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Experimental and analytical study on vibration control effects of eddy-current tuned mass dampers under seismic excitations

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ABSTRACT

Eddy-current tuned mass dampers (EC-TMDs) are non-contacting passive control devices and are developed on the basis of conventional tuned mass dampers. They comprise a solid mass, a stiffness element, and a damping element, wherein the damping mechanism originates from eddy currents. By relative motion between a non-magnetic conductive metal and a permanent magnet in a dynamic system, a time-varying magnetic field is induced in the conductor, thereby generating eddy currents. The eddy currents induce a magnetic field with opposite polarity, causing repulsive forces, i.e., damping forces. This technology can overcome the drawbacks of conventional tuned mass dampers, such as limited service life, deterioration of mechanical properties, and undesired additional stiffness. The experimental and analytical study of this system installed on a multi-degree-of-freedom structure is presented in this paper. A series of shaking table tests were conducted on a five-story steel-frame model with/without an EC-TMD to evaluate the effectiveness and performance of the EC-TMD in suppressing the vibration of the model under seismic excitations. The experimental results show that the EC-TMD can effectively reduce the displacement response, acceleration response, interstory drift ratio, and maximum strain of the columns under different earthquake excitations. Moreover, an analytical method was proposed on the basis of electromagnetic and structural dynamic theories. A comparison between the test and simulation results shows that the simulation method can be used to estimate the response of structures with an EC-TMD under earthquake excitations with acceptable accuracy.

1. Introduction

Since Yao introduced the concept of vibration control in civil engineering in 1972 [1], relevant structural control theories and methods have been significantly developed and have been proven to be economical and efficient in practice. The various control strategies, proposed by several researchers worldwide, can be classified into active control, passive control, hybrid control, and semi-active control, among which passive control is the prevalent strategy owing to its simplicity and lack of reliance on additional energy input [2]. Among numerous passive control devices, the tuned mass damper (TMD), wherein

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the input energy is dissipated by tuning the frequency, is widely used owing to its simple characteristics, convenient installation, low cost, and favorable control effects at specific tuning frequencies [3].

The damping component of a TMD is mostly provided by conventional fluid viscous dampers. However, in practice, several issues arise in viscous dampers. In particular, these dampers may leak over time, thus limiting the service life. The physical properties may degrade in high-temperature environments, resulting in failure [4,5]. The stiffness of the overall system increases because of the viscous dampers, which is unexpected for some structures. Moreover, it is difficult or rather expensive to change the damping ratio of the TMD once the viscous dampers are installed. Consequently, some innovative damping mechanisms have been developed to address the shortcomings of conventional TMD technology. For example, some researchers replaced viscous damping with particle damping. However, the damping mechanism of particle dampers has not been thoroughly understood because of their high nonlinearity [6–13]. Another simple and effective solution involves using eddy current damping.

Eddy current damping is a non-contacting damping mechanism which is suitable for solving the aforementioned problems. Because the device in eddy current damping is usually made of metal, it hardly degrades in its life cycle, making it useful for high-temperature applications. Owing to the non-contacting property, eddy current damping does not lead to an increase in the overall stiffness of the structures; therefore, the stiffness characteristics of the structures remain unaffected. Furthermore, the damping ratio can be easily adjusted by varying the air gap between the permanent magnet and the conductor.

The damping mechanism via eddy currents has been reported by many researchers [14–18]. By the relative motion between a non-magnetic conductive metal and a permanent magnet or by changing the strength of the field magnets, a time-varying magnetic field is induced in the conductor, thereby generating eddy currents (shown in Fig. 1). The eddy currents induce another magnetic field with opposite polarity, thereby causing repulsive forces, i.e., damping forces. Because of the electrical resistance of the conductor, the induced currents dissipate in the form of heat at the rate of I^2R, where I and R represent the current intensity and electrical resistance of the conductor, respectively. Therefore, the vibration energy of the main structures is transferred into the conductor and is dissipated in the form of heat.

Eddy current damping is largely employed in the field of magnetic backing, and another application involves suppressing the lateral vibration in rotor shafts [20], which was reviewed by Henry and Bae [16]. In the field of structural vibration control, Matsuzaki et al. presented a vibration control system wherein the motion of a beam with an eddy current damper (ECD) could be suppressed. They derived a theoretical solution for the beam and demonstrated the viability of the concept [21]. In another study, an experiment was conducted to demonstrate the effectiveness of the ECD. Their results show that the electromagnetic force is capable of damping the first few modes of vibration of the beam [22]. In another study, Zheng et al. analyzed the effectiveness of an ECD in suppressing the free vibration response of a beam by numerical simulation and found that the damping effect of the ECD varies with the amplitude of the beam. The larger the amplitude, the greater is the effective damping [23]. Kwak et al. developed a new type of ECD to suppress the vibration of a beam. The ECD comprised a copper plate, which was rigidly fixed onto the end of the beam, and two permanent magnets. The ECD was constructed and tested to analyze the efficiency [15]. Later, Bae at el. developed the theoretical model of the ECD proposed by Kwak et al. and investigated the damping performance of a new ECD model. The experimental and simulation results demonstrate the potential of the ECD in controlling the vibration of a cantilever beam [14]. Sodano et al. proposed a new damper configuration providing more damping to the beam structure and developed an improved theoretical model with enhanced accuracy [24]. The

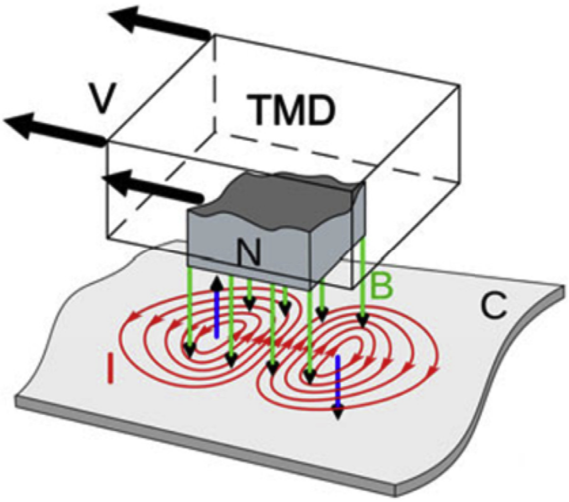

Fig. 1. Eddy current induced by the relative motion between a non-magnetic conductive metal and a permanent magnet [19].