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Energy harvesting via structural control systems: a wind-excited Benchmark structural model case study

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Abstract

The needs of developing sustainable control system for suppressing structural vibrations via energy harvesting approach have been demonstrated recently. The current paper is focused on comparing control effectiveness versus control effort for different structural control schemes and the results will be utilized to justify the reason of choosing Active Mass Driver/Damper (AMD) for energy harvesting instead of using interbedded control devices, such as dampers and braces. The comparison and discussion will be made based on the Benchmark problem established by the International Association of Structural Control and Monitoring (IASCM). The results will form part of the basis for developing new AMD system with energy harvesting capabilities for structural vibration control.

Keywords: Benchmark; structural vibration control; active mass driver; interbedded control

1 Introduction

The International Association of Structural Control and Monitoring (IASCM) initiated Benchmark problem for structural control research since the late of 1990s. So far, the 3rd generation Benchmark of the wind-induced vibration control of the Melbourne 76-floor building structure has attracted a number of intensive research foci.

In the past few years, a lot of control strategies have been proposed and evaluated based on the Benchmark model. The followings are some selective results: Ahlawat *et al.* (2004) carried out the fuzzy logic control based multi-objective optimization for this Benchmark study where both the safety and occupant comfort criteria for the building has been considered and utilized to generate control command of the FLC-driven ATMD system. Battaini *et al.* (2004) discussed the adoption of a fuzzy controller for the benchmark problem where a minimum of two sensors were engaged to drive the single actuator for wind induced vibration control. Kim *et al.* (2004) proposed the sliding mode fuzzy control strategy to address the existence of disturbances within large civil infrastructure, where the controller is composed of compensation and a convergent part, and the compensation part uses the structural response measurement and the disturbance measurement resulting in a feedback-feed forward control loop which is efficient for reducing the wind-induced vibrations. Lus *et al.* (2004) presented an approach outlining the system identification and damage detection algorithm for the linear Benchmark 76-floor structure, where a state space model using the Observer/Kalman filter identification algorithm and the second-order dynamic model parameters from the realized state space model were both investigated. It contributed the system model from a view point of health monitoring approach which is critical when engaging precisely state space based system model for carrying out active control analysis. Mei *et al.* (2004) proposed the Model Predictive Control strategy for the Benchmark problem where the MPC is based on the minimization of the difference between the predicted and desired response trajectories which is also subjected to input/output hard constraints prescribed constraints, and the results demonstrated the effectiveness and robustness where the building with minus/positive 15% stiffness uncertainty was considered. Peng *et al.* (2004) introduced a sinusoidal reference control strategy which is able to realize adaptive feed-forward vibration control, where the recursive-least-squares algorithm is used and a higher frequency sinusoidal signal is adopted as the reference signal, and both the numerical and experimental results showed that the proposed strategy can reduce structural vibration and achieve adaptability in real time with regard to dynamic uncertainties and modeling errors. Pham *et al.* (2004) investigated traditional linear quadratic Gaussian control approach where a reduced order of system and a balanced controller was designed to achieve minimizing control cost on the order of one-third less than the standard LQG solution together with guaranteed stability performance. However, the higher desired performance may require a significant control effort to be exerted.

Samali *et al.* (2004b) established the framework of the active tuned mass damper (ATMD) incorporated with the fuzzy logic controller, where the inherent robustness and ability to handle nonlinear behavior of structure without a mathematical model has been presented, and the results have also shown the performance of such a control strategy dealing with uncertainty in stiffness which is similar and somewhat advantages over LQG controller. Samali *et al.* (2004c) also investigated using liquid column vibration absorbers (LCVAs) for the Benchmark problem based on previous successful implementations of LCVAs into similar practical structures. Here the LCVA adopted is composed of four identical columns of water. Different configurations in the LCVA, e.g. without additional damping enhancing mechanisms, or with orifice plates have been considered for direct comparison. Besides, the robustness issue, the sensitivity of the LCVAs to mistuning has also been investigated, and the performance of LCVA has also been compared against the tuned mass damper (TMD) control strategy, where the comparable results show the LCVA is more attractive due to low cost and associated advantages.

Varadarajan *et al.* (2004) proposed the novel semi-active variable stiffness-tuned mass damper (SAIVS-TMD) and continuously retuning its frequency due to real time control thus it is robust to changes in building stiffness and damping. The control strategy incorporates a Hilbert transform instantaneous frequency algorithm, and the results show the effectiveness is comparable and robust only at an order of magnitude less power consumption than pure active control.

