bracings to mitigate the response of a 60 in. tall, 2D three-story scaled-model frame under earthquake loading, and find that the SMC provides 10% more reduction in displacements and accelerations than the LQR and skyhook controllers (a controller that applies a damping control force only when the force and velocity have the same sign).

Sodeyama et al. built two 20- and 200-kN capacity MR dampers that use a bypass-type orifice mechanism, and determined their damping properties experimentally and analytically.

Liu et al. explore the use of MR fluid dampers for semi-active control of bridges. They performed shake table tests on a 1:12 scale overpass highway bridge equipped with two MR fluid dampers, using energy minimization (adjusting of the damping force to minimize the rate of change of the system energy), Lyapunov-based (based on the Lyapunov function) fuzzy logic, and variable structure system fuzzy logic (FLC, with addition of a sliding mode) control strategies. All control strategies were found to decrease the RMS deck displacements compared with the uncontrolled case; the FLC having the greatest effect and requiring the least amount of power.

Renzi and Serino performed shake-table tests on a scaled four-story, 4.5-m tall, 3.2- by 2.1-m in plan steel frame fitted with MR dampers in active bracing systems. Each active bracing system used one MR damper and spanned two stories. The authors used an instantaneous optimal control algorithm and the motion of the 1976 Friuli, Italy, and 1994 Northridge earthquakes, and a synthetic accelogram as input. They reported reductions in displacement of 30%–35%, compared with the passive MR damper condition.

Xu et al. assess the effectiveness of semi-active MR dampers on scaled models of buildings with a podium structure. Using a seismic simulator, a 3D, 12-story, 2.4-m tall steel-frame with a surrounding three-story, 0.6-m tall podium structure was subjected to the scaled 1940 El Centro earthquake motions. Four different cases were tested: no connection between the podium and inner structures, without any vibration control; a rigid connection between the podium and inner structures, without any vibration control; a passive MR damper (with no voltage applied) connecting the podium and inner structures; and a semi-active MR damper connecting the podium and inner structures using a multilevel logic control algorithm. RMS displacements and accelerations using the semi-active system were decreased up to 70% and 60%, respectively, compared with the uncontrolled system, and up to 34% and 25%, respectively, compared with the passive control system.

Yoshida and Dyke use MR dampers to manage the behavior of two irregularly shaped 3D buildings subjected to seismic loadings. One replicated a nine-story, 40.25-m tall, composite steelreinforced concrete office building in Japan with plan irregularity due to the placement of shear walls. The other was an L-shaped, eight-story, 35.1-m tall, steel braced benchmark building with setbacks. Placement of MR control devices was determined by Genetic Algorithms (GAs). A clipped-optimal control algorithm with H_2/LQG controller was used. The first building had 110 MR dampers and was subjected to one-dimensional motion of the 1940 El Centro earthquake. The second building had 146 and 168 MR dampers in $x$and y-directions, respectively, and was subjected to 1995 Kobe earthquake ground motions in two directions, simultaneously.

Loh et al. investigate the use of MR dampers, employing a wireless control system to manage the seismic response of a three-story, half-scale, steel structure, two by three meters in plan and nine meters tall, subjected to the 1940 El Centro earthquake motion, on a shaking table. The 20kN capacity MR dampers were placed in each story in the form of K bracings, and wireless sensors were placed throughout the structure. Using an LQG controller, the authors considered both fully centralized (control force determined from each DOF throughout the entire system) and fully decentralized (where each control device receives input from a local controller rather than one central controller, thus splitting the control system into many subsystems) control strategies. They suggest the decentralized strategy to be more practical due to its robustness and high sampling rate. Loh and Chang also evaluate centralized and decentralized LQG control strategies for reducing the seismic response of a 3D, 80.77-m tall, 5-bay by 6-bay, 20-story frame employing MR dampers subjected to the motion of the 1940 El Centro earthquake. They used thirty-two 140kN MR dampers and four strategies: fully centralized, fully decentralized, half-centralized (control gain for each device determined independently), and partially decentralized (global system is divided into subsystems, but each subsystem takes into account more DOFs than fully decentralized). They concluded that the decentralized control system performed just as well as the centralized system and is more robust.

