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CONSTRUCŢII. ARHITECTURĂ

STRUCTURAL CONTROL SYSTEMS IMPLEMENTED IN CIVIL ENGINEERING

BY

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Over the past three decades, a great interest has been generated by the use of protection systems to mitigate the effects of dynamic environmental hazards on civil engineering structures, such as earthquakes and strong wind. These control systems develop controllable forces to add or dissipate energy in a stucture, or both, due to the specific devices integrated with sensors, controllers and real-time processes to operate. The paper includes the advantages of these technologies consisting of the following sections: § **1** represents an introduction, § **2** deals with passive control system, § **3** regards some control techniques, § **4** concerns hybrid control techniques, § **5** contains semi-active control techniques, and § **6** is dedicated to general conclusions.

1. Introduction

Structural control has a long and successful history in civil engineering for mitigating dynamic hazards. The traditional approach to reduce vibrations due to the earthquake and wind loads is to design structures with sufficient strength and deformation capacity in a ductile manner. This approach, based on the ensuring of strength–ductility combination, provides the strong wind or seismic action as ultimate loads, accepting a certain number of structural or non-structural degradations. Usually, for a steel structure, the dissipation of the energy introduced in structure by dynamic action occurs only in the plastic hinges. For this reason, taking into account the way in which the load bearing structural elements of a steel system function together, a global plastic mechanism is generated.

In recent years, it has been paid a considerable attention to new concepts of structural control including a large variety of techniques, that can be defined in four classes: passive, active, hybrid and semi-active. From historical point of view, passive control techniques, such that base isolation and passive control devices, are the first of them implemented. A lot of researches have studied structures equipped with these passive techniques and a lot of practical realizations have already implemented in many countries [14], [15]. These devices do not need an external power source and they are more economic and easy in applications.

New concepts of active control, designed in such a way that the control forces be supplied to the structure through the employment of the actuators, may exclude the inelastic deformations in the elements of the structural system. These systems require large external power sources that may reach several megawatts for large structure.

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 control techniques make the rehabilitation of passive control systems, while they can bring similar performances of active control systems.

Hybrid control techniques blend passive and active control techniques. In the scheme of hybrid control the forces generated by the actuators are aimed to increase the efficiency of passive control devices.

Active, hybrid and semi-active control techniques have been studied extensively from a theoretical, numerical and experimental point of view for their performances [3],..., [6], [8], [9], [13], [14], etc.

Nowadays, structural control systems implemented in civil engineering structures can comprise one or more control techniques. The four control techniques are defined in what follows.

2. Passive Control

A passive control system consists of one or more devices, attached or embedded to a structure, designed to modify the stiffness or the structural damping in an appropriate manner without requiring an external power source to operate, developing the control forces opposite to the motion of the structure [10], [4].

Control forces are developed as a function of the structural response at the structural response at the location of the devices (Fig. 1). Passive control may depend on initial design of the structure, on the frictional contact between elements of the structure or on the use of the contact dampers at the joints in structure [1].

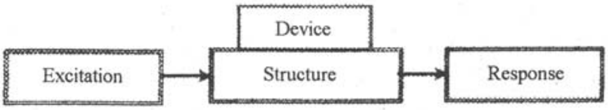


Fig. 1.- Components of an passive control system.

From energetical point of view the passive control systems are divided into two classes:

a) *Base isolation.* Isolation dampers, such as elastomeric bearings or sliders (metal blocks), as well as isolation layers as fine sand or graphite material, are introduced between the foundation and superstructure. Consequently, the *reducing of the input energy* of an earthquake in superstructure as well as the increasing of displacements across the isolation level are achieved due to the flexible decoupling between superstructure and foundation [2]. The most common adopted technique is the laminated rubber bearing with alernating layers of rubber and steel (Fig. 2). The stiff steel plates provide lateral constraint of each rubber layer when the bearing is subjected to vertical load, but does not constrain the horizontal shearing deformation of the rubber layers. This produces a bearing that is very stiff in the vertical direction and very flexible in the horizontal one. A base isolation system depends of natural frequencies of a structure in its design.

