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PRACTICAL APPLICATIONS OF SEMI-ACTIVE CONTROL SYSTEMS TO CIVIL ENGINEERING STRUCTURES

BY

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During the last few years, it has been paid a considerable attention to the searching and developing of some procedures and mechanisms of structural control to mitigate the effects of dynamic environmental hazards on civil engineering structures. In this paper we review some full-scale applications of semi-active control systems for the protection of the civil structures under dynamic actions.

1. Introduction

Passive devices have been used, very successfully, to civil structures such as tall buildings and long bridges, to reduce vibration due to the earthquake and wind load. A lot of researches have studied structures equipped with these passive techniques and a lot of practical realizations have already implemented in many countries [1], [3], [8], [9]. These devices can be used for enhancing damping, stiffness and strength, do not need an external power source and are more economic and easy to realize in civil structural applications.

An active control device is designed in such a way that the control forces are supplied to the structure through the employment of the actuators [7]. This active control system requires large external power source that may reach several megawatts for large structures.

The promising alternative between the passive and active techniques has been developed recently in a form called *semi-active technique*. In another way said, semi-active techniques allow the adjustment of the mechanical properties of the passive control systems, while they can bring similar performances of active control systems [17].

The authors have done their best to present clearly some significant implementations of the semi-active control systems.

2. Semi-Active Control

A semi-active control system is defined as one that needs energy only to change the mechanical properties of the devices and to develop the control forces opposite to the motion of structure [3], [10].

Semi-active control systems are a class of active control systems for which the external energy requirements are smaller amounts than those of typical active control. Also a semi-active control system originates from a passive control system which dissipates energy in main such as phase transformation in metals, deformation of visco-elastic solids or fluid orificing and sliding friction are modified to behave in a semi-active manner [17]. A battery power, for instance, is sufficient to make them operative to control in real time parameters of the structure such as spring stiffness or the viscous damping coefficient. The stability is guaranteed, in the sense that no instability can occur, because semi-active devices use the motion of the structure to develop the control forces. A semi-active device will never destabilize a structural system whereas an active device may destabilize a structural system even though it has a low energy demand. Examples of such common semi-active devices have been classified as following:

a) semi-active hydraulic devices;
b) variable stiffness devices;
c) controllable friction dampers;
d) controllable fluid dampers;
e) semi-active tuned mass damper;
f) semi-active tuned liquid damper;
g) variable orifice tuned column liquid damper.

3. Applications of Semi-Active Control Systems to Civil Structures

For the first time, K a r n o p p [4] performed analytical studies of semi-active devices for automotive vibration isolation applications, investigating a semi-active fluid viscous damper. Two valves are used independently to control the damping during compression and tension (Fig. 1). The common skyhook strategies were examined with respect to minimize the absolute velocity of a vehicle.

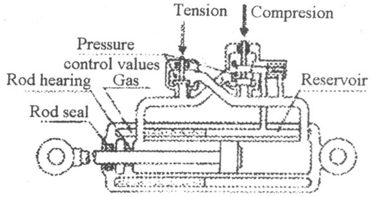


Fig. 1.– Semi-active fluid damper described by Karnopp.

