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Sustainable energy harvesting control system for wind-induced vibration control of structures

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Abstract

This paper presents the conception of a novel Energy Harvesting Control (EHC) system for structural vibration control. The needs for developing sustainable structural control system are discussed at first. Then, a preliminary design of EHC system is investigated and details are described which will be built on previous research outcomes including electromagnetic mass damper with energy harvesting ability. This innovative system is designed to provide local power source charged through the actuator-damper-structure interaction as well as providing additional damping during times of low levels of vibration or disturbance. During period of severe disturbances, such as earthquakes or strong winds, the actuator actively drives the EHC mass to suppress structural vibrations. Energy flow chart between EHC control system and structure is described and the feasibility of EHC control system is discussed, which shows EHC to be a promising sustainable system for structural vibration control.

Keywords: structural vibration control; active/hybrid mass damper/driver control system; energy harvesting

1 Introduction

Natural hazards such as earthquakes, severe storms, hurricanes, tornadoes, floods, tsunami, volcanic eruptions, landslides and wildfires are occurring more frequently in recent years throughout the world. Some of these natural hazards, such as wind related disasters, are believed to be associated with climate change due to global warming. These natural hazards not only cause considerable economic losses but also pose a significant threat to the safety and serviceability of critical civil infrastructures. The dynamic loads associated with these hazards, particularly earthquakes and storms, can cause severe and/or sustained vibratory motion, so that the extent of protection required for these structures may range from structural survivability and reliable operation to human occupant comfort. The challenge faced by civil engineers is to develop safer civil infrastructures to better withstand natural hazards with more efficient and sustainable designs that optimize the use of limited resources.

The use of high strength material and advanced construction techniques produces high-rise buildings and structures with greater heights as well as striking and slender shapes. These increasingly wind-sensitive buildings possess low natural frequencies of vibration, which positions the buildings within an operating range susceptible to enhanced wind excitations such as along wind turbulence buffeting and crosswind vortex-induced excitation, particularly for structures located in high wind speed regions, e.g. coastline of continents. Enhanced wind excitations, coupled with inherently low structural damping values make these buildings and structures prone to wind-induced vibrations which, in addition to structural safety concerns, can heighten occupant perception of vibration and cause fear and alarm. Prolonged exposure to these vibrations can cause discomfort, trigger dizziness and migraine, affect task concentration and productivity (Kwok et al., 2009).

To address the above issues, the structural vibration control approach has been widely adopted when structural design means are unable to achieve the desirable vibration mitigation targets. In 1972, Yao introduced modern control theory to vibration control of civil engineering structures (Yao, 1972), which started the new era of research on structural active control. Thereafter in the ensuring development of more than 30 years, Active Mass Driver/Damper (AMD) control, with the better control effect and cheaper control cost, has taken the lead in various active control options, becoming the most extensively used and researched control method in practical applications (Soong, 1990; Housner *et al.*, 1997; Spencer *et al.*, 1997; Ou, 2003). Several important journals in civil engineering field, such as ASCE Journal of Engineering Mechanics (issue *4th*, in 2004), ASCE Journal of Structural Engineering (issue *7th*, in 2003), Earthquake Engineering and Structural Dynamics (issue *11th*, in 2001 and issue *11th*, in 1998), reviewed the-state-of-the-art in research and engineering applications of semi-active control and active control, especially AMD control. In addition, Spencer and Nagarajaiah (2003) systematically reviewed the applications of active control in civil engineering. Up to date, more than 50 high-rising buildings, television towers and about 15 large-scale bridge towers have been equipped with AMD control systems for reducing wind-induced vibration or earthquake-induced vibration of the structures.

Amongst many structural control approaches, the effectiveness of hybrid control over pure passive control and pure active control, in terms of protection of structural safety and especially its advantageous in enhancing serviceability performance of structures, has been well-documented. The superiority of hybrid control system over pure active control system are the most compelling in the following aspects: 1) Active structural control system requires a significant energy input when actuator is working in a pure "active" situation; 2) Active control system may cause a significant heat generation or energy loss due to its continuous operation or its "ready mode" to respond to active actuation. For example, the hydraulic oil based actuator requires a high oil pressure to maintain actuator readiness to exert energy onto the structure. In contrast, pure passive control dissipates energy from structures; 3) Long term active and ready mode operation cause oil contamination and pollution, oil leaking and noise associated with high oil pressure within pump, pipeline, actuator and accumulator of the whole mechanical system (Zhang, 2005).