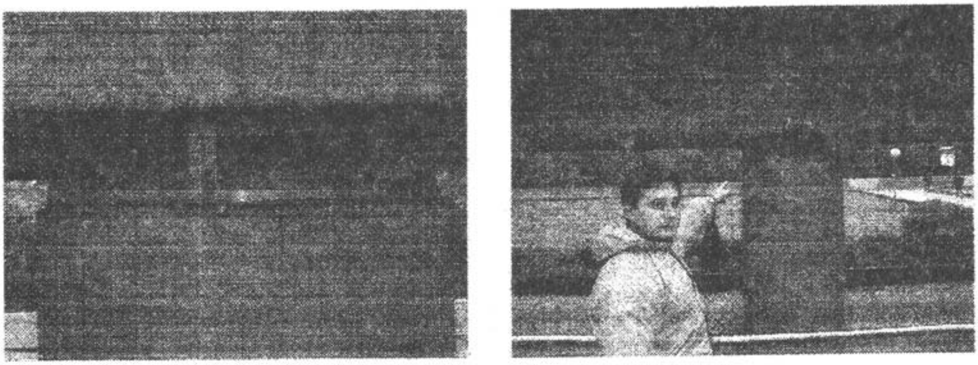


Fig. 2.- View of passive isolation dampers (elastomeric bearings) implemented on Reichsbrucke bridge, Vienna.

b) *Passive control devices.* The control passive devices generally *dissipate or absorb energy inputted to a structure.* The motion of the structure is utilized to produce a relative motion within the passive control devices, thereby the energy is dissipated. They may be also divided in two classes: energy dissipating devices, which are independent w.r.t. the natural frequencies of a structure for their design, and tuned or resonant devices, which depend on the natural frequencies. An exception of frequency-independent devices is the visco-elastic dampers. Most of dissipating devices, known as friction damper, hysteretic damper, visco-elastic damper or fluid viscous damper, operate on principles such as frictional sliding, phase transformation in metals, deformation of visco-elastic solids or fluid orificing. The plastic hinges are created in the structure when the elements of the structure are designed as energy dissipating devices.

The second class includes tuned mass damper (TMD), tuned liquid damper (TLD), tuned liquid columns damper (TLCD), suspended pendulum mass damper, mass pump, and so on. TMD and TLD systems have been extensively studied from point of theoretical, numerical and experimental view to control mostly wind input vibrations. Generally, inertial mass is attached near the top, through a spring and a viscous damping mechanism (*e.g.* fluid damper or visco-elastic damper).

The achievement of dissipative zones through stuctural, viscous and hysteretic damping must not affect the stability of the structure. Base isolation and passive control devices have been widely used in a number of civil structures in the Europe, USA, Japan, Taiwan, New Zealand, etc.

3. Active Control

An active control system is defined as one in which a large external power source or many, from tens kilowatts to several megawatts, control actuators that apply forces to the structure in a prescribed manner [10], [4].

Such active control devices are: the active mass driver system (AMD), the active tendon system and the active bracing system [6]. These forces can be used to both add and dissipate energy in the structure. The control forces within the framework of an active control system are generated by a wide variety of actuators that can act hydraulic, pneumatic, elctromagnetic, piezoelectric or motor driven ball-screw actuation. The controller (*e.g.* a computer) is a device that receives signals from the response of the structure measured by physical sensors (within active control using feedback) and that on basis of a pre-determined control algorithm compares the received signals with a desired response and uses the error to generate a proper control signal [8]. The control signal is then sent to actuator. In feed-forward control, the disturbance (input signal), not the response (output signal), is measured and used to generate th control signals. Both feedback and feed-forward principles can be used together in the same active control system.

