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Design and control of a self-powered hybrid electromagnetic damper

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A B S T R A C T

In this paper, the characteristics of a hybrid regenerative electromagnetic (EM) damper are first determined and experimentally examined. The main idea is to have two modes of operation for the EM damper, namely passive energy harvesting and semi-active modes. In the passive mode, the vibrational energy of an underlying structure is harvested and stored in a rechargeable battery. The harvested energy can then be employed in the semi-active control mode to supply the power demand for the required sensors and microcontroller. This hybrid damper would thus be capable of realizing the characteristics of a self-powered EM damper. A prototype of the damper was designed and tested under different harmonic excitations. The mechanical and electrical characteristics of both passive and semi-active modes were investigated and verified. The average harvested power and current were measured, and the efficiency of the different elements of the damper is determined. Next, for tuning the semi-active mode, a sliding mode control algorithm was proposed which considers the inherent nonlinear parasitic force of the EM damper. The proposed algorithm aims to track the response of an optimally controlled structure, by having knowledge of the bound of the nonlinear parasitic force. Finally, the effects of the proposed damper and sliding mode controller for vibration mitigation of a small-scale structure is demonstrated through a series of shake table tests, under harmonic and random excitations.

1. Introduction

The physical principle behind electromagnetic (EM) transducers is in converting mechanical into electrical energy and vice versa. Depending on the conversion interface, they can be used as actuators, dampers, sensors, or energy harvesters. When employed in a vibration control system, EM dampers have the advantage of recovering the vibrational energy which needs to be removed from the structure. By applying harvesting techniques, this energy can be harvested and stored in the form of electrical energy. In comparison, most of the other types of dampers, such as viscous, magnetorheological (MR), and frictional dampers, would eventually dissipate the absorbed energy as heat. In the past few decades, there has been a surge of interest in energy harvesting from the vibrational source induced by an environmental disturbance. In civil engineering, these

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harvesters can be small-scale oscillators attached to a host structure which have a negligible damping on the underlying structure [1–4], or large-scale regenerative dampers that can accommodate both damping and harvesting features [5,6]. Either employed in a tuned mass damper [7–11] or as a single device [12–15], these harvesters aim to harness the damped energy and to power the sensing and processing units of a structural monitoring and control system. It also seems feasible to engage regenerative dampers with a semi-active control action as their power demand is lower [8,9,11,16].

For an EM damper, no additional power is necessary to generate the damping force and its equivalent damping can be adjusted using a simple switched circuit [8]. However, an MR damper requires an external power supply to the current driver in order to generate the magnetic field. Researchers proposed smart regenerative dampers by attaching an MR damper to an EM harvester [17–19]. In those cases, damping is mainly produced by the MR damper, rather than the EM harvester. Alternatively, incorporation of the damper and harvester in a single EM device could be more efficient. Moreover, using an EM damper has this advantage that the vibrational energy can be recovered outside the machine. This reduces the problem associated with self-heating of the damper [14].

In a typical regenerative semi-active damper, the various devices, like sensors and microcontrollers, drain the harvested energy. Because of the random nature of the harvested power, it is possible that the available energy is less than the operational requirement of the system. Therefore, energy outages are very likely, and could negatively affect the control performance. In Ref. [20], a hybrid EM damper was proposed which separates the passive energy harvesting and semi-active modes. The damper switches from the passive mode to the semi-active mode, once sufficient energy is harvested. This allows a robust realization of the self-powered damper, without compromising the vibration control performance.

There are a number of electrical circuits and configurations that can facilitate the energy harvesting function [21–25]. Each interface circuit exhibits a different electrical impedance, which is linked directly to the constitutive relation of the damper. In particular, Lefeuvre et al. [24] proposed a circuitry based on a buck-boost converter that was able to emulate a constant optimal resistance. This favorable property was utilized by Shen and Zhu [13] for simultaneous energy harvesting and passive damping. However, the operating conditions associated with most of the harvesting circuits make them less flexible to be tuned in a semi-active system [8,11,24]. This could diminish the effectiveness of the semi-active controller by limiting the range of damping coefficients that could be provided. As one of the possible remedies, it was proposed in Ref. [20] to separate the operation of an EM damper into a passive energy harvesting mode and a semi-active control mode. As a result, the semi-active mode could cover a larger area of force-velocity domain, without dealing with the complications of the energy harvesting circuit. Consequently, the performance of the damper in mitigating the vibration could be improved.

In this paper, the physical realization of the damper proposed in Ref. [20] is presented. First, the mechanism of the damper and its potential advantages are described in Section 2. Section 3 elaborates on the prototyping of the damper, and Section 4 presents the experimental test results of the prototype. In Section 5, a semi-active control algorithm is proposed for the case that the damper is utilized to suppress the vibration of a single degree-of-freedom (SDOF) structure under ground motion. In Section 6, two modes of the hybrid damper are experimentally investigated for vibration control of a small-scale shear frame model under base excitation. This section aims to demonstrate the real application of the damper.

2. Background

Fig. 1(a) illustrates the schematic diagram of a linear EM motor attached to the proposed hybrid control circuit. According to Faraday's law of induction, the linear velocity of the motor $\dot{x}$ creates a back electromotive force (back-emf) voltage e, when the terminals of the coil are left open. When the motor is connected to the circuit, this back-emf causes current i to flow inside the circuit. Based on Lorentz law, a reactive force f_{em} is exerted in the opposite direction to the motion. Mathematically, the electro-mechanical relationship of the motor can be described as,

$$e(t) = k\dot{x}(t) \tag{1}$$

$$f_{\mathrm{em}}(t) = ki(t) \tag{2}$$

where k is the linear motor constant. The circuit attached to the coil governs the relationship between i and e and determines the relationship between the velocity and the force generated due to the electromagnetic action. In an ideal case, this force is equal to the total force f exerted by the damper. However, in practice, the total force f comprises an additional term f_p, which can be attributed to the presence of parasitic damping and friction,

$$f = f_{\mathrm{em}} + f_p \tag{3}$$

For the proposed damper, the circuit demonstrated in Fig. 1(b) is able to realize the hybrid feature. By controlling switch 1 (SW1), the damper's mode of operation can alternate between the passive and semi-active modes. The available energy harvested from the vibration can be employed to choose the mode adjustment.

2.1. Passive energy harvesting mode

Once SW1 is connected and SW2 is left open, the damper begins to harvest energy and the EM motor exhibits a constant damping coefficient. As shown in Fig. 1(b), the EM motor is first connected to a diode bridge rectifier, which converts the AC