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Outrigger tuned inertial mass electromagnetic transducers for high-rise buildings subject to long period earthquakes

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ABSTRACT

This paper proposes outrigger tuned inertial mass electromagnetic transducer (TIMET) systems for high-rise buildings subject to long period earthquake excitations. The proposed outrigger TIMET systems consist of the outrigger and TIMET parts. The outrigger damping systems have been proposed as a novel energy dissipation approach to high-rise buildings, in which control devices are installed vertically between the outrigger and perimeter columns to achieve large energy dissipation. While the TIMET has been developed based on the mechanism of the tuned viscous mass damper (TVMD) which can improve energy absorbing capability by taking advantage of resonance effect. However, instead of a viscous material, the damping of the TIMET is provided by a motor which can convert mechanical energy to electrical energy. The focus of this study is to investigate the structural control performance and energy harvesting efficiency of the proposed outrigger TIMET system for high-rise buildings subjected to long period earthquakes through numerical simulations.

1. Introduction

As new materials and technologies have been developed, the number of high-rise buildings has been rapidly increasing especially in urban areas all over the world. However, at the same time this achievement brings new problems regarding protection of these buildings against strong winds and severe earthquakes. In particular, because high-rise buildings have dominant natural frequencies in low frequency range, the vulnerability to long period earthquakes has been pointed out. Therefore structural control strategies targeting the specified frequency range is demanding for protecting high-rise buildings.

Traditionally, a tuned mass damper (TMD) [1] has been employed to accomplish this objective. However, due to the restricted auxiliary mass for practical reasons, the effectiveness of the TMD systems to earthquake ground motions is limited [2]. To address this issue, recently, for the purpose of the seismic response reduction of civil structures, various types of control devices utilizing a tuned inerter has been developed by many researchers, including the tuned viscous mass damper (TVMD) [3], tuned inerter damper (TID) [4,5], tuned mass damper inerter (TMDI) [6], and T tuned inerter damper (TTID) [7]. As explained in [8] originally, the amplified equivalent mass effect, i.e., *inertance*, is realized by a mechanism such as the hydraulic [9], ball screw [3], or rack and pinion inerter [8,10] and the force proportional to the relative acceleration between both ends is produced.

For example, the TVMD proposed in [3] consists of two parts: a rotational mass damper and a tuning spring. Moreover, the rotational mass damper part can be divided into a ball screw mechanism, a rotating mass, and a viscous damper. The ball screw mechanism is employed to convert translational motion to rotational behavior. Then by rotating the relatively small physical mass, an amplified equivalent mass effect, i.e., inertance, is obtained. The device producing up to on the order of thousandfold equivalent mass has been already developed [11]. This makes it possible for the TVMD to realize large mass ratio to the structure enough that a typical TMD can not realize. And the input energy is absorbed by the viscous material as heat. In this system, the inertance and the viscous damper are connected in parallel and the tuning spring is arranged in series with them. Then the TVMD is connected to the structure through the spring. Thus the energy absorption efficiency and vibration mitigation performance can be improved by tuning the spring stiffness so that the rotational inertial mass resonates with the structure [3].

Based on the mechanism of the TVMD, the first author proposed a tuned inertial mass electromagnetic transducer (TIMET) [12], in which a motor is employed instead of a viscous material to convert mechanical energy into electrical energy. And the effectiveness of the TIMET on the civil structures subjected to earthquake loadings was verified using the small-scale three story benchmark building model through numerical simulation studies [13]. During seismic events, an external power

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source is not guaranteed, so the generated energy by the motor is of value to self-powered control, structural health monitoring, emergency power supply and so on. Similar energy harvesting devices employing the tuned inerter mechanism for civil structures have been proposed by other researchers [14,15].

In this research, to take full advantage of the TIMET on high-rise buildings, the outrigger damping system [16–18] is combined with the TIMET. The outrigger damping system employs damping devices installed between outrigger walls and perimeter columns in a frame-core-tube structure to enhance structural dynamic performance. This paper seeks to verify the efficacy of the outrigger TIMETs for high-rise buildings subject to long period earthquakes. First the mechanism of the TIMET is reviewed briefly. Then the equation of motion of the outrigger TIMET system is developed and the parameter design method is introduced. Numerical simulation studies are carried out by using long period earthquakes and the vibration reduction performance and energy harvesting capability are investigated. Finally, conclusions obtained from this research follow.

2. Tuned inertial mass electromagnetic transducer

In this section, the mechanism and model of the TIMET is overviewed. Also the definition of generated energy used in this paper is derived.

