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An electromagnetic rotational energy harvester using sprung eccentric rotor, driven by pseudo-walking motion

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HIGHLIGHTS

- An electromagnetic energy harvester using sprung eccentric rotor is proposed.
- System dynamics of the device has been investigated through numerical analysis.
- Model validation is performed by testing a prototype under pseudo-walking motion.
- Harvest higher level of power (6 times) than its conventional counterpart.
- Able to harvest higher power from human wrist motion during walking, running/jogging.

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ABSTRACT

In this work, an electromagnetic energy harvesting device using a sprung eccentric rotor has been designed, optimized and characterized to harvest power from pseudo-walking signals (a single frequency sinusoidal signal derived from motion of a driven pendulum that approximates the swing of a human-arm during walking). Our analysis shows that a rotor with an eccentric mass suspended by a torsional spring enhances the mechanical energy captured from low-frequency excitations (e.g., those produced during human walking, running/jogging). An electromagnetic transducer in the sprung eccentric rotor structure converts the captured mechanical energy into electrical energy. An electromechanical dynamic model of a sprung eccentric rotor has been developed and an optimization routine was performed to maximize output power under pseudo-walking excitation. The structure of the electromagnetic transducer was refined using Finite Element Analysis (FEA) simulations. A prototype energy harvester was fabricated and tested in a pseudo wrist-worn situation (by mounting on a mechanical swing-arm) to mimic the low-frequency excitation produced during human walking. A series of pseudo-walking motions was created by varying the swing profile (angle and frequency). The prototype with optimal spring stiffness generates a maximum 61.3 μW average power at $\pm 25^{\circ}$ rotational amplitude and 1 Hz frequency which is about 6-times higher than its unsprung counterpart under same excitation condition. The experimental results are in good agreement with the simulation results.

1. Introduction

Modern portable and wearable consumer electronic devices (e.g., smart watches, body sensors, activity trackers, smart training shoes, etc.) contain a number of fully-embedded wireless sensors with multi-functional and low-power consuming features [1]. However, these low-power sensors still require external power, and are generally powered by conventional electrochemical batteries (e.g., Li-ion, Li-Po, fuel cells, etc.). Electrochemical batteries have a limited lifetime and require periodic charging or replacement which is often inconvenient, or even impossible in remote locations and contingent situations [2]. Moreover, since most of the batteries contain toxic metals (such as cadmium, mercury, lead, lithium, or manganese), disposal of the expired batteries and cells produces hazardous waste that exacerbates environmental pollution and poses threats to both human and animal health. Therefore, there is great interest in developing self-powered electronics for sustainable and long-lasting operation by eliminating the need for recharging or replacing their external power sources. Energy harvesting from ambient/environmental energy sources (e.g., light, heat, sound, vibration, etc.) is considered one solution to address these circumstances [3–5]. Mechanical vibration, in the form of kinetic energy, is one of the most available ambient/environmental energy sources in

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machinery operations, civil infrastructures, air-ground transportations, as well as human-body-induced motion which can be converted into electrical energy by employing compatible electromechanical transduction systems [6]. Commonly used electromechanical transduction mechanisms include piezoelectric [7,8], electromagnetic [9,10], electrostatic [11,12], magnetostrictive/magnetoelectric [13,14], and triboelectric [15,16] mechanisms.

The performance of a vibration energy harvester greatly depends on the characteristics of the vibration source, type of transduction mechanism used and how the transducer is coupled to the mechanical system. Generally, vibration energy harvesters utilize inertial mechanism for electromechanical coupling. A proof-mass, mounted in a reference frame attached to the vibrating body, couples the kinetic energy (while the body is in motion) to a transducer (piezoelectric, electromagnetic, or other) that generates electrical power. Depending on the source of vibration, some harvesters have been developed as resonant [17–19], others as wideband [20–22]. Among different sources, vibration produced by the motion of the human-body during daily activities (e.g., walking, running/jogging, performing an office task, etc.) exhibits low-frequency, large-amplitude, and random characteristics [23,24]. In order to capture energy from such low-frequency, large-amplitude motion of the human-body, clever design approaches are required. Numerous design approaches including a non-linear spring, mechanical/magnetic plucking, and mechanical impact have been proposed over the past few years. Saha et al. [25] developed a nonlinear magnetic spring based electromagnetic generator for human body motion during walking and slow running. Liu et al. [26] investigated a similar nonlinear electromagnetic energy harvester for hand-shaking vibration. Wei et al. [27] demonstrated a mechanically plucked piezoelectric energy harvester from human walking motion for different speeds. Halim et al. [28] presented a miniaturized electromagnetic energy harvester for human-body-induced motion using an impact-driven frequency up-conversion technique. And, Geisler et al. [29] reported a 1D inertial electromagnetic energy harvester using a free-moving magnet stack between two repulsive magnets. All of these inertial devices use linear inertial-mass motion. However, the power output of such linear energy harvesters can be limited by the internal travel range of its inertial-mass motion, especially for low-frequency excitations (e.g., human-body-induced vibration). To overcome this limitation of linear motion based harvesters, devices with rotational inertial mass have been adopted by researchers that utilize an eccentric rotor structure to couple the kinetic energy into the transducer element. Romero et al. [30] presented a micro-rotational electromagnetic energy harvester for extracting energy from human motion at joint locations. Pillatsch et al. [31] introduced a rotational piezoelectric energy harvester for human upper arm motion during walking/running using magnetic plucking principle, Nakano et al. [32] reported the development of an electret-based microelectromechanical system (MEMS) rotational energy harvester by patterning fan-shaped electrets and guard electrodes on an eccentric rotor, and interdigitated electrodes on the stator for capturing the kinetic energy of human-motion. Lockhart et al. [33] presented a compact, wearable piezoelectric on-body harvesting system using a small eccentric mass to mechanically deflect a set of micromachined piezoelectric cantilevers when excited by the low frequency movements of the human-body. However, the proof-mass rotational amplitude of such eccentric rotor structures is quite small during walking; a larger rotational amplitude results in higher power output. Effective design of the rotational unit enhances the rotational amplitude, which, in turns, increases the output power. Yeatman [34] mathematically analyzed the maximum achievable power of both non-resonant oscillating and resonant oscillating rotational devices by using a planar rotor model which accounted for rotational and linear excitations separately. However, the mathematical analysis was not further explored either via simulation or by experiment. Due to complex nature of human-body-induced motion, a multidimensional model is required to estimate the maximum possible power generation from such rotational energy harvesting devices. We have extended the rotational model presented in [34] to three dimensions and have included linear and rotational excitations together (including the effect of gravity) [35]. Recently, we have presented an improved (sprung) eccentric rotor architecture (by the extended three dimensional model) to evaluate (via simulation) the maximum power output using real walking data from a number of subjects as inputs [36]. It reported that the estimated power outputs were different for different subjects because of the unique walking pattern (e.g., swing frequency and amplitude, bias angle, etc.) of each subject. Moreover, in a real-world situation (test on human subject while walking/running), the same result may not be reproduced (on the same subject) due to variation in the motion from one run to another. Therefore, an extensive analysis and a robust validation is required for fair evaluation of the proposed rotational energy harvesting structure.

In this work, we have presented an electromagnetic rotational energy harvester using an improved (sprung) eccentric rotor structure to harvest kinetic energy from a pseudo-walking signal generated by a human-arm-like mechanical swing-arm. An electromechanical dynamic model has been developed and optimized. Both numerical and finite element method (FEM) simulations have been performed to predict the performance of the proposed electromechanical structure. Finally, a prototype device has been fabricated and characterized on the bench-top test setup under a series of pseudo-walking excitation inputs. Results show that under optimal conditions (electrical damping, torsional spring stiffness, etc.), a harvester with a sprung eccentric rotor enhances the mechanical energy capture and outperforms its unsprung counterpart. Following the introduction, Section 2 will discuss the design of the sprung eccentric rotor structure and the development of an electromagnetic energy harvester using the sprung eccentric rotor, from which the prototype system architecture will be developed. The dynamic behavior and system performance will be investigated in Section 3. The fabrication of a prototype and the measurement of its damping characteristics will be discussed in Section 4. Subsequently, the performance of the fabricated prototype will be verified by carrying out a series of pseudo-walking tests in Section 5. Finally, Section 6 concludes the article.

2. Architecture of the proposed energy harvesting system

2.1. Sprung eccentric rotor design

Our design procedure starts with the development and analysis of a generalized three-dimensional model of an energy harvester comprised of an eccentric seismic mass and a torsional spring that couples the seismic mass to the reference frame and allows it to rotate about an axis on a low-friction bearing, as shown in Fig. 1. Note that the torsional spring holds the seismic mass vertically upwards at $\pi/