Christenson et al. use real-time hybrid simulation to carry out experiments on the effects of MR dampers on structural control. Real-time hybrid simulation involves only physically testing the important components of a system, while the rest of the system is simulated numerically. A scaled 2D, three-story, four bay, steel frame with a 200 kN capacity MR fluid damper on each floor was used. The finite element method was used to model and simulate the response of the structure, while the MR fluid dampers were the physical component of the hybrid simulation. The authors used the 1979 Imperial Valley, California, earthquake as the experimental input. The results of this hybrid simulation echoed the results of earlier simulations, that MR dampers are effective at controlling the response of a structure to stochastic loadings.

Aly Mousaad Aly presents vibration control of a building model under earthquake loads. A magnetorheological (MR) damper was placed in the building between the first floor and ground for seismic response reduction. A new control algorithm to command the MR damper was proposed. The approach was inspired by a quasi-bang-bang controller; however, the proposed technique gave weights to control commands in a fashion that was similar to a fuzzy logic controller.

J Berasategui et al. showes that the MR damper's power dissipation capacity is determined by the time spent in the pre- and the post-yield damping regimes. This time is determined by its design, by the MR fluid's rheological behavior and by the type of movement applied to the MR damper. To analyze those working regimes, two types of movement with different amplitudes have been applied to the MR damper at different magnetic field intensities and excitation frequencies. The first movement is an imposed harmonic movement, and in the second, power controlled unrestrained movement is obtained.

Guan Xinchun presents a novel magnetorheological (MR) damper with a self-powered capability, which is proposed to have energy harvesting and MR damping technologies integrated into a single device. Vibration energy harvesting mechanisms were adopted, based on ball-screw mechanisms and a rotary permanent magnet dc generator, to convert the external vibration energy into electrical energy to power the MR damping unit.

Tarek Edrees Alqado et al. present a novel application of a semi active posicast control scheme for structures with magneto-rheological (MR) damper. MR dampers are considered to be highly promising of semi-active control systems, which are becoming increasingly popular for alleviating the effects of dynamic loads on civil engineering structures because they combine the merits of both passive and active control systems.

M. W. Trikande et al. propose experimental method to characterize the Magnetorheological (MR) damper for realization of the suspension control for multi-axle military vehicle. An ac-curate model of MR damper based on the laws of physics to be embedded in real time controller for suspension system increases the computational load and implementation intricacies attracting higher costs and attendant issues [16-25].

2.2. Semi-active stiffness dampers

Semi-Active Stiffness Dampers (SASD) consist of a fluid-filled cylinder, a piston and a motor controlled valve. The motor regulates the opening of the valve, thus controlling the flow of the viscous fluid (most commonly oil) and adjusting the damping coefficient in real time. Patten et al. present a primer on SASD (also referred to as semi-active vibration absorbers). Jabbari and Bobrow use the Resetting Semi-Active Stiffness Dampers (RSASD) for control of a 2D, threestory, three-bay frame under random excitations. This system works by adding stiffness to the system when the valve is closed and dissipating the absorbed energy when the valve is open (periodically resetting the position of the piston, while not exerting any force onto the system). The authors find that the RSASD system using a decentralized control algorithm provides adequate structural control.