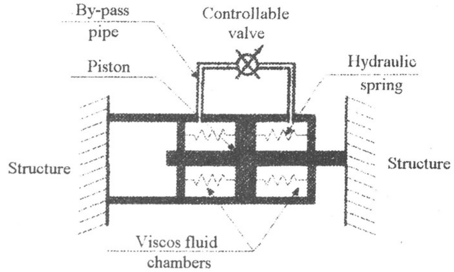
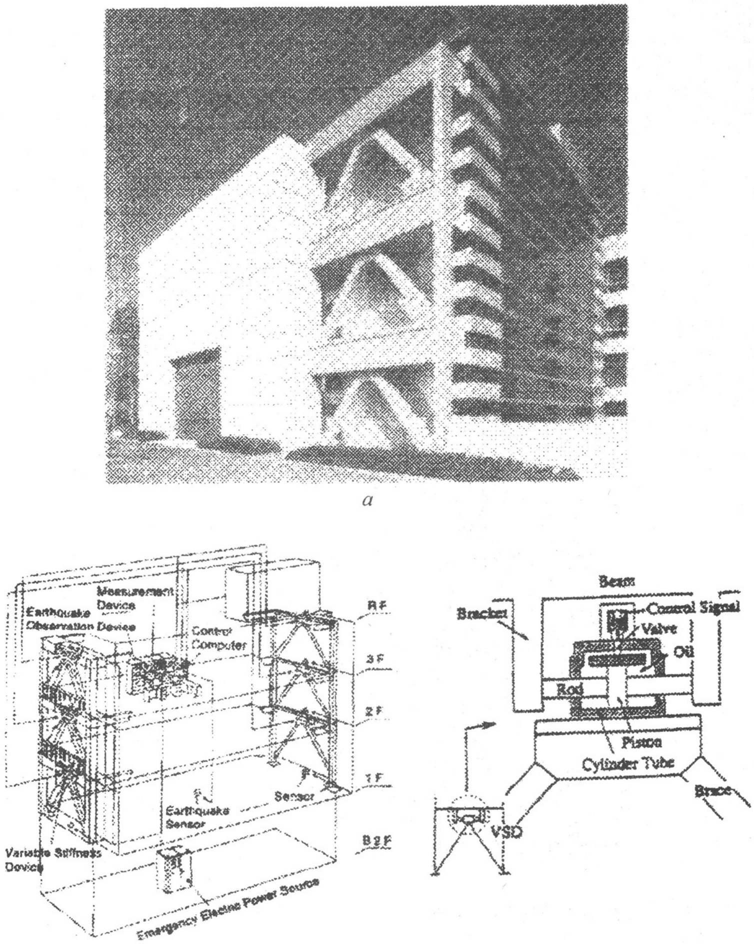


Fig. 2.– Scheme of variable orifice fluid damper.

The variable orifice damper is the common device of the semi-active hydraulic devices [6]. The device consists of a fluid viscous damper combined with a variable orifice on a by-pass pipe containing a valve in order to control the reaction force of the devices (Fig. 2). The damping characteristics of a variable orifice can be controlled between two damping values (low damping when the valve is completely opened and high damping when the valve is completely closed) by varying the amount of flow passing through the by-pass pipe from one chamber of the piston in the other. In the intermediate positions of the valve opening process, the device produces a specific damping dissipation. The adjustment of the valve can be made usually electromechanically (*e.g.* servo-valve or solenoid valve).



b *c*

Fig. 3.– *a* – External view of Kajima Research Laboratory building; *b* – scheme of semi-active control system; *c* – active Variable Stiffness device.

A variable stiffness device is achieved to get an auxiliary structure or stiffness element be attached or detached from the main structure so that structural system can be change to realize non-resonant states to dynamic hazard mitigation [5].

The Kajima Research Laboratory was first building equipped semi-active systems using three Active Variable Stiffness devices (Figs. 3 *a* and *c*) [16]. Kajima Corporation built the structure for own research centre in Tokyo. The control system may be called semi-active because the lock mechanism of one bracing system within the structure has on–off behaviour. It is composed of a normally closed solenoid valve regulating oil flow from one chamber of the piston in the other. The operation of valve requires a power of 20 W. The natural frequencies of the structure may be changed due to their independent controllability of devices. The information received from the sensors that are distributed at each floor is conducted to a digital computer where the control strategy is implemented (Fig. 3 *b*).

During his live the building was subjected to three little earthquakes in order to activate the system. The record of the response has shown a better behaviour than that with numerical simulations of the structure without the semi-active control system.

