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Circuit nonlinearity effect on the performance of an electromagnetic energy harvester-structure system

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ABSTRACT

Scavenging energy from structural vibration requires an efficient energy harvesting circuit which could introduce nonlinearity into the harvester-structure system. This study examines the performance of a linear structure equipped with an Electromagnetic (EM) energy harvester connected to a nonlinear standard energy harvesting circuit (SEHC) consisting of a full-wave bridge rectifier and a capacitor in parallel with a resistor. To facilitate the understanding of the nonlinear circuit effect on the behavior of the coupled harvester-structure system under sinusoidal excitation, a first-order harmonic balance approximation method is employed. Numerical simulation and experimental study are conducted to validate the accuracy of the proposed approximation method. Results suggest that the blockage effect of diodes in the bridge rectifier in the SEHC should be reduced by using diodes with small voltage drop value or by designing an EM energy harvester with large electromechanical coupling coefficient to improve the vibration mitigation performance and to enhance the optimal energy harvesting capability of the EM energy harvester. Results also show that circuit nonlinearity should be considered in order to estimate the response of the system accurately.

1. Introduction

Research on scavenging energy from structural vibration while simultaneously mitigating the response of a structure is proliferating [1]. This research direction is attractive since an energy harvester which can convert mechanical energy into electricity, not only safeguards the structure from excessive vibration, but also offers a possibility of powering essential sensors for structural health monitoring system. To justify the feasibility of such application, it is imperative to examine the performance of the structural system and the harvester system.

For instance, Tang and Zuo [2] studied the use of electromagnetic (EM) energy harvester to scavenge vibration energy from a structure equipped with a tuned mass damper. They showed that attaching a properly tuned secondary system can improve the energy harvesting performance while effectively reducing the vibration of the primary structure. Shen et al. [3] also developed a self-powered EM tuned mass damper which could reduce the peak structural displacement response while generating 312.4 mW power under a 0.05 g root-mean-square ground acceleration excitation. To scavenge train-induced vibration energy, Wang et al. [4] developed a harvester with bidirectional-to-unidirectional motion mechanism. Analysis showed that the proposed harvester could generate 10–50 W of power, which was sufficient to power a trackside equipment such as an LED light. Shen and his colleagues [5,6] studied both numerically and experimentally the energy harvested from a cable of the Stonecutters Bridge in Hong Kong under wind-induced vibration. The energy harvesting system was capable of producing 82.5 mW–2.40 W of power for wind speed ranging between 9 and 15 m/s. The control performance of the energy harvester was comparable to that of an optimal viscous damper. Comparing to the cable without any dissipative device, the EM harvester with a properly designed circuit could reduce the RMS acceleration response of the cable by about 2.5 times under a wind speed of 25 m/s. Caruso et al. [7] investigated the possibility of harvesting energy from the aerodynamic vibration of a bridge using an EM harvester. They showed that the optimal power that could be extracted was about 600 W under a mean wind speed of 20 m/s with a 2° attack angle. These results indicated that the EM energy harvester not only harvests significant amount of energy from structural vibration but also offers a vibration mitigation capability comparable to that of a conventional damper.

Energy harvesting circuit is a key component in energy scavenging as it controls the current flow, regulates the output voltage, and stores electrical energy [8]. Guyomar and Lallart [9] discussed the Standard Energy Harvesting Circuit (SEHC) that consisted of a full-wave bridge rectifier and a capacitor in parallel with a resistor. They noted that the output voltage of this SEHC was highly influenced by the voltage source which can lead to low efficiency and undesired output voltage. To

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address this problem, extensive research has been conducted. Lefeuvre et al. [10] developed a DC-DC buck-boost converter that can potentially decouple the output electrical load from the voltage source using high frequency switch. Guyomar et al. [11] studied different types of Synchronized Switch Harvesting on Inductor (SSHI) circuit to improve the efficiency of the energy harvesting. It was shown that the SSHI could increase the harvested energy by approximately ten times when compared to using the standard circuit [9,11]. Other alternative circuit topologies such as the Synchronous Electric Charge Extraction (SECE) circuit [12] and the Double Synchronized Switch Harvesting (DSSH) circuit [13] were also developed to improve the energy efficiency.

Importantly, it is noted that the electromechanical effect of the aforementioned circuit topologies is nonlinear in nature. This electromechanical nonlinearity, leading to nonlinear damping force-velocity relationship, could affect the behavior of the structural system if the energy harvester is also designed for the purpose of vibration mitigating [14,15]. In some preliminary studies [16–20], the energy harvesting circuit was modelled as an equivalent resistor, termed as the Purely Resistive Circuit (PRC) to study the response of the electromechanical coupled system. This simplified linear approach however ignores the effects of some essential electronic components such as converters, and hence cannot portray the response of an actual energy harvesting circuit accurately.