In addressing occupant perception or serviceability requirements, long duration vibration should be controlled to an acceptable limit while at minimum cost. This objective is not economically achievable by ordinary control systems other than by hybrid control, for example introducing the energy harvesting system to dissipate energy from main structure and to suppress its vibrations during frequently occurred wind excitations as well as to maintain the potential ability to exert control force during major disaster attacks, such as earthquakes or strong winds.

Regenerative actuation, or energy harvesting, which can be found in areas of automation and control, is another promising improvement. Nerves and Krishnan concluded that this type of regenerative power supply is considered to be an ideal power source (Nerves et al., 1996). Energy harvesting from ambient vibration sources for self-powered micro-systems has been reported, and a variety of mechanisms or materials have been explored, including electromagnetic induction, piezoelectricity, electrostatic generation, dielectric elastomers (Kornbluh et al., 2002; Mitcheson et al., 2004; Beeby et al., 2006; Anton et al., 2007; Priya et al., 2009). This trend has also been implemented in structural health monitoring networks and systems recently. Scruggs examined the implications of limited storage capacity of available energy storage system, which can result in saturation and exhaustion of the supply system (Scruggs et al., 2005). It is noteworthy that in civil engineering field, regenerative actuators have received much less attention in civil engineering applications, which have been limited to a single device with local energy storage. Tang investigated energy harvesting using TMD (Tang et al., 2011). Zhu conducted modelling and testing on electromagnetic device for vibration damping and energy harvesting (Zhu et al., 2012).

2 The energy harvesting control system

Zhang (2005) made a systematically comparison for different control schemes based on the benchmark control problem (Yang et al., 2004), and discovered that the AMD control was the best control scheme due to a number of notable merits, including the best ratio of control effect over control effort, least number of actuators and simple to be implemented. Moreover, through analysis of typical important large-scale structures subjected to different excitations, the effectiveness and feasibility of employing AMD control for civil structures has also been documented (Ou, 2003), including wind and earthquake induced vibration control of high-rising buildings and bridge towers, ice induced vibration control of offshore platforms, wind-wave-current coupling excited control of deep sea platforms.

Usually, an AMD control system is composed of a mass piece, an actuator, stiffness component (coil spring is the most commonly used device), a damper, a stroke limiting device, a brake protector, sensors, a data acquisition and processing system, computerized real-time control software and hardware system . In addition, a power supply system is needed for operating all the electrical devices mentioned above.

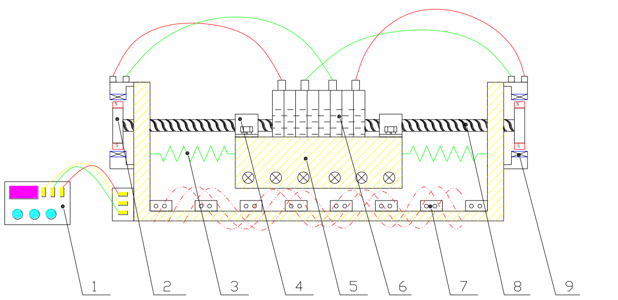
However, in traditional AMD system, the most commonly used actuators are hydraulic cylinders or electrical servo motors, which may have the following disadvantages: large in system volume, complicated in construction, time delay, slow to response, and limited mass stroke (Zhang, 2005). To address these issues, several new special devices were put forward to replace the traditional actuators (Nerves, 1996; Scruggs, 2005). Learning from the motion control principle of magnetic suspended vehicle, the electromagnetic mass damper (subsequently called the “EMD”) control system, as an innovative active control system, was proposed for structural vibration control (Zhang, 2005), which uses the driving technology of linear electric machines, transforming the electric energy directly into mechanical energy of EMD system, for example, the kinetic energy of EMD mass. Although EMD can overcome some limitations posed by traditional AMD system, it belongs to active control system which requires an external power supply which poses challenges associated with reliability and practicality, particularly during earthquakes when the power grid is susceptible to destabilization and blackouts.

Although some research promoted advanced active control systems and strategies, focusing primarily on enhancing actuator force ability, very few are sustainable and environmental friendly. This paper conceptualise a novel Energy Harvesting Control (EHC) system which is designed to transfer local power source charged through the actuator-damper-structure interaction as well as providing additional damping during times of low levels of vibration or disturbance. During period of severe disturbances, such as when earthquakes or strong winds strike structures, the actuator will actively drive the EHC mass to suppress structural vibrations.