The second application of semi-active control systems was achieved on a bridge on the interstate highway I-35, USA (Fig. 4). Some variable orifice dampers were installed under the deck to dissipate the energy induced by traffic. In 1994 S a c k and P a t t e n experimented the system and later, in 1997, Patten *et al.* monitored it for two years, between 1997 and 1999, demonstrating the implementation effectiveness of this technology [11], [12], [14]. The principle of the device is based on on–off behaviour requiring only a power from a battery to switch the valve.

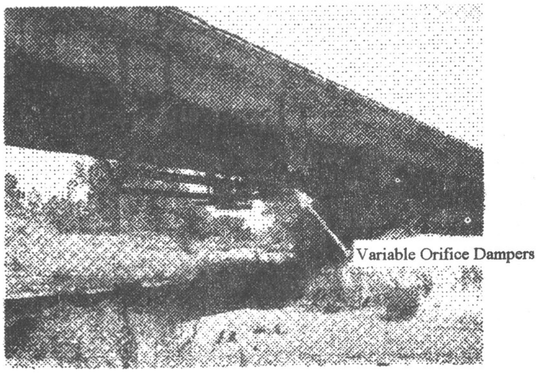


Fig. 4.– External view of Walnut Creek Bridge.

In 1998, Kajima Corporation implemented other semi-active system in the Kajima Shizuoka Building, in Japan [15]. The building has five floors, and at each storey, excepting the last one, inside the walls on the both sides of building are implemented semi-active devices; so in total there are implemented 8 semi-active dampers. Each device contains a flow control valve, a check valve and an accumulator and can generate damping coefficient in a continuous range between 200 and

1,000 Ns/mm (Fig. 5). The control algorithm is based on Linear Quadratic Regulator (LQR) theory (M a r a z z i, 1997).

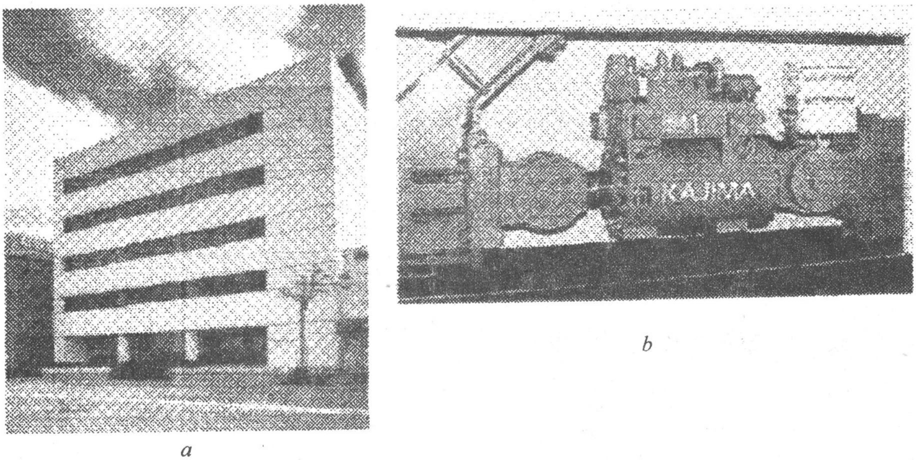


Fig. 5.– *a* – External view of Kajima Shizuoka Building; *b* – view of semi-active hydraulic damper.

The controllable fluid dampers are based on magneto-rheological or electro-rheological fluid that changes its viscosity very quick in the presence of an adjustable magnetic or electric field [13]. Recently, design examples of these devices have been