Motivated by the need to understand the effects of circuit nonlinearity, this study examines the performance of a structure equipped with an EM energy harvester connected to a SEHC. In particular, the nonlinear effects of this energy harvesting circuit on the mechanical behavior of the harvester-structure system are investigated. A first-order harmonic balance approximation is adopted to characterize the nonlinear effect of the circuit topology and to estimate the response of the harvester-structure system. The accuracy of this approximation is validated numerically and experimentally. Comparison between the results of coupled system when the EM harvester is connected to PRC and SEHC is conducted to justify the pros and cons of circuit nonlinearity.

2. Modeling of an EM energy harvester-structure system

The equation of motion of a linear elastic single-degree-of-freedom (SDOF) structure equipped with an EM energy harvester (Fig. 1a) under sinusoidal excitation can be written as,

$$m\ddot{x} + 2m\xi_s\omega_s\dot{x} + m\omega_s^2x + F_{em} = F_o\sin(\omega t) \tag{1}$$

where x, $\dot{x}$, $\ddot{x}$, m, ξ_s, and ω_s are the displacement, velocity and acceleration, mass coefficient, damping ratio and natural frequency of the structure, respectively, F_{em} is the force produced by the EM energy harvester, F_o and ω are the magnitude and the frequency of the sinusoidal excitation, respectively. The EM energy harvester is composed of two major components: a magnet attached on a moving shaft and a coil connecting to an energy harvesting circuit (see Fig. 1b). Assume that the shaft carrying the magnet is connected to the structure while the coil is fixed to the compartment of the EM harvester is connected to the ground. When there is a relative movement between the magnet and the coil, the magnetic flux of the coil is changed and a back electromotive force (emf) voltage V_{in} is produced in the energy harvesting circuit. If the circuit is closed, an induced current I_{in} is produced. Following the Lorentz's Law and the Faraday's law, the force generated by the EM harvester F_{em} and the back emf voltage V_{in} generated in the circuit can be expressed respectively as [21],

$$F_{em} = k_{em}I_{in} \tag{2}$$

$$V_{in} = k_{em}\dot{x} \tag{3}$$

where k_{em} is the electromechanical coupling coefficient between the structure and the EM harvester. Note that the relationship between V_{in} and I_{in} is needed to determine the EM harvester force F_{em}. This relationship depends on the topology of the energy harvesting circuit. In the following, two energy harvesting circuit models are examined: the PRC (Fig. 1c) and the SEHC (Fig. 1d).

2.1. Purely Resistive Circuit (PRC)

Typically, an EM harvester is modelled as a back emf voltage V_{in} connected in series with a coil resistor with a resistance of R_c and a coil inductor with an inductance of L_c. Normally the ratio of L_c/R_c is in the range of 10^{-4}–10^{-2} s [22] and the typical range of excitation frequency $\omega/2\pi$ for civil engineering application is between 0.1 and 10 Hz [21]. Under such conditions, the inductance of the coil can be neglected in the analysis [3,18]. For the PRC modelling, the output electronic elements are lumped as an equivalent resistor with resistance R to emulate any external device such as sensors, a data processor or a DC-DC converter operating in discontinuous conduction mode [5,10]. The PRC is the most ideal and simplest circuit, which is normally used as a first

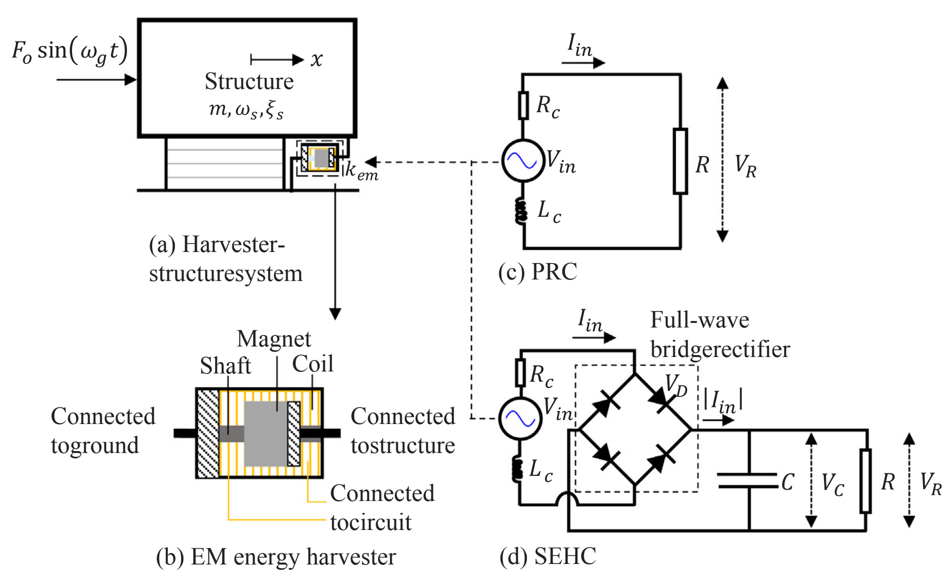

Fig. 1. (a) A coupled EM energy harvester-structure system; (b) EM energy harvester; (c) Purely Resistive Circuit (PRC); (d) Standard Energy Harvesting Circuit (SEHC).