Agrawal et al. use Switching Semi-Active Stiffness Dampers (SSASD), RSASD with linear springs, and linear and nonlinear viscous fluid dampers for the vibration control of the aforementioned ASCE benchmark cable-stayed bridge. Similar to RSASD, an SSASD system works by periodically opening and closing the valve on the cylinder. When the valve is opened completely, no damping is provided, but when closed, the SSASD behaves as a normal SASD. The authors use a linear boundary layer semi-active friction controller for both semi-active stiffness damper types. The authors report that the RSASD system with linear springs performed better at reducing the displacement of the bridge deck, and shear and moment at the tower base, than semi-active friction dampers and linear and non-linear passive viscous dampers. Kurino et al. also use a semi-active control system similar to SASD, and a decentralized control algorithm allowing each damper to act independently, to control a 2D, 20-story frame subjected to the 1940 El Centro and 1968 Hachinohe earthquakes.

Nishitani et al. discuss the use of variable-slip force SASD, where a bilinear hysteresis in the dampers provides a given ductility factor, independent of the magnitude of the seismic excitation loads. Bilinear hysteresis is maintained through the use of slipping dampers. Once a certain level of damping force is reached, the damper actuator arm "*slips*" and continues to displace, but applies the same amount of damping force. Once a certain level of displacement has occurred, the applied damping force and displacement begin to decrease until a certain level of negative or opposite force is reached, and the same slippage mentioned above occurs. This pattern of behavior repeats itself, forming a loop, until the excitation has subsided. A decentralized control algorithm is used to maintain the ductility factor and determine the slip-force level. The authors applied this method to a 2D, 20-story, 20 DOF structural model of an actual building in Japan, subjected to the 1940 El Centro earthquake, with an SASD in each story, and linear behavior in the structure was achieved.

Fukukita et al. compare the effectiveness of an SASD system using an LQG controller with viscous damping walls (walls composed of two plates with a viscous fluid filling the void between them) for controlling a 2D, 20-story, benchmark model under the 1940 El Centro, 1968 Hachinohe, 1994 Northridge, and 1995 Kobe earthquakes. They found the passive viscous damping walls to provide better control under the given conditions, with eight and 24% greater reduction in peak acceleration and drift. Bhardwaj and Datta discuss vibration control of a 2D frame model of the five-story steel building presented by Kurata et al. with SASDs installed in each story in cross bracings using an FLC algorithm. They performed a parametric study using the 1940 El Centro earthquake as input and concluded that the damping coefficients of the dampers, maximum damping coefficients, and the damper capacity were the factors having the greatest influence on the controlled response. The authors study optimal combinations of these three parameters for the controlled response of the structure due to motions caused by the 1940 El Centro earthquake, and find that the FLC controller provides slightly better control of the top floor acceleration and base shear than the LQR controller.

Yang et al. utilize pressurized gas RSASD to control a three-story, half-scale steel structure, two by three meters in plan and nine meters tall, under the 1995 Kobe, 1999 Chi Chi, and 1940 El Centro earthquake motions. The authors varied the number, location and pressure level of the RSASD and employed a Lyapunov-based decentralized control strategy, and found that the pressurized gas RSASD decreased peak and RMS inter-story drift and RMS floor acceleration, but was ineffective at decreasing peak floor acceleration [25-30].

2.3. Semi-active tuned liquid column damper

The Tuned Liquid Column Damper (TLCD) system was introduced by Sakai et al. and as another type of passive damping system. In a TLCD system, the solid mass is replaced by liquid (commonly water) and control forces are based on the motion of a liquid column through an orifice in a U-like container to counteract the forces acting on the structure and The passive TLCD system has been employed in a 48-story building in Vancouver, Canada, completed in 2001. (It consists of two 227,300 L water tanks.) Sloshing of the water in the tanks counteracts the sideway vibration of the building. The largest passive TLCD system in the world has been used in the 57-story, 1009ft tall Comcast Center in Philadelphia.