2.1. Model

The TIMET employed in this research is illustrated schematically in Fig. 1(a) and its model is shown in Fig. 1(b). As can be seen, the TIMET consists of three parts: a motor, a ball screw mechanism with a rotational mass, and a turning spring. The TIMET provides damping by the motor to decay vibration and vibration energy is converted into electrical energy. In this paper, the damping coefficient provided by the motor is denoted by c_t. In parallel with the motor, inertance m_t, which is realized through a ball screw mechanism, is installed. And the linear spring whose stiffness is k_t is installed in series with the motor and inertance. To improve energy absorbing efficiency and vibration mitigation performance, we need to design the value of k_t and c_t appropriately.

The damping c_t can be decided by controlling the current into the motor i. The relationship between the current and voltage is defined as

$$i = -Yv \tag{1}$$

where Y is a time-invariant feedback gain, which can be adjusted by a transistor such as a MOSFET. Under this feedback law, the electrical load can be considered a resistor. Thus Y has units of admittance. And the voltage v can be expressed, through the back-EMF constant e_t, as

$$v = e_t \dot{x}_t \tag{2}$$

where x_t is the displacement of the inertance m_t. Let the electromechanical transduction power be P_e and the damping force by the motor be f_c. Since the electromechanical transduction power is preserved between mechanical and electrical sides of the transducers,

$$P_e = iv = f_c \dot{x}_t \tag{3}$$

with the convention that positive $P_e(t)$ implies energy flow from the electrical network to the mechanical system. Under this definition, the damping force by the motor is given by

$$f_c = -c_t \dot{x}_t \tag{4}$$

Thus from Eqs. (1)–(3), we have

$$-Ye_t^2 \dot{x}_t^2 = -c_t \dot{x}_t^2 \tag{5}$$

Hence the damping c_t can be expressed as

$$c_t = Ye_t^2 \tag{6}$$

Therefore, we know that the desired damping can be obtained by choosing appropriate Y. Thus, hereafter m_t,k_t, and c_t are used as design parameter for the TIMET.

2.2. Energy harvesting objective

To assess the energy harvesting efficiency for the proposed system, the power delivered to storage needs to be defined. As in [19,20], the power delivered to storage P_g is defined as the power extracted by the transducer minus the transmission losses in the transducer and power electronic circuitry P_l, i.e.,

$$P_g(t) = -P_e(t) - P_l(t) \tag{7}$$

Typically the expression for the transmission losses $P_l(t)$ is quite complicated because the transmission losses happen due to various causes on the electronic hardware. However, for the purpose of this paper, we assume simply that the transmission loss is resistive; i.e.,

$$P_l(t) = i^2 R = \frac{c_t^2 R}{e_t^2} \dot{x}_t^2 \tag{8}$$

where $R > 0$ is the transmission resistance. For example, if the losses were entirely comprised of coil losses in the transducers, then R is equal to the coil resistance. For more complex loss models, which incorporate MOSFET and diode conduction losses in the converters, past work has shown that these situations can also be conservatively approximated by a resistive loss term, together with a static power offset [21]. Defining $\bar{c}_t = e_t^2/R$, which is a positive value with units of viscous damping, gives

$$P_l(t) = \frac{c_t^2}{\bar{c}_t} \dot{x}_t^2 \tag{9}$$

and physically $\bar{c}_t$ represents the supplemental viscous damping that would relate the velocity $\dot{x}_t$ to the output force $c_t \dot{x}_t$ if the coil of the transducer is shorted. Thus $\bar{c}_t$ is determined by the specification of the transducer and represents the maximum viscous damping the transducer can exert.

With the above definitions and assumptions, we can now define the power delivered to storage as

$$P_g(t) = \left(c_t - \frac{c_t^2}{\bar{c}_t}\right) \dot{x}_t^2 \tag{10}$$

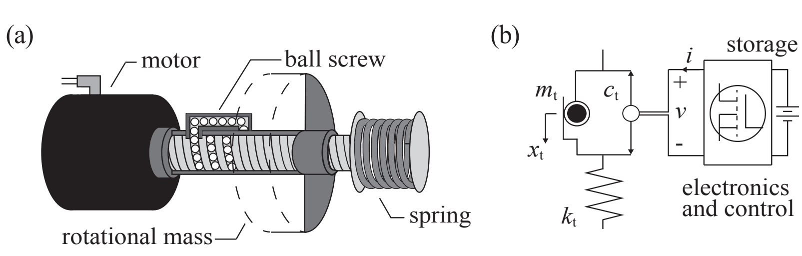

Fig. 1. TIMET: (a) Schematic illustration. (b) Model.