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ACTIVE VIBRATION CONTROL AND ENERGY HARVESTING USING AN ELECTROMAGNETIC DAMPER

JIAYANG SHEN[*] AND SONGYE ZHU[†]

[*] Department of Civil and Environmental Engineering
The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong
e-mail: jiayang97.shen@connect.polyu.hk

[†] Department of Civil and Environmental Engineering
The Hong Kong Polytechnic University
Hung Hom, Kowloon, Hong Kong
e-mail: songye.zhu@polyu.edu.hk

Abstract. Wind-induced vibration has been a significant concern in high-rise buildings. Among different types of structural control methods, active control provides superior control performance at the expense of high energy demand, prohibiting the promotion of its applications. In recent decades, the electromagnetic actuator has attracted researchers' attention due to its ability to convert kinetic energy into electrical energy. This feature enables the energy conversion between the host structure and the actuator, suggesting the possibility for active control with zero or negative energy consumption. This study investigates the feasibility of employing an electromagnetic damper with LQG control for vibration suppression and energy harvesting purposes. A simulation for a full-scale 76-story benchmark building with the proposed device is conducted. The proposed electromagnetic device outperforms the optimized passive system. Average output power at the kilowatt level is achieved for energy harvesting performance. The results above confirm the viability of adopting electromagnetic devices in structures.

Key words: Active Control, Energy Harvesting, Electromagnetic Damper, Tuned Mass Damper.

1 INTRODUCTION

In recent decades, wind-induced vibration has been a significant concern in high-rise buildings. The tuned mass damper (TMD) is a passive vibration control system that can effectively reduce the amplitude of vibrations. It is acknowledged that raising the mass ratio could enhance control performance for a single TMD. However, several restrictions on construction projects make the use of a single TMD with a high mass ratio impossible. Gutierrez Soto and Adeli [1] investigated the application of TMDs and found that TMDs heavier than 500 tons were rarely used for anything other than towers. Due to the limitations of traditional TMDs, adjustments were made to provide better vibration suppression performance [2]. Passive multi-TMDs [3, 4] were studied to attenuate the resonance further,

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and semi-active control strategies [5], such as tunable stiffness or damping, were used to improve the compatibility of control devices. Active control outperforms passive and semi-active control methods at the cost of excessive energy demand, which prevents its widespread use.

Electromagnet dampers (EMD), a new type of damper that can convert mechanical energy into electrical energy, are becoming more popular in structural control [6]. The use of electromagnetic (EM) shock absorbers in structural control systems could potentially reduce energy consumption and improve the sustainability of the built environment. Self-powered active control devices were investigated and proven to be feasible on small-scale systems [7], medium-scale systems [8], and large-scale systems like vehicles [9], whereas the vast majority of EM regeneration devices continue to use a passive control technique. This research aims to investigate the viability of using an active tuned mass damper (ATMD) system, which incorporates an EMD with an H-bridge for simultaneous vibration control energy harvesting. The proposed ATMD is used to simulate a benchmark building [10]. Two optimal passive TMDs, with mass ratios of 0.67% and 2%, are also simulated for reference.

2 SYSTEM CONFIGURATION AND WORKING MECHANISM

2.1 Active tuned mass damper

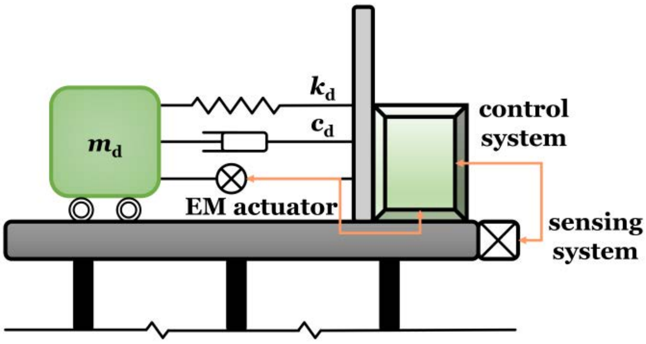

Figure 1: Configuration of ATMD

For the 76-story benchmark building, an active tuned mass damper (ATMD), as shown in **Figure 1**, is taken into consideration. The ATMD system comprises three major components. The sensing system collects structural responses, while the control system, a microcontroller unit (MCU) in this paper, is responsible for compiling the designed control algorithm. Lastly, a TMD with an EM actuator connected to an H-bridge circuit is employed to provide active control force.

