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RECENT APPLICATIONS OF SOME ACTIVE CONTROL SYSTEMS TO CIVIL ENGINEERING STRUCTURES

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The application of control systems to civil engineering structures has been investigated in recent years to demonstrate the efficiency of these systems during exceptional natural events such as earthquakes and severe winds. In this paper, a review of some full-scale implementations of active and hybrid control systems for the protection of the civil structures to dynamic actions is performed.

1. Introduction

The traditional approach of decreasing the vibrations due to earthquakes and wind loads is concretized in building structures with enough resistance and capacity of deformation in a ductile way. This approach, based on insuring the combination resistance–ductility of the elements of a structure, considers the seismic action as a load at which the structure must resist, accepting a certain level of structural and non-structural degradations. Alternatively, newer concept of structural control, including passive, active, hybrid and semi-active systems, may exclude the inelastic deformations in the structural system.

The authors present clearly, in what follows, some significant applications of the active systems and the combinations of passive and active systems, so-called *hybrid systems.* Active/hybrid control systems are force delivery devices integrated with real-time processing controllers and sensors within the structure.

2. Applications of Active Control Systems to Civil Structures

An active control system may be defined as a system which requires a large power source, from tens kilowatts to several megawatts, for control of actuators that apply forces to the structure in a prescribed manner [1], [6],...,[8].

Such active control devices are the active mass driver system (AMD), the active tendon system and the active bracing system [2]. These forces can be used to both add and dissipate energy in the structure [1]. The control forces within the framework of an active control system are generated by a wide variety of actuators that can act hydraulically, pneumatically, electromagnetically, piezoelectrically 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 [5]. 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 the control signals. Both feedback and feed-forward pries can be used together in the same active control system.

The Kajima Corporation installed the first application of active mass driver system to Kyobashi Seiwa Building in 1989, in Japan (Fig. 1). 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 active mass dampers (AMD) was installed on the top building that has 11 storeys and a height of 33 m. The primary AMD is used for transverse motion and has a mass of 4 t, while the secondary AMD has a mass of 1 t and is employed to reduce torsion motion. 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 [10].

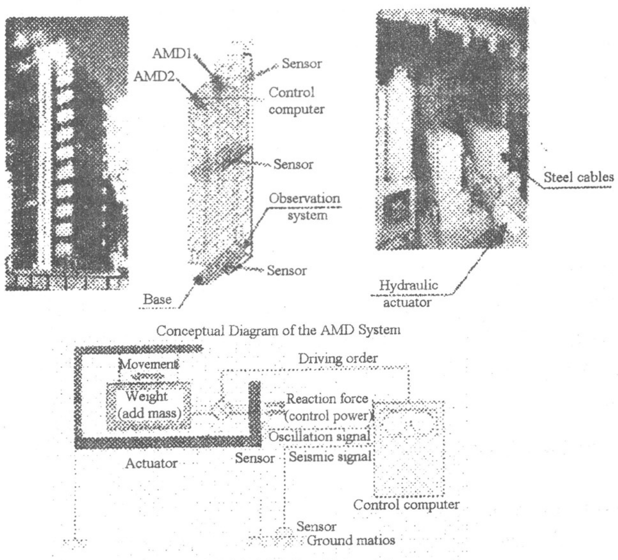


Fig. 1.- Controllability of Kyobashi Seiwa Building.

The results of simulation analysis have shown the effectiveness and reliability of this system to reduce building vibrations under strong winds and moderate earthquake excitations.

This achievement in civil engineering has stimulated further research and development of active structural control.

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 [4]. 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 [4], [9]. The tested structure is a model of a cable-stayed bridge, equipped with two actuators on the two longest stay-cables (Fig. 2). 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 ten times when 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.