The major components of the innovative EHC control system are illustrated in Figure 1(a), which integrates the following four subsystems. A passive Tuned Mass Damper (TMD) subsystem (Subsystem (i)) with energy dissipation and conversion function where traditionally either viscous fluid damper or visco-elastic damper or other types of energy dissipative device is replaced by fly-wheels embedded with coils (Subsystem (ii)), which are connected to a power flow management module (Subsystem (iii)). The power module is utilized to store and release electrical energy, which is composed of a full bridge rectifier, nickel metal hydride batteries or capacitors, and a switching DC-DC step down converter, which is designed to enhance charging efficiency at higher excitation levels. This module is regulated via a real-time Digital Signal Processing (DSP) unit, such as the C2000 series TMS320F2812. The fourth subsystem (iv) is an AMD, which is based on the electromagnetic mass driver (Zhang et al., 2008), where active force is realized by using soft magnetic material based actuator driven by system stored energy.

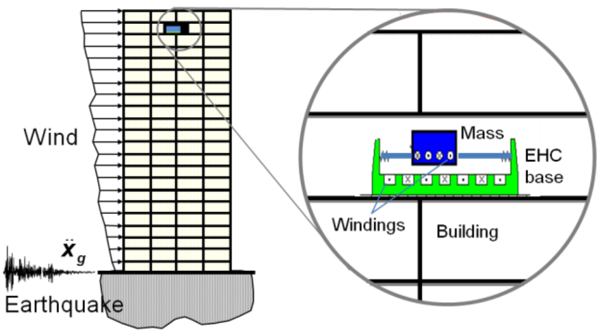
Integrating smart materials may also enhance EHC system versatility, in terms of transiting function modes and fine tuning of frequency via stiffness changes to realize adaptability. According to recent investigations, appending auxiliary lead zirconate titanate (PZT) beam with tip mass to the EHC mass can increase system flexibility, thus widening the operation bandwidth of the passive TMD subsystem. These PZT-mass structures can be considered as serial dynamic subsystem to the main TMD subsystem, and can be designed to multi-resonant frequencies to guarantee the adaptability of the whole system. Furthermore, although PZT is one of the most widely used material, given the fast development in smart materials technique, nano-scale piezoelectrical Zinc Oxide (ZnO) fiber composite is more flexible, and can be designed to be integrated into the restoring force element of the vibratory mass to further fine tune and enhance the energy harvesting capability of the TMD subsystem when working in the hybrid control mode. Energy harvesting via such smart materials embedded in polymer matrix has been successfully validated. Nano smart composites are also sensitive to low frequency input, e.g. the electrical power generated by a high output nano generator subjected to a low frequency excitation, e.g. 0.33 Hz, can reach 0.44 mW/cm^2 with a small strain of 0.1% (Zhu et al., 2010). This is a very promising indication to incorporate such smart materials into the EHC system development. When the mass vibrates due to external excitations, the cyclical deformation of embedded piezoelectrical fiber and PZT beams will generate electron, which provides power to slightly adjust resistance of the system to adapt to optimal energy dissipating and harvesting. This can also serve as sensors which provide additional information about motion of the mass, thus can replace displacement sensor, e.g. traditional laser scales.. Furthermore, the EHC system also includes a fly-wheel body with reducer and accelerator based on coupled gear sets, electrical power generating and harvesting circuit loop, high power storage battery and super capacitor, electronic and electrical regulator, as well as mechanical couplings and necessary attachments for smooth force transferring and delivering.

Figure 1(b) illustrates how the EHC system will be implemented into a building structure. The working principle of the EHC system can be described as: once the structure begins to vibrate due to dynamic disturbance, the mass will respond by vibrating along its guide rails and cause the couplings to rotate the fly wheels thus transforming linear motion into rotation motion. The embedded coil will transversely cut the magnetic field and generate induction currents. The generated electricity will be stored in the system backups which will be re-utilized later, such as during emergency events when earthquake strikes or strong gust wind attacks. Moreover, the reducer and accelerator gear sets are to be built into the rotation system, to improve efficiency of regenerating electrical power, and therefore parametric optimization on gear ratio and damping coefficient can be carried out accordingly.



(a) Conception sketch of EHC system

Legend: 1: digital controller, 2: fly-wheel(s), 3: piezoelectrical fibre polymer springs, 4: linear-rotation couplings with controllable friction, 5: damper mass embedded with PZT-mass substructures, 6: energy storage unit, 7: controllable excitation coils, 8: system support rails with controllable fiction to adjust system damping, 9: dissipative coils