Wu *et al.* (2004) also proposed the modified sliding mode control (MSMC) strategy using dynamic output feedback which incorporates a pre-filter to modulate the control force together with a Kalman–Bucy filter based observer using limited acceleration measurements only at strategic locations, and the simulation results demonstrate the control effectiveness of structural vibrations as well as it robustness.

Yang *et al*. (2004a) proposed two multi-objective control strategies to the Benchmark problem, i.e. the energy-to-peak based controller and the peak-to-peak based controller, which were to minimize the sum of weighted peak responses with the constraints or penalties on the peak values of control resources.. Additionally, both the state feedback and dynamic output feedback controllers are compared, and simulation results illustrate that the proposed control strategies are advantageous as compared with the linear quadratic Gaussian controller.

In addition to the aforementioned researches regarding the wind induced vibration control Benchmark problem, Active Mass Driver/Damper (abbreviated as "AMD") control has also received intensive investigations by researchers within structural control area. Since Yao (1972) proposed the concept of structural active control, the AMD control, recognized by better control effectiveness against control cost, has taken the lead in various structural control options and become one of the most extensively researched and applied technique in practical applications (Soong, 1990; Mita *et al*., 1992; Housner *et al*., 1997; Spencer *et al*., 1997, 2003; Ou, 2003; Zhang *et al*., 2010b). Several important journals in civil engineering field, such as Journal of Engineering Mechanics ASCE (issue *4th*, 2004), Journal of Structural Engineering ASCE (issue *7th*, 2003), Earthquake Engineering and Structural Dynamics (issue *11th*, 2001; and issue *11th*, 1998), included the-state-of-the-art of research and engineering applications of semi-active control and active control, particularly AMD control, e.g. this IASCM Benchmark control problem. Spencer and Nagarajaiah has made a systematical overview about the applications of active control in civil engineering (Spencer *et al.*, 2003). Up to date, more than 50 high-rising buildings including television towers and nearly 15 large-scale bridge towers have been equipped with AMD control systems for reducing wind-induced vibrations or earthquake-induced vibrations of the structure. Although AMD control has achieved success, there are still un-discovered problems and issues concerning incorporating semi-active devices into active systems (Horvat *et al.*, 1983; Pinkaew *et al.*, 2001; Ou, 2003; Ricciardelli *et al.*, 2003; Zhang *et al*., 2010b). On one hand, understanding differences existing in control strategies is essential for designing and to achieve best performance in terms of seeking the compromise or trade-off between control effectiveness/efficiency and control cost. On the other hand, understanding the phenomena behavior as well as intrinsic mechanism of active control force corresponding to each control strategy realized by different control systems will contribute to identifying the best suitable systems for application considerations. Ou and Li (2010) found that linear quadratic regulator (LQR) based active control force can be decomposed of an elastic restoring force component and a damping force component. According to the analysis of the proportions of the elastic restoring force and the damping force to the total active control force, two sets of indices were developed to quantify the damping characteristics and the negative stiffness characteristics, respectively. The latter issue has also been intensively discussed by Iemura *et al*., (2005). These indices can be used to quantify capability of a semi-active damping system and a passive damping system achieving the performance of a full active control system. Numerical results also indicate that negative stiffness characteristics of an active control force exist in an active control system, which has also been successfully realized by semi-active magnetorheological (MR) damping systems demonstrated through a site test of a stay cable of the Binzhou Yellow River Highway Bridge. As a simultaneous investigation, for example, the structural interbedded active control strategy for the IASCM Benchmark problem has also been studied, where behavior of active control force were found to be essential damping force, which indicated that the active actuators can be replaced by semi-active devices or even passive viscous damping devices based on proper designing, however, the phenomena behavior of active force of AMD system was found to be case dependent, which means the actuator of AMD system can't be simply replaced by semi-active or passive device (Zhang *et al.*, 2010a). The intrinsic mechanism of AMD control force need to be investigated thoroughly, particularly on the basis of a representative/typical civil structure background, and the IASCM Benchmark model is shown to be most appropriate.