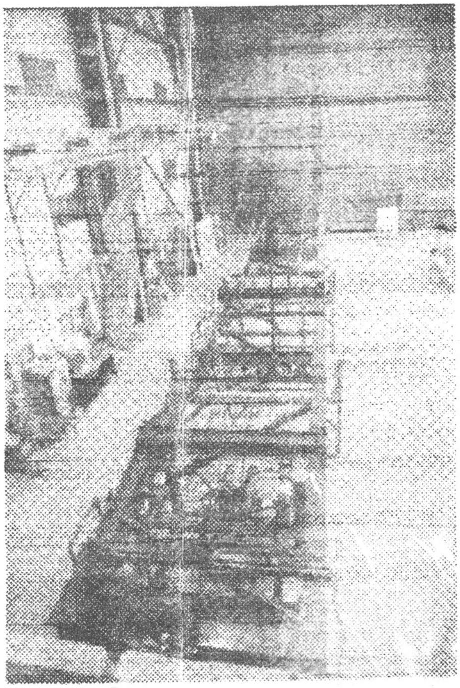


Fig. 2.– Large-scale cable-stayed bridge mock-up.

An active control system has the disadvantage of power failure during vibrations and great costs to implement such a technology. Such devices not depend on the natural frequencies of a structure.

3. Applications of Hybrid Control Systems to Civil Structures

A hybrid control system is defined as one that implies the combined use of active and passive control system [1], [6],..., [8].

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 the hybrid mass damper (HMD) that combines a passive one (TMD) and an actuator. Another difference is that a HMD depends on the natural frequency of a structure whereas an AMD 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 [3]:

a) multi-step pendulum HMD, for example, one is installed in Landmark Tower in Yokohama (Fig. 3), the tallest building in Japan;

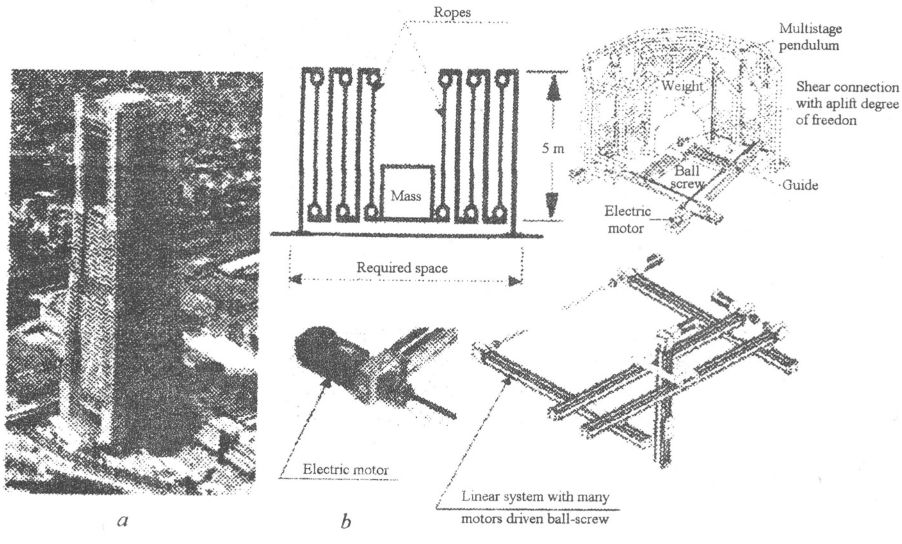
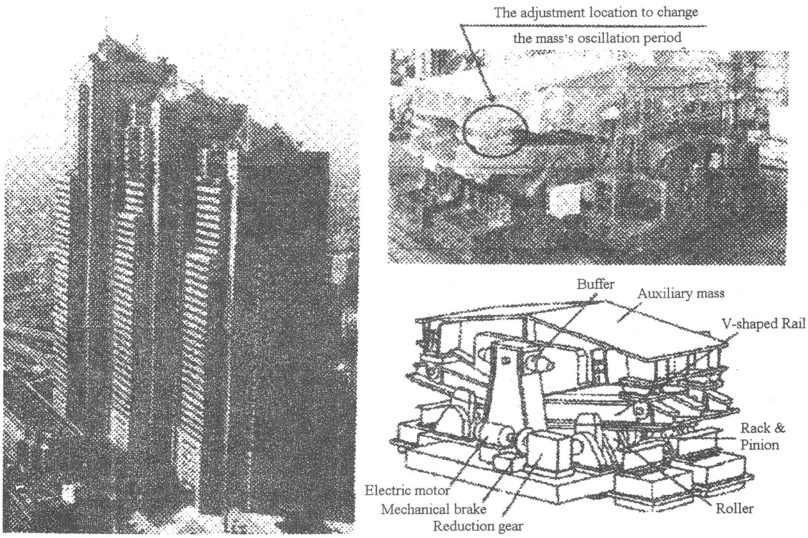