In the original passive TLCD, the size of the orifice is fixed. In a semi-active TLCD system, the size of the orifice is changed in real time to control the rate of headloss. Yalla and Kareem investigate the use of semi-active tuned liquid column dampers as a control mechanism. They ran tests using a shaking table on a scaled model of a 60-story, 183-m tall, square-based building excited by wind to determine the optimal absorber parameters, such as damping ratio and tuning ratio, for a 0.038 m-diameter, 0.81 m-long U-tube. Results showed that the semi-active TLCD located on the roof with these optimal parameters decreased the reaction of the building 15%–25% more than a passive system, where the fluid is free to move between the two columns during excitation. Chen and Ko use a semi-active TLCD that utilizes propellers to change the height of liquid in the columns instead of a variable orifice. They performed laboratory tests on a pendulum-like model, using the propeller TLCD system and a feedback optimal controller to reduce the response due to the motion of 1995 Kobe earthquake with significant reduction in the response of the rig over the passive TLCD system observed [30-34].

2.4. Piezoelectric dampers

Piezoelectric (PZT) dampers utilize PZT materials (most commonly ceramic or crystalline in structure) that react to the application of electric current and generate a significant amount of strain/stress, the level of which can be adjusted through the level of current applied. These materials are utilized as stack actuators (an actuator consisting of a stack of PZT material that provides displacement when current is applied) or in active struts (linear actuators with variable stiffness). Kamada et al. use PZT stack actuators to mitigate vibrations through control of bending moments in columns for a scaled, four-story, 3.7-m tall steel frame with a rectangular plan. They tested two different placement schemes on a shaking table subjected to sinusoidal loadings: one with eight actuators placed vertically under the base of each column at ground level and another with four actuators placed vertically at the base of the column at ground level, and four between the first and second floors. The authors found that both placement schemes performed similarly using the $H\infty$ control algorithm. Udwadia et al. use semi-active members consisting of PZT stack actuators to control simple MDOF systems. Xu et al. use PZT actuators and an LQR controller to reduce large displacements of the top machinery room of a 30-m tall, 57.8 by 119.7 m in plain ship lift under seismic excitation. Chen and Chen present a power-saving control algorithm to manage the response of a benchmark 20-story model, using PZT actuators in cross-bracings subjected to 1995 Kobe, 1940 El Centro, 1994 Northridge, and 1965 Hachinohe earthquakes, finding that adequate control can be achieved while only requiring 2 kW of operating power.

Preumont et al. discuss vibration control of a scaled 1.68-m tall space truss tower controlled by two PZT struts, utilizing the integrated force feedback controller subjected to the 1940 El Centro earthquake motion. They report that the PZT actuators provide better control than resistive shunting (which turns the PZT actuator into a passive vibration absorber). Muanke et al. discuss the use of a dry friction mechanism consisting of two PZT stack actuators that apply varying normal force to friction pads to generate damping force through friction.

Xu and Ng present the results of semi-active control testing of a piezo-driven variable friction damper on a scaled laboratory model of a rectangular, steel-frame, 2.4-m tall, 12-story building surrounded by a three-bay by one-bay, 0.6-m tall, three-story podium structure. The piezo-driven variable friction damper works by utilizing a PZT actuator to apply pressure to a sliding steel plate, thus generating a friction force. The authors compared four cases using an LQG controller: no connection between the two buildings, a rigid connection at all three bottom floors, a passive damper connecting the third floors, and a PZT variable friction damper connecting the third floors. The authors subjected the model to the motions of the 1940 El Centro, 1968 Hachinohe, 1995 Kobe, and the 1994 Northridge earthquakes, and found that the PZT variable friction damper reduced the interstory drifts and accelerations by 17% and 20%, respectively, compared with the case of passive dampers [30-38].

2.5. Semi-active TMD

In this approach, a variable damping device, such as an MR damper, is added to a TMD system to adjust its tuning capability in real time. Lin et al. investigate a TMD-MR system to control a 2D, 12-story frame excited by the 1940 El Centro and 1995 Kobe earthquakes. Using a clipped optimal control strategy, the authors compare the performance of the system with that of an ATMD system, and conclude the latter to be more effective, but the former to be more economical due to its small power requirement and ease of installation.