This study adopts Arduino Uno for the controller unit. The initial steps involve inputting the measured information into the MCU. In order to achieve the desired control force, computational processes based on the pre-coded control algorithm, the LQG control algorithm in this research, is to be carried out. The EM actuator performs a two-way transformation of electrical and kinetic energy. For the EM transducer adopted in this study, the relationship between the electrical and mechanical properties can be expressed as

$$V_{em} = K_{em} \cdot \dot{x}_{em} \tag{1}$$

$$f_{em} = -K_{em} \cdot i_{em}$$

where K_{em} denotes an inherent parameter of the EM transducer provided by the manufacturer. $\dot{x}_{em}$ denotes the relative velocity difference between two ends of the EM actuator; i denotes the current; and V_{em} and f_{em} are the counter-electromagnetic force (counter-emf) and the electromagnetic control force, respectively. The EM motor is connected with an H-bridge circuit to realize the target control force. Li [11] discussed the detailed working mechanism of the H-bridge system. This study follows the design proposed previously; in this case, the duty cycle of the H-bridge can be calculated by the target current, as presented as

$$D_1 = \frac{1}{2} + \frac{V_{em} - f_{em} R_t / K_{em}}{2V_{batt}} \tag{2}$$

where D_1 is the duty cycle ranging from 0 to 1. D_1 represents the 'ON' state of pulse-width modulation (PWM) signals. R_t represents the total electrical resistance of the circuit, and V_{batt} represents the voltage of rechargeable batteries. The proposed system operates alternatively between energy-consuming and energy-harvesting modes. The necessary condition for energy harvesting is described as shown.

$$\frac{f_{em}}{\dot{x}_{em}} < \frac{K_{em}^2}{R_t} \tag{3}$$

3 SIMULATIONS OF ATMD ON BENCHMARK BUILDING

3.1 Basic information

A 76-story office building in Melbourne, Australia, was used for simulation in this study [10]. The building was made of reinforced concrete with a total mass of 153,000 metric tons. The structure is wind-sensitive, with a height-to-width ratio of 7.3. The first three natural frequencies are 0.160 Hz, 0.765 Hz, and 1.992 Hz, respectively. Using Rayleigh's method, the structure's inherent damping ratio was calculated to be 1%. Wind tunnel experiments were conducted to find the quantity of force the wind was putting on the benchmark building in both directions. The model-to-prototype scale was set at 1:400, and the wind velocity scale was set at 1:3. At a scale of 1:133, the data was collected for 27 seconds. The following results do not consider any static deflection that may have occurred in the benchmark building. The wind loading was scaled to be 20 meters per second at 10 meters in height for all the simulation results presented below.

3.2 Results and discussions

Three simulation cases are presented in this section, including two optimized reference TMDs, weighing 250 t and 750 t, respectively. At the same time, this study focuses on a 250 t ATMD installed on the top of the building. The parameters of chosen ATMD system is presented in the table below.

Table 1: Design parameters of ATMD

Component	Parameter	Value
ATMD	Mass, m_d	250 t
	Damping ratio, ζ_d	0.0856
	Tunning ratio, f_{opt}	0.9934
	Mass ratio (of 1^{st} modal mass)	0.667%
	Mass ratio (of total mass)	0.185%
EM actuator	Motor constant, K_{em}	4000 N/A or V·s/m
H-bridge	Total resistance, R_t	35 Ω
	Voltage, V_{batt}	21,600 V
Others	Parasitic damping coefficient, C_p	4.761 kN·s/m

As shown in **Figure 2**, the simulation findings reveal that the suggested ATMD reduces the root-mean-square (RMS) top floor displacement by 46.31% compared to the uncontrolled case. The 750 t TMD reduces RMS top floor displacement by 43.69% compared to the ATMD, which can offer marginally better performance while significantly lowering the mass ratio. The optimized TMD, which is the same weight as the ATMD, further reduces vibration by an additional 9.33% for the ATMD.

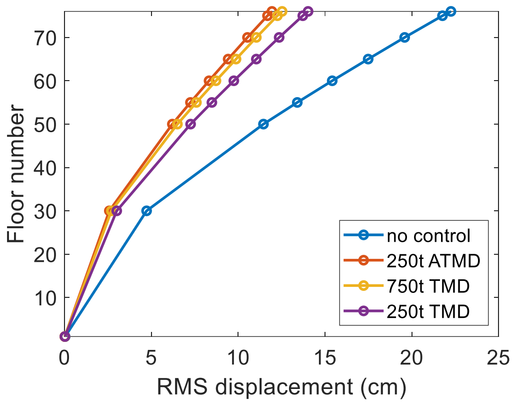

Figure 2: RMS displacement responses

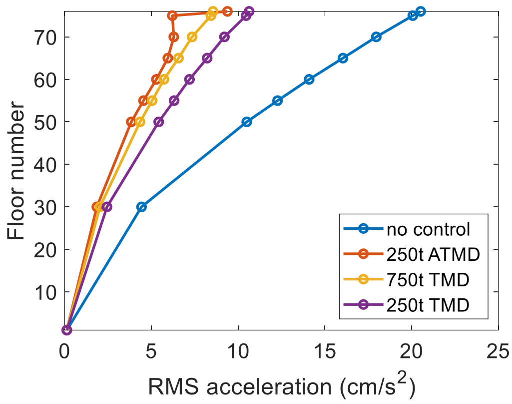

Figure 3: RMS acceleration responses

The optimum 250 t TMD results in a 48.17% response reduction on the 76th floor when compared to the uncontrolled case for RMS acceleration responses, as shown in **Figure 3**. The proposed ATMD also permits a further reduction of another 6.10%. The 750 t TMD offers the best performance among all categories, which results in a reduction ratio of 58.32% compared to the uncontrolled case, in contrast to the earlier displacement suppression results. It is observed that the ATMD affects the acceleration reduction ratio on the 75th floor. The RMS acceleration of the 75th floor is reduced by 47.87% and 57.97%, compared to optimal passive TMDs of 250 t and 750 t, while the value is increased to 69.06% by ATMD.