Fig. 3.– *a* – External view of Yokohama Landmark Tower;
b – Multi-Step Pendulum Hybrid Mass Damper.

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

c) passive TMD upon which sits an active mass driver (Fig. 5). The active mass driver at top the tuned mass provides the force necessary 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.



a *b*

Fig. 4.– *a* – External view of Shinjuku Park Tower;
b – V-shaped Hybrid Mass Damper installed in Shinjuku Park Tower.

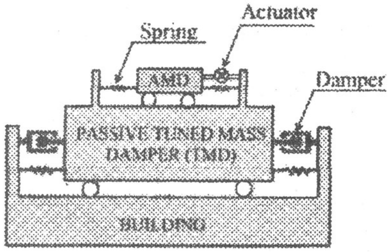


Fig. 5.– Concept of HMD with a passive TMD upon which sits an active mass driver.

Two multi-step pendulum HMD were installed in the Landmark Tower (height 296 m above the ground, weight 260,000 t, 70 stories) at first floor of the building's penthouse (282 m above the ground). Each unit HMD contained an additional pendulum mass installed in the centre of a three-nested steel structure with the three frames connected by triplicating wire ropes. An active system with many motors driven ball screw can move the pendulum in two directions and tune it from a period of 6 s to 4.3 s, through the use of a natural period regulator, in order to correspond to natural modes of the tower. Each unit measured 9 m square, standing 5.0 m tall and weighing 250 t, including the pendulum with its weight, which is 170 t. Maximum pendulum stroke is 1.7 m. Variable orifice dampers (semi-active device) were installed between each frame to insure stability and safety. The damping coefficient is 3,000 N.s/cm when the device stops and 300 N.s/cm while the system is functioning, which corresponds to the optimum damping coefficient for a passive TMD. This hybrid system can reduce until 50% of vibrations induced by wind and moderate earthquakes [3].

Three V-shaped HMD, measuring 7.6 m×4.4 m×3.5 m, were installed in 1994 on the 39th floor of southern tower in the Shinjuku Park Tower which has 233 m height, 56 stories and is the largest building in Japan. The first 37-stories are used as office space while the next stories until the top of the tower are occupied by The Park Hyatt Hotel. The building is composed of three connecting square towers building (each of a square shape measuring 32 m × 32 m) and realized from four steel mast-columns at the four corners of the three square shapes. Each mast column is composed of four steel I-sections bound together by very deep and stocky beams. Medium sized columns between the mast columns carry some additional load. The location of the medium columns along the exterior face of the building changes on the 37th storey where the office floors end and the hotel begins. A belt truss links the columns in order to realize the discontinuity of the medium columns on 37th floor and give a greater stiffness to the building. Dynamic analysis of the tower indicated that first two modes are transversal with a period of 5.24 s, respectively 4.5 s, and the third mode is a torsion motion with a period of 3.98 s. The vibration period of a damper may be tuned to a range of frequencies between 3.7 and 5.8 s by adjusting the rail angle to increase or decrease the length of apparent pendulum so that the mass oscillation period increases or decreases. This adjustment is achieved by altering the thickness of the spacers between the rail and the additional mass. The active control forces are applied on mass *via* an electric motor with the reduction gear and the rack-pinion mechanism. The reactions of the inertial forces become the control forces on structure. Each unit has a mass of 110 t, with a maximum stroke of ±100 cm. The auxiliary masses of the system weigh only about 0.25% of the aboveground building weight. Within the tower are disposed accelerometers that measure the acceleration of the building at all times. These sensors are located on the 1th, 10th, 20th, 30th, 39th and 52th floor but only the sensor placed on the 39th floor is used to calculate the necessary control force to reduce structural vibrations. The other sensors send their measurements to the basement of the tower where these data are used for validation purposes. The sensor situated on the 39th floor sends its acceleration measurements to the control computer, also on the 39th floor, to be used in an acceleration feedback algorithm. This system can reduce displacement from 33% to 50% during the wind and moderate earthquake vibrations [3].