Setareh et al. explore the use of a TMD-MR system to mitigate floor vibrations. They performed experiments comparing TMD-MR and passive TMD systems on a test floor, consisting of a 30×8 foot metal deck with a five-inch thick concrete slab on top and excited by an electromagnetic shaker. The authors concluded that the TMD-MR system is more effective than passive TMDs at mitigating vibrations due to off-tuning caused by non-even floor mass distribution due to equipment or other non-human loads. Conversely, they found that TMDs perform better when offtuning vibrations are caused by humans [32-42].

2.6. Other methods

Patten et al. tested an Intelligent Stiffener Bracing system utilizing actuators on an actual 122-m long, two-lane, four-span, steel girder bridge to reduce vibrations induced by live traffic loads to prolong the life of the structure. They installed the bracings and actuators on one of the middle spans on three of the five girders (the middle and the two outside girders) and powered the system using two 12-V automotive batteries. The batteries have an operating life of two years and the system is controlled using a Lyapunov-based controller. The authors conducted tests on the bridge with 32- and 54-metric ton trucks and found that the semi-active control system reduced the peak measured bending stress in the girders by approximately seven MPa.

Krstulovic-Opara et al. propose using shape memory alloys embedded in high-performance fiber reinforced concrete as “self-actuating fuses”, to increase the capacity of areas with high ductility demand in reinforced concrete frames. Shape memory alloys can undergo large inelastic deformations (up to 8% strain), which are reversible with the application of a certain level of stress or heat. The authors use a 2D, four-story, three-meter tall, three-bay reinforced concrete frame with the self-actuating fuse regions in the first floor columns and beams. They subjected the shape memory alloy-strengthened frame and an identical standard frame to the scaled motions of the 1952 Taft earthquake, and found that the standard frame sustained irreparable damage, while the frame with fuse region reinforcement did not. Casciati et al. also report the use of shape memory alloy devices for vibration control of structures under seismic loading.

Scruggs and Iwan propose using a Brushless Direct Current (BDC) motor to control the response of a structure. The BDC provides damping by converting mechanical energy to electrical energy and works much like an actuator, with the motor powering an arm that controls movement. They simulated the idea on a 2D, three-story frame with a BDC motor located on the first floor using the clipped-optimal control algorithm. Simulation results indicate the vibration control provided by the BDC motor is comparable with that provided by MR dampers.

Collins et al. discuss the use of a Variable Stiffness Tuned Mass Damper (VSTMD) which is a TMD with dampers whose stiffness can be varied to match a desired frequency for control of wind vibrations. They applied wind loads based on the Davenport Spectrum on a single DOF structure, using a bang–bang control strategy and found that the semi-active VSTMD system reduced vibrations of the structure considerably. The bang–bang controller rapidly switches between two extreme states (i.e. on or off) and does not operate between the two bounds.

Zhou and Sun suggest the use of a semi-active fluid damper, utilizing “*porous micro-particles suspended in water-based ferrofluids*”, excited using a magnetic field generated by an 18-layer copper coil surrounding the cylinder containing the fluids. The level of magnetization applied varies the damping force in the cylindrical damper. Tests results showed that the damping force in the cylinder could be varied 32% by adjusting the magnetic field, and that the colloidal damper generated very little heat (four percent of that generated by a conventional MR damper) [40-51].

3. Conclusion

Recent research on active and semi-active control of structures performed since 1997 was reviewed in this paper. In recent years, research has moved mostly from active control to semiactive and hybrid vibration control of structures. Semi-active and hybrid control systems provide more practical approaches for actual implementation of the smart structure technology. But earlier, as well as current, research on active vibration control provides a solid and necessary foundation to move the frontiers of smart structure technology forward, and make this technology a practical alternative. In the companion paper, hybrid control systems, as well as control strategies, are reviewed and a number of conclusions are summarized.

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