(b) Implementations to the structure

Figure 1. Sketches of the innovative EHC system

Basic energy flow equations are established according to the energy balance requirement, i.e. the total input energy to a structure subjected to earthquake or wind excitations should always be equal to the summation of kinetic energy of structural mass, elastic strain energy restored by structural lateral force resisting members, dissipative energy by structural inherent damping such as joint connection and internal friction, and the rest dissipative energy by control devices. Unique control strategy will be developed to realize an optimal energy harvesting-releasing function and cost effectiveness based on structure-damper interactions. Figure 2 illustrates such an energy flow chart. Based on instantaneous interaction (electromagnetic and mechanical damping) force with relative velocity, the input power can be formulated which is equal to the summation of open loop function, coil loss and storage portion by EHC. Furthermore, the average power is introduced in terms of integration of instantaneous power where force can be replaced by multiplication of equivalent damping coefficient with velocity. Based on stochastic equivalent linearization method, the equivalent damping coefficient, corresponding to when the EHC system is operating in a passive energy dissipating and harvesting mode, can be achieved. Similarly, energy conversion under different circuit cases, such as an open circuit, with constant resistor, with rectifier and superconductor or rechargeable battery, will be evaluated. These works provide a theoretical basis for optimization design, in accordance with parametric analysis involving power, force, and circuit intensity to develop the nominal optimal damping coefficients and dynamic models for the system.

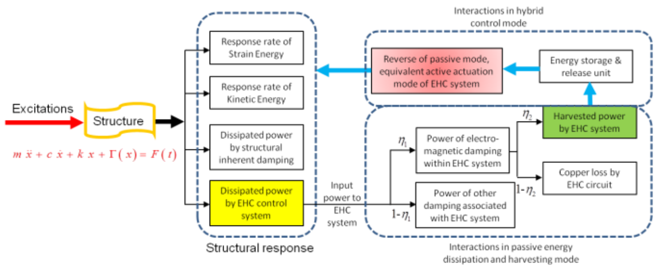


Figure 2. Energy flow chart and interactions between EHC control system and structure

In the following, analysis and design procedure of the EHC system is discussed. When the structure vibrates, the mass moves driving the couplings rotation which transforms linear motion into rotation, and the embedded coil cut the magnetic field and generates induction currents and stored in the batteries which will be utilized at a reasonable occasion. If reducer or accelerator is incorporated into the system, the efficiency of generating electrical power can be greatly improved through optimal gear ratio and damping coefficient. Analysis and design procedure of the EHC system can be developed to address the requirement of a specific structure, such as the benchmark structural models (Zhang, 2005). The specific steps include: first, determine optimal mass ratio, stiffness and damping coefficients according to classical theoretical approach; then, set control objectives which compromise between structural responses criteria with control cost, such as mass strokes and control forces or powers. Furthermore, the control strategy development thereof will be carried out under the frame work of optimal control. Real-time implementation steps include: acquire feedback information through embedded structural health monitoring system; identify and update system states based on state observers and filters; calculate required control force based on the control algorithms; command DSP, for example to switch system modes; update EHC system and structural response as well as external excitation information if applicable then evaluate system performance against the desirable objectives; rectify possible undesirable effects associated with the EHC control system, such as over stroke limit and actuator saturation.

For the optimization calculation, the weight parameters in the objective function are adjustable to adapt to different excitation scenarios. In accordance with the structure-damper-actuator interaction models, algebra Riccati equations can be solved to reach proper control command to the DSP of the EHC system. Therefore, mode switching of EHC system between passive and active is not only dependent on control effectiveness but also on the energy dissipating and harvesting efficiency, which can be quantitatively calculated using spectrum integration and the residue theorem when system subjected to random excitations.

Regarding the implementation of EHC system, first the design should be inclusive of SHM to the control system and establish corresponding communications; then upgrade the control command with available information acquired through SHM; perform RST tests to verify mathematical models; perform parametric optimization to update algorithm parameters and control strategy; carry out field operational experiments to monitor and evaluate the system performance on-site.

In the following, feasibility of utilizing such kind of EHC system for suppressing structural vibrations will be briefly discussed. This will be focused on the electrical energy loops of the system, because the other major parts will be benefited from either AMD or TMD control, which are relatively matured techniques. Currently, a commercial high-power capacitor can be used to store energy up to 3MJ, where its energy density will be 1.35kJ / kg and about 1.5kJ / dm^3, thus the mass will be about $2m^3$ and the weight will be approximately 2tons. Therefore, a moderate scale EHC system may store energy equivalent to 3MJ, which is adequate for continuous actuation of control system for more than 200 seconds. Normally, earthquake or strong wind induced dynamic loading is limited to the duration within several dozens of seconds only. Thus, the stored energy is significant to counteract structural peak response which may surpass certain safety threshold during first several cycles of vibrations. Then, following the transient response, the structural self-damping will be enhanced due to inherent interactions between control system and structure, which will play an important role in dampening consequent nontrivial vibrations, rather than deformation which is more likely to occur during “extreme” long period of wind.