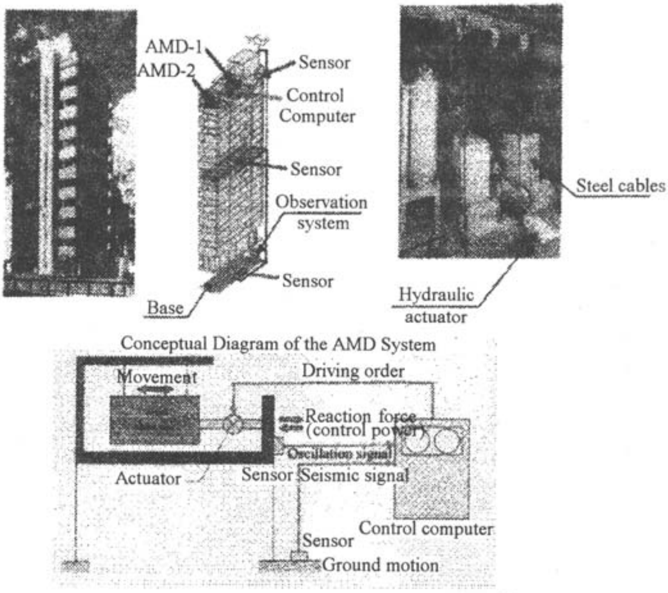


Fig. 3.- Controllability of Kyobashi Seiwa Building.

The Kajima Corporation installed the first application of active mass driver system to Kyobashi Seiwa Building, in 1989, in Japan (Fig. 3). The eigenvalues analysis of the structure shows that the first dominant mode of vibration is in the transverse motion with a period of 1.13 s. The second mode is in the torsion motion with a period of 0.97 s, while the third mode is in the longitudinal motion with a natural period of 0.76 s. An active mass driver system consisting of two AMD was installed on the top building that has 11 storeys and height of 33 m. The primary AMD is used for transverse motion and has a mass of 4 t, while the scondary AMD has a mass of 1 t and is employed to reduce torsion motion. The results of simulation analysis have shown effectiveness and reliability of this system to reduce building vibrations under strong winds and moderate earthquake excitations.

The cables are efficiently structural elements used in suspension bridges, cable-stayed bridges or other cable structures but they have the disadvantage of great flexibility and low damping [12]. The active tendon control systems based on damping techniques has been proposed to mitigate cables vibrations by many researchers in the recent time. Damping techniques consisting of a tendon actuator collocated with a force sensor were analysed and widely tested at ELSA (European Laboratory for Structural Assesment) on a large-scale cable-stayed mock-up [10]. The tested structure is a model of a cable-stayed bridge, equipped with two actuators on the two longest stay-cables. Due to the tendon actuator actively controlled the results show an important reduction in vertical displacement regarding the deck and a damping of whole structure increasing more then times as the bridge is subjected to an excitation. Consequently, the fatigue effects are mitigated. These technologies can be directly applicable to the real structure by scaling up the devices.

An active control system has the disadvantage of power failure during vibrations and great costs to implement such a technology. Such devices are independent of the natural frequencies of a structure for design.

4. Hybrid Control

A hybrid control system is defined as one that implies the combined use of active and passive control system [10], [4].

A hybrid control system consists of employment of an active control device to improve and supplement the performance of passive control system. Alternatively, the passive devices embedded in a structure can decrease the amount of required energy power if an active control system is installed in that structure. For example, a base isolation system can be improved using actuators that act to decrease the displacement of structure or a structure equipped with passive damping devices supplemented upon its top with an active mass damper in order to enhance reduction efficiency of imputed vibrations.

Essential difference between an active and hybrid control system is the amount of external required energy power to generate control.

A better control system using a less energy amount than active control system is hybrid mass damper (HMD) that combines a passive TMD and an actuator. Another difference is that a hybrid mass damper depends on the natural frequency of a structure whereas an active mass damper doesn't depend on the natural frequency. These devices are similar to a tuned suspended mass damper or tuned mass damper with the exception that an actuator attached to the tuned mass can dynamically extend the amplitude of natural motion of the TMD. The designs of HMD configuration include [7]:

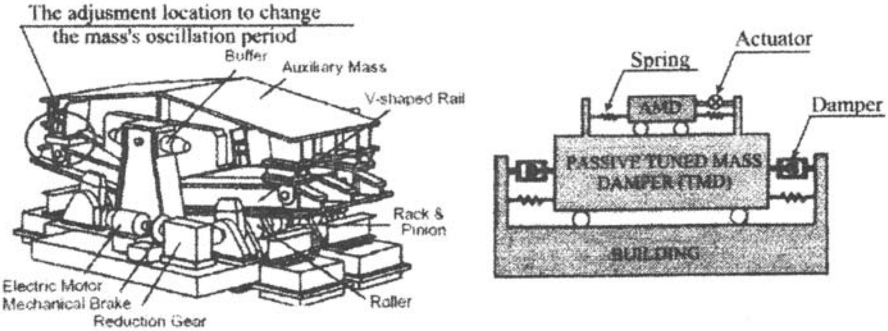
a) multi-step pendulum HMD, for example, one is installed in Landmark Tower in Yokohama, the tallest building in Japan;

b) roller-pendulum HMD (Fig. 4 *a*), for example, arch-shaped HMD or V-shaped HMD are devices designed to behave like a mass pendulum fashion;

c) passive TMD upon which sits an active mass driver (Fig. 4 *b*);

The active mass driver at top of the tuned mass provides the necessary force to speed up the motion of the tuned mass at the start of the loading and provides a braking force at the end of the loading.

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, thus being more economical [15].



a *b*

Fig. 4.– *a* – V-Shaped Hybrid Mass Damper installed in Shinjuku Park Tower, *b* – concept of HMD with a passive TMD upon which sits an active mass driver.

5. 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 [10], [4].

Semi-active control systems are a class of active control system for which the external energy requirements are smaller amounts than those of typical active control. A battery power, for instance, is sufficient to make them operative. Semi-active devices cannot add or remove energy to the structural system, but can 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. These control devices are often viewed as controllable passive devices. Examples of such common semi-active devices can be categorized 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.

For the first time, K a r n o p p [5] 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. 5). The common skyhook stategies were examined with the goal to minimize the absolute velocity of a vehicle.

The variable orifice damper is the common device of the semi-active hydraulic devices. The device, described by M a r a z z i [10], 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. 6). 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).

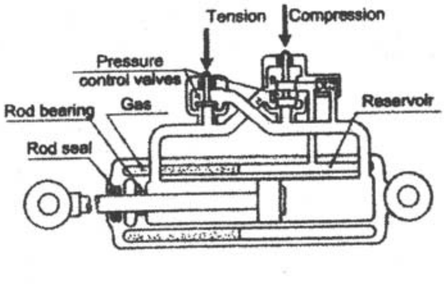


Fig. 5.– Semi-active fluid damper dscribed by Karnopp.

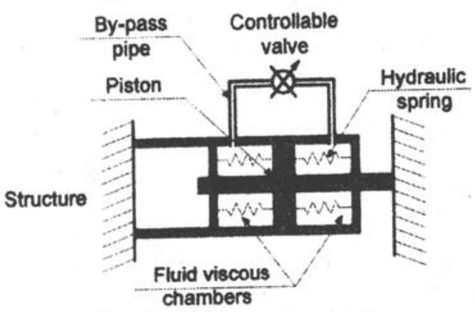


Fig. 6.– Scheme of variable orifice fluid damper.

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 proposed in literature by many researchers, for application to civil structural control.

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 [3].

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 [11].

The variable stiffness devices can make an auxiliary stiffness element to be active so that structural system can be changed to realize non-resonant states to dynamic hazard mitigation [6].

6. Conclusions

It's obviously that active, hybrid and semi-active control techniques consist of a number of important components as: sensors, controllers, actuators and power generators. These devices must be partly integrated into the structural system, with realistic evaluation of their performance and verification of their ability for long-term operation.

The overall goal of this paper is to introduce the main concepts of the passive, active, hybrid and semi-active control systems. These systems must be analysed regarding the stability, effectiveness, cost and required energy source consumption. The accepting of innovative systems represent a future potential research and the practical application is one of big concern worldwide.