2 Comparison between AMD control and STI control

Yang *et al.* (2004b) proposed the Benchmark reference control strategy, where the AMD inertia mass is 500 ton, i.e. nearly 0.33% of the total structural weight. A standard MATLAB program has also been developed for running simulations. Under the input of first 900 seconds of wind load acquired through wind tunnel tests (Samali *et al.*, 2004a; Yang *et al*., 2004b). It is worth noting that the second generation Benchmark problem was based on the simulated wind loading, but the third generation Benchmark problem was based on the Wind Tunnel tests done in Sydney University where a 1:400 rigid model was tested and sufficient long wind force was acquired for further analysis. The standard solution of control force, cost and effectiveness, for the Benchmark problem can be acquired based on the simulation program. The standard analysis is conducted on a reduced order of structural model, however, in the current paper, the non-reduced original structural model with 76DOFs is found to be more appropriate for the purposes of control strategies comparison. On the other hand, structural interbedded active control (STI) is referred to adding actively controlled actuators into each or selected adjacent structural inter-storeys, which can be realized by such well-known approaches as active brace systems (ABS) or active tendon systems (ATS), where active control force is exerted directly onto the structural floors or column-beam joints. Under the assumption of in-plane infinite stiffness of structural floors, the active control force contributes to structural anti-lateral resistance capacity during events such as earthquakes excitations. However, for the purpose of numerical analysis, the control force and its accompanied reaction force should be considered simultaneously in the equation of motion of the whole system. For example, if the active force generated by each actuator has the similar magnitudes, owing to the reaction and counter force effect, the ultimate effect for the continuously placed actuators will equal to merely adding two control forces with the same magnitude but opposite directions, i.e. one at the bottom floor and the other one at the top floor. It results in an equivalent effect of an active moment or force couple counteracting the bending deformation of the whole structure during lateral vibrations. As a comparison, AMD control system utilizes only one actuator with the inertia mass function as supporting point for the reaction force, therefore, it is different from STI control with regard to calculation.

Since the optimal placement of actuators for STI control strategy is not the concerned issue, it is assumed that actuators are distributed uniformly throughout the building. Zhang *et al*. (2010a) have made a thorough comparison on control algorithms as well as weight parameters to exclude potential impact of corresponding parameter settings. Based on the above settings, the calculated structural response, as given in figure 1, is shown to be controllable within the same range by the two control strategies.

Figure 2 presents a comparison of control forces corresponding to AMD and STI control strategies. Figure 2(a) shows the time history of AMD control force, and figure 2(b) shows the time history of STI control force at the 60th floor. In addition, the peak and RMS control force of each floor actuator by STI control strategy has the similar amplitude and waveforms as shown in the figure 2(b). It is concluded that STI control has achieved a comparable effectiveness at the cost of several times of the AMD control in terms of control force magnitudes and numbers of devices. The quantitative results are: 1) For the AMD control, the peak force is 265kN and the RMS value is 63.5kN; 2) For the STI control, it needs 76 actuators, and the peak forces range from 372kN to 527kN with an average of 438kN. The RMS force values range from 100kN to 150kN with an average of 125kN.

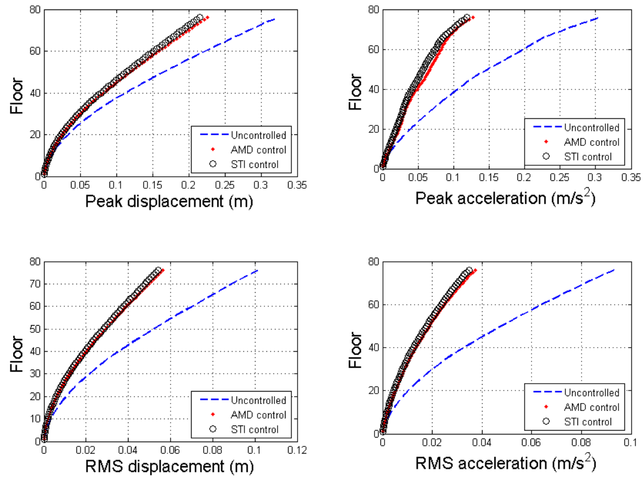
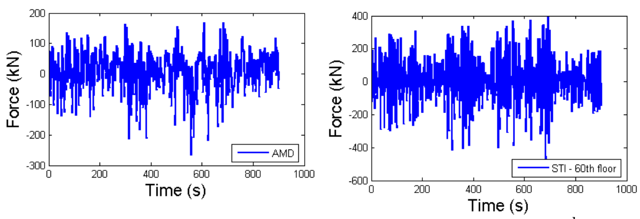


Figure 1. Comparison of structural response by AMD and STI control strategies



(a) AMD control force (b) STI control force at 60th floor

Figure 2. Comparison of time history of active control force by AMD and STI control strategies

Table 1. Comparison of control results between AMD and STI control strategy

Control results	Reduction of displacement (%)		Reduction of acceleration (%)		Actuator devices	
	Peak value	RMS value	Peak value	RMS value	Peak force (kN)	Quantity
AMD control	30.0	43.3	58.7	59.9	265	1
STI control (Zhang et al., 2010b)	33.2	46.5	61.3	62.7	372~527	76
STI control (Ou, 2003)	33.5	-	46.8	-	110~1500	20

In addition, Ou (2003) has put forward another STI control strategy based on the optimal placement of actuators, where a total number of 20 actuators were employed and placed at every four floors from the 1st bottom floor to the top floor. The quantitative results of the two STI control strategies as well as AMD control strategy are summarized in Table 1.