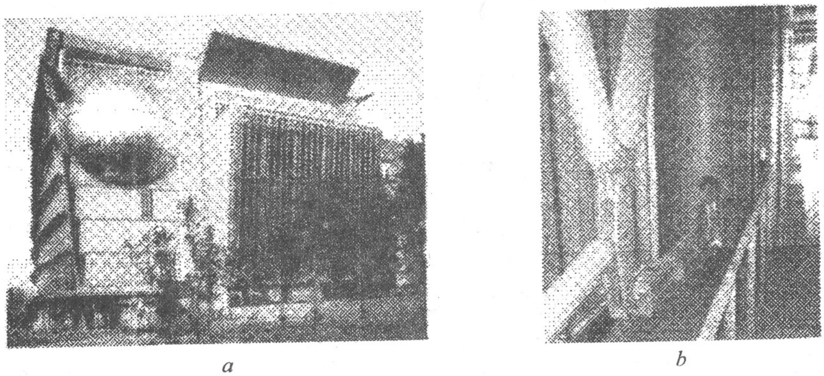
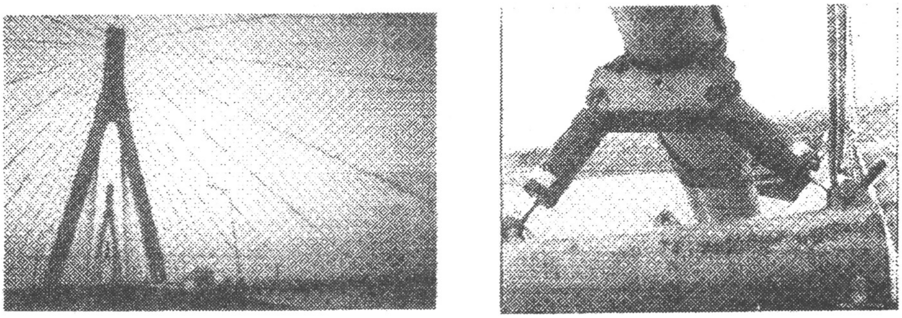


Fig. 6.– *a* – External view of building; *b* – view of a couple of dampers implemented.

proposed in literature by many researchers for application to civil structural control. In 2001, the first implementation for civil engineering using magneto-rheological fluid damper was achieved in the Tokyo National Museum of Emerging Science and Innovation (Fig. 6) [15]. The dampers were built by Sanwa Tekki using the Lord Corporation MR fluid.

For first time on the structure of a bridge, another application of magneto-rheological fluid was achieved in the Dongting Lake Bridge in Hunan, China (Fig. 7 *a*) [15]. Two Lord SD-1005 MR dampers are being installed on each cable to mitigate cables vibrations due to the weather conditions (Fig. 7 *b*).



a *b*

Fig. 7.– *a* – External view of Dongting Lake Bridge; *b* – view of the two MR dampers installed at a cable.

Semi-active tuned mass damper (STMD) consist of a variable orifice damper or a controllable damper attached at the passive tuned mass damper in order to control the damping coefficient of the STMD [2].

The controllable friction devices utilize the force generated by surface friction to dissipate the energy. The optimal behaviour of the device is chosen by a control algorithm that manipulates the air pressure of a gasket through a power source in order to change the friction force at the sliding surface [9].

4. Conclusion

The aim of this paper is to explain and discuss some recent implementation of semi-active control systems for the protection of the civil engineering structures under dynamic loads. The accepting of innovative systems represents a future potential research and the practical application is one of big concern worldwide. Detailed examples of practical applications of such devices applied buildings and bridges were provided.

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REFERENCES

1. Constantinou M.C., Symans M.D., Tsopelas P., Taylor D.P., *Fluid Viscous Dampers in Application of Seismic Energy Dissipation and Seismic Isolation* Proc. of ATC-17-1 Seminar of Seismic Isolation, Passive Energy Dissipation and Active Control, Vol. **2**, 1993, 581-591.
2. Hrovat D., Barak P., Rabins M., *Semi-Active versus Passive or Active Tuned Mass Dampers for Structural Control.* ASCE J. Eng. Mech., 109, 7, 691-705 (1983)