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REFERENCES

1. Budescu M., Ciongradi I.P., Ţăranu N., Gavrilaş I., Ciupală M.-A., Lungu I., *Rehabilitation of Constructions.* Edit. Vesper, Iaşi, 2001.
2. Ciupală M.-A., *Optimal Procedures for Increasing the Safety of Constructions Subjected to Seismic Motions Considering Torsion Effect* (in Romanian). Ph. D. Diss., "Gh.Asachi" Techn. Univ., Jassy, 1998.
3. Hrovat D., Barak P., Rabins M., *Semi-active versus Passive or Active Tuned Mass Dampers for Structural Control.* ASCE J. Engng. Mech., **109**, *3*, 691-705 (1983).
4. Housner G.W., Bergam L.A. Cauchy T.K., Chassiakos A.G., Claus R.O., Skelton S.M. 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).
5. Karnopp D.C., Crosby M.J., Harwood R.A., *Vibration Control Using Semi-active Force Generators.* ASME J. of Engng. for Ind., **96**, *2*, 619-626 (1974).
6. Kabori T., *Mission and Perspective Towards Future Structural Control Research.* Proc. of the Sec. World Conf. on Struct. Control., **I**, Kyoto, Japan, 1999.
7. Jerome P.L., *Active Structural Control Research at Kajima Corporation.* The Nation. Sci. Found.'s Summer Inst. in Japan Program, 1998.
8. Magonette G., Marazzi F., Tognoli P., Buchet P., Renda V., *Experimental Analysis of Active Control of Vibration of a Large-Scale Cable-Stayed Bridge Mock-up.* Proc. of the 7th Internat. Seminar on Seism. Isol., Pass. Energy Dissip. and Active Control of Vibr. of Struct., Assisi, Italy, 2001.
9. Marazzi F., Magonette G., *Active and Semi-active Control of Structures: A Comparison.* Europ. Meeting on Intell. Struct., Ischia, Italia, 2001.

10. M a r a z z i F., *Semi-active Control of Civil Structures: Implementation Aspects* (in Italian). Ph. D. Diss., Univ. of Pavia, Struct. Mech. Dept., 2002.
11. P a s t i a C., *Passive and Semi-active Control Systems : Theoretical, Numerical and Experimental Aspects.* Techn. Report, JRC Special Publ.1.04.94, European Commission, Inst. for the Protection and the Security of the Citizen, Ispra (VA), Italy, 2004.
12. P ă u l e ţ - C r ă i n i c e a n u F., *Seismic Response Control of Long Cable-stayed Bridges.* Proc. of the Second World Conf. on Struct. Control, Kyoto, Japan, **2**, J. Willey & Sons, Chichester, 1999, 959-964.
13. P r e u m o n t A., *Vibration Control of Active Structures: An Introduction.* 2nd Edition, Kluwer Acad. Publ., 2002.
14. S o o n g T.T., S p e n c e r B.F., *Supplementary Energy Dissipation: State-of-the-Art and State-of-the-Practice.* Engng. Struct., **24**, 243-259 (2002).
15. S p e n c e r B., S a i n M.K., *Controlling Buildings: A New Frontier in Feedback.* IEEE Control. Syst. Mag. on Emerging Technol., Special Issue, **17**, *6*, 19-35 (1997).

SISTEME DE CONTROL STRUCTURAL APLICATE ÎN CONSTRUCŢII CIVILE

(Rezumat)

De peste trei decenii, un mare interes a fost generat de folosirea sistemelor de protecţie pentru a reduce efectele evenimentelor dinamice întâmplătoare în structurile construcţiilor civile precum cutremure şi vânturi puternice. Aceste sisteme de control dezvoltă forţe controlabile pentru a introduce sau/şi disipa energie într-o structură prin dispozitive specifice, suplimentate de senzori, controlori şi procese de informare în timp real. Lucrarea include avantajele acestor tehnologii şi constă în următoarele secţiuni: § **1** – introducere; § **2** tratează sistemele de control pasiv; în § **3** se prezintă tehnicile de control activ; în § **4** se studiază tehnicile de control hibrid; în § **5** se cercetează tehnicile de control semi-activ, în timp ce § **6** conţine concluziile generale.