The ability of the HMD to reduce structural responses relies mainly on the natural motion of the TMD. The energy and forces required to operate a typical HMD are far less than those associated with a fully active mass damper system and comparable performances are noted.

Some researchers include the hybrid mass dampers in class of the active control systems.

4. Conclusion

The goal of this paper is to explain and show some recent implementation of active and hybrid control systems for the protection of the civil engineering structures under dynamic loads. 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. H o u s n e r G.W., B e r g a m L.A., C a u c h y T.K., C h a s s i a k o s A.G., C l a u s R.O., S k e l t o n S.M., S k e l t o n R.E., S o o n g T.T., S p e n c e r B.F., Y a o J.P.T., *Structural Control: Past, Present and Future Control.* J. of Engng. Mech.,**123**, *9*, 897-971 (1997).
2. K a b o r i T., *Mission and Perspective towards Future Structural Control Research.* Proc. of the Second World Conf. on Struct. Control, Vol. **I**, Kyoto, Japan, 1999.
3. J e r o m e P.L., *Active Structural Control Research at Kajima Corporation.* The National Sci. Found. Summer Inst. in Japan Program, 1998.
4. M a g o n e t t e G., M a r a z z i F., T o g n o l i P., B u c h e t P., R e n d a V., *Experimental Analysis of Active Control of Vibration of a Large-Scale Cable-Stayed Bridge Mock-Up.* Proc. of the 7th Internat. Seminar on "Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures", Assisi, Italy, 2001.
5. M a r a z z i F., M a g o n e t t e G., *Active and Semi-Active Control of Structures: A Comparison.* Europ. Meeting on Intell. Struct., Ischia, Italy, 2001.
6. M a r a z z i F., *Semi-Active Control of Civil Structures: Implementation Aspects.* Ph.D.Diss., Univ. of Pavia, Italy, 2002.
7. P a s t i a C., *Passive and Semi-Active Control Systems: Theoretical, Numerical and Experimental Aspects.* Tech. Report, JRC Special Publ. 1.04.94, European Commission, Inst. for the Protection and the Security of the Citizen, 21020 Ispra (VA), Italy, 2004.
8. P a s t i a C, L u c a S.G., L u c a F., R o ş c a V.O., *Structural Control System Implemented in Civil Engineering.* Bul. Inst. Politehnic, Iaşi, **LI (LV)**, *1-2*, s. Constr. a. Archit., 41-51 (2005).
9. P r e u m o n t A., *Vibration Control of Active Structures: An Introduction.* 2nd Edit., Kluwer Acad. Publ., Dordecht, the Netherlands, 2002.
10. S p e n c e r B.F., S a i n M.K., *Controlling Buildings: A New Frontier in Feedback.* IEEE Control. Syst. Magaz. on Emerging Technol., Special Issue, **17**, *6*, 19-35, (1997).

APLICAŢII RECENTE ALE CÂTORVA SISTEME DE CONTROL ACTIV ŞI HIBRID LA STRUCTURILE CONSTRUCŢIILOR

(Rezumat)

Aplicarea sistemelor de control în structurile construcţiilor a fost cercetată în ultimii ani pentru a demonstra eficacitatea acestor sisteme în timpul evenimentelor naturale excepţionale precum cutremurele şi vânturile puternice. În lucrare se trec în revistă câteva implementări, la scară reală, a sistemelor de control activ şi hibrid pentru protecţia construcţiilor la acţiuni dinamice.