3 Discussions

The STI control is shown to be more consumptive than AMD control in terms of force resources cost, for example, to achieve a comparable effectiveness, the magnitude of total RMS force required by STI control is 150 times bigger than that of AMD control. Based on the phenomena observation, the primary reason can be attributed to the reaction/quits effect between each adjacent placed actuator. Therefore, it is not cost-effective to engage pure active actuators into inter-storeys for vibration control of tall building structures, although the actuator stroke is relatively small compared with AMD actuator stroke. The following section will develop a further analysis on the intrinsic mechanism of active force corresponding to STI control.

Ou and Li (2010), Zhang *et al*. (2010a) proposed the index denoting the direction relation between control force and velocity etc. Based on the index, properties of control force corresponding to different scheme can be compared. The results have illustrated that behaviour of control force corresponding to these two schemes are different. The STI control force is basically damping force behavior, but the AMD control force is irregular in terms of velocity or displacement relevant behavior. As a result, although achieving similar control effectiveness, the characteristics of control forces by the two control strategies are completely different from each other.

In order to exclude any potential impact attributable to control algorithms and weight parameters, the AMD control strategy is also examined based on three independent algorithms: Linear Quadratic Regulator (LQR), output feedback optimal control (named as LQRY), and Linear Quadratic Gauss (LQG) control. As a result, figure 5 shows the peak response at the top structural floor under different control algorithms, where all weighting parameters within Q matrix are set to be unit, except parameters corresponding to the state of inertia mass are assigned to be non-zero small numbers. The acquired parametric impact results agree well with the standard Benchmark solution as well as other proposed Benchmark solutions based on stochastic controllers (Yang *et al.*, 2004b; Mei *et al.*, 2004; Pham *et al.*, 2004; Samali *et al.*, 2004b).

Based on the numerical analysis results, the STI control is shown to be ineffective in terms of active energy exertion. AMD control with a comparable control effect only requires less than 1% control forces but at the cost of significant bigger mass strokes. This result leads to the challenging of actuator realization, however, it also indicates that the mass of the control system can be fully excited under wind loading and thus to function as active control force providing supporting point. Leaving control effect alone, this result brings the opportunity to replace actuator with reversible electric motor, which is able to transfer localized power source charged through the motor-structure interaction as well as providing additional damping during times of low levels of vibration or disturbance; then, during period of severe disturbances, such as when earthquakes or strong winds strike structures, the stored energy will be utilized to drive actuator to actively drive the system mass to suppress structural vibrations. This is the basic working principle of the energy harvesting control system. Therefore, based on the comparison, the AMD system is shown to be more suitable than STI control to harvest structural vibration energy to realize sustainable vibration control systems for structures.

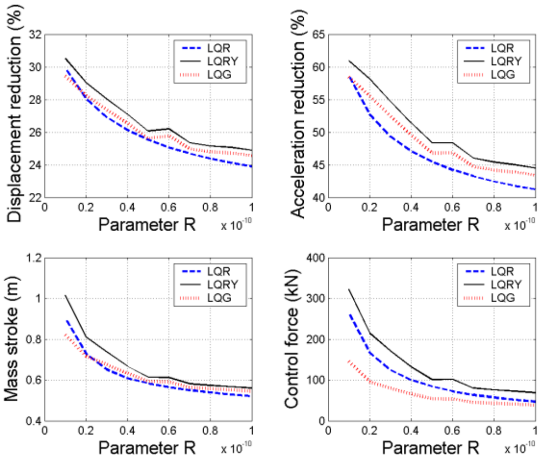


Figure 5. Parametric impact of AMD control based on the non-reduced structural model

Conclusions

To achieve the similar control results, AMD utilizes smaller control force and far less numbers of actuators, but relatively large mass strokes and velocities compared with STI control. on the other hand, to achieve energy harvesting, using electro-magnetic method will require relatively large velocity to generate substantial Lorenz force so as to regenerate sufficient electricity in the system mechanical-electrical loop. From this point of view, AMD is shown to be the most economical way to harvest energy when a damper mass is in-place on top of such high-rising building structure; however, if multi devices can be installed within inter stories, then piezo-electric material based e.g. adjustable friction dissipation device is more appropriate due to the large force requirement and relatively small constrained strokes and velocities under low frequencies of structural vibrations.

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