It is evident that ATMD has the potential to achieve a control performance that far exceeds the norm. In general, when comparing RMS responses, ATMD provides vibration control performance comparable to 750 t TMD while having the added benefit of a much smaller mass ratio.

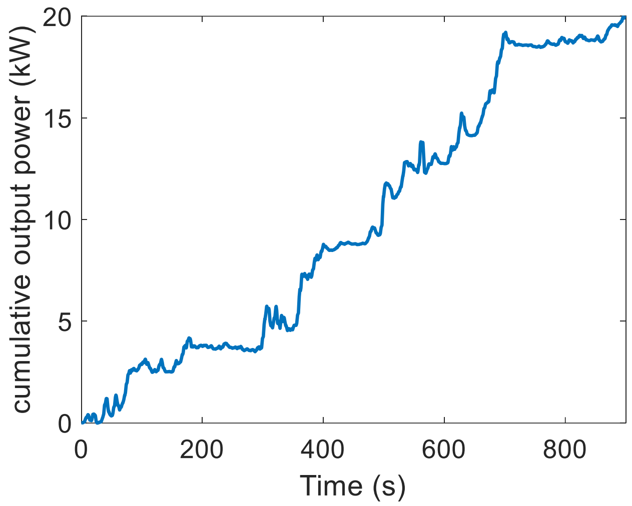

Figure 4: Cumulative output power during the simulation time of 900 s

In terms of control force, the EM motor has an RMS value of 98.52 kN and a maximum weight of 407.96 kN. More than 97% of the excitation at 900s is compatible with positive energy flow. The amount of energy harvested at 20 m/s average wind speed is 22.138 kW, as presented in **Figure 4** and **Figure 5**. In this case, a significant amount of positive energy output validates the feasibility of the proposed design.

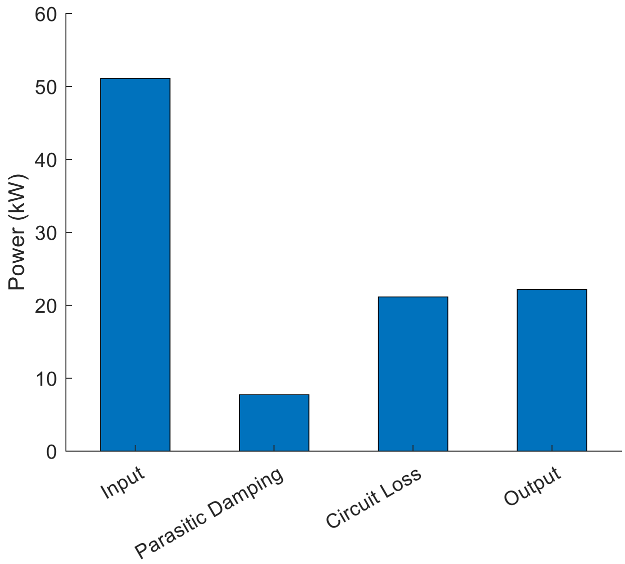

Figure 5: Power distribution

There are still several methods available to further improve the performance. For example, limiting total circuit resistance allows the energy-harvesting condition to be met more easily, therefore increasing harvesting potential. Furthermore, using actuators with greater electromechanical capacity, or higher K_{em}, would reduce the current intensity and the heat loss in the circuit. Finally, the frictional force could be reduced to further moderate parasitic damping.

4 CONCLUSIONS

This study proposes an innovative ATMD for controlling a 76-story benchmark building under wind loadings. H-bridge EMD performs the energy harvesting function by tracking and providing a user-specified target force. The target force is calculated with the help of the MCU and determined using the LQG control algorithm. The performance of both vibration mitigation and energy harvesting is investigated. It is demonstrated that the ATMD outperforms the classical TMD with optimized parameters. In comparison with the optimized TMD of the same weight, ATMD with a mass of 250t introduces a 9.33% reduction in RMS displacement on the 76th floor and a 21.19% reduction in RMS acceleration on the 75th floor. The control performance provided by ATMD is comparable to or even slightly better than that of an optimized TMD weighing 750t. At the same time, it reduces the mass to one-third that of the passive counterpart. Though the use of active control devices is currently limited due to the high energy demand, the ATMD can absorb energy from structural vibration. The proposed device could accomplish an electrical output of 22.138kW while maintaining a consistent output power flow for most of the time. These numerical results provide strong support for the feasibility of the ATMD system, indicating a promising future for large-scale application.

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