3. Housner G.W., Bergam L.A., Cauchy T.K., Chassiakos A.G., Claus R.O., Skelton S.M., Skelton R.E., Soong T.T., Spencer B.F., Yao J.P.T., *Structural Control: Past, Present and Future Control.* J. of Engng. Mech., **123**, *9*, 897-971 (1997).
4. Karnopp D.C., Crosby M.J., Harwood R.A., *Vibration Control Using Semi-Active Force Generators.* ASME J. of Engng. for Ind., **2**, 619-626 (1974).
5. Kabori T., *Mission and Perspective towards Future Structural Control Research.* Proc. of the Sec. World Conf. on Struct. Control, Vol. **I**, Kyoto, Japan, 1999, 25-34.
6. Kurino H., Kobori T., *Semi-Active Structural Response Control by Optimizing the Force Deformation Loop of Variable Damper.* Proc. of the Sec. World Conf. on Struct. Control, Vol. **I**, Kyoto, Japan, 1999, 407-416.
7. Marazzi F., Magonette G., *Active and Semi-Active Control of Structures: A Comparison.* Europ. Meeting on Intell. Struct., Ischia, Italy, 2001.
8. Marazzi F., *Semi-Active Control of Civil Structures: Implementation Aspects.* Ph.D.Diss., Univ. of Pavia, Italy, 2002.
9. Pastia C., *Passive and Semi-Active Control Systems: Theoretical, Numerical and Experimental Aspects.* Tech. Report, JRC Special Publ. I.04.94, Europ. Comm., Inst. for the Protection and the Security of the Citizen, Ispra (VA), Italy, 2004.
10. Pastia C., Luca S.G., Luca F., Roşca V.O., *Structural Control System Implemented in Civil Engineering.* Bul. Inst. Politehnic, Iaşi, **LI (LV)**, *1-2*, s. Constr., Archit., 41-51 (2005).
11. Patten W.N., Sun J., Li G., Kuehn J., Song G., *Field Test of an Intelligent Stiffener for Bridges at the I-35 Walnut Creek Bridge.* Earthquake Engng. a. Struct. Dyn., **28**, 109-126 (1999).
12. Patten W.N., Kuo C.C., He Q., Liu L., Sack R.L., *Suppression of Vehicle-Induced Bridge Vibration via Hydraulic Semiactive Vibrartion Dampers.* Proc. of the First World Conf. on Struct. Control, Pasadena, CA, USA, August 3-5, 1994, FA1-30-38.
13. Preumont A., *Vibration Control of Active Structures: An Introduction.* 2^{nd} Edit., Kluwer Acad. Publ., Dordrecht, The Netherlands, 2002.
14. Sack R.L., Patten W., *Semi-Active Hydraulic Structural Control.* Proc. of the Internat. Workshop on Struct. Control, USC Publ. Number *CE-9311*, 1994, 417-431.
15. Soong T.T., Spencer B.F., *Supplementary Energy Dissipation: State-of-the-Art and State-of-the-Practice.* Engng. Struct., **24**, 243-259 (2002).
16. Spencer B.F., Sain M.K., *Controlling Buildings: A New Frontier in Feedback.* IEEE Control. Syst. Mag. on Emerging Technol., Special Issue, **17**, *6*, 19-35 (1997).
17. Symans M.D., Constantinou M.C., *Development and Experimental Study of Semi-Active Fluid Damping Devices for Seismic Protection of Structures.* Techn. Rep. NCEER-95-011, National Centre for Earthquake Engng. Res., Buffalo, New York, 1995.

APLICAŢII PRACTICE ALE SISTEMELOR DE CONTROL SEMI-ACTIV LA STRUCTURILE CONSTRUCŢIILOR

(Rezumat)

În ultimii ani, o atenţie deosebită a fost acordată căutării şi dezvoltării unor procedee şi mecanisme de control structural pentru a reduce efectele evenimentelor dinamice întâmplătoare asupra structurilor construcţiilor civile. În lucrare se trec în revistă câteva implementări la scara reală a sistemelor de control semi-activ pentru protecţia construcţiilor la acţiuni dinamice.