Conclusions

In this paper, an innovative Energy Harvesting Control (EHC) system for structural vibration control is conceptualised and introduced. The preliminary design of EHC system is investigated. Sketch and energy flow chart between EHC control system and structure are also discussed. Furthermore, the possibility of incorporating smart materials and preliminary feasibility analysis are also carried out. Based on the preliminary analysis, the EHC system is shown to be a promising sustainable alternative to pure active control system for suppressing structural vibrations.

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References

Anton S.R., Sodano H.A. A review of power harvesting using piezoelectric materials (2003-2006). Smart Mater Struct 2007;16: R1-R21.

Beeby SP, Tudor MJ, etal. Energy harvesting vibration sources for micro systems applications. Meas Sci Technol 2006;17:R175-195.

Housner G. W., Bergman L. A., Caughey T. K., Chassiakos A. G., Claus R. O., Masri S. F., Skelton R. E., Soong T. T., Spencer B. F. and Yao J. T. P.. Structural Control: Past, Present, and Future, ASCE Journal of Engineering Mechanics. 1997, 123(9): 897-971.

Kornbluh R.D., Pelrine R., Pei Q., Heydt R., Stanford S., Oh S., Eckerle J. Electroelastomers: applications of dielectric elastomer transducers for actuation, generation, and smart structures. In: Proc. of SPIE Smart Struct. Mater. Conference; 2002. p. 254-270.

Kwok K.C.S., Hitchcock P.A., Burton M.D. Perception of vibration and occupant comfort in wind-excited tall buildings, Journal of Wind Engineering and Industrial Aerodynamics, 97 (2009) 368-380.

Mitcheson P.D., Miao P., Stark B.H., Yeatman E.M., Holmes A.S., Green T.C. MEMS electrostatic micro-power generator for low frequency operation. Sensors and Actuators A 2004;115:523-9.

Nerves A.C., Krishnan R. A strategy for active control of tall civil infrastructures using regenerative electric actuators.Proc., 11th ASCE Eng. Mech. Spec. Conf., Ft. Lauderdale, FL, 1996, 503-506.

Ou J.P. Structural vibration control - active, semi-active and smart control, China science press, 2003.

Priya S., Inman D.J. Energy harvesting technologies. LLC: Spinger Science Business Media; 2009.

Scruggs J.T., Iwan W.D. "Structural Control with Regenerative Force Actuation Networks." Journal of Structural Control & Health Monitoring, (2005), 12(1), 25-46.

Soong T. T.. Active Structure Control Theory and Practice. Longman Scientific & Technical. New York, USA. 1990.

Spencer B. F.Jr. and Nagarajaiah S. State of the Art of Structural Control. ASCE Journal of Structural Engineering. 2003, 129(7): 845~856.

Tang, X., & Zuo, L. (2011). Enhanced vibration energy harvesting using dual-mass systems. J. Sound & Vibration, 330(21), 5199-5209.

Tse, K. T., Kwok, K. C. S., & Tamura, Y. (2012). Performance and cost evaluation of a smart tuned mass damper for suppressing wind-induced lateral-torsional motion of tall structures. Journal of Structural Engineering, 138(4), 514-525

Yang J. N., Agrawal A. K., Samali B. and Wu J. C. A Benchmark Problem for Response Control of Wind-Excited Tall Buildings. ASCE Journal of Engineering Mechanics. 2004, 130(4): 437-446.

Yao J. T. P. Concept of Structure Control. Journal of Structure Division, ASCE 1972, 98(ST7): 1567~1574.

Zhang C.W. Electromagnetic AMD systems and their relevant theory and experiments for structural vibration control. Ph.D thesis of Harbin Institute of Technology, 2005

Zhang C.W., et al., Recent advances on structural vibration control and blast resistance research in Hit blast resistance and protective engineering laboratory, 1st Asia pacific young researchers and graduates symposium, p132-187, Feb. 26-28, 2009, South Korea.

Zhang C.W., Ou J.P. Control Structure Interaction of Electromagnetic Mass Damper System for Structural Vibration Control, ASCE Journal of Engineering Mechanics, 2008, 134(5), 428-437.

Zhu G., Yang R., Wang S. and Wang Z.L., Nanoletter 10 (2010) 3151-3155.

Zhu S.Y., Shen W.A., Xu Y.L. Linear electromagnetic devices for vibration damping and energy harvesting: Modeling and testing, Engineering Structures, 34 (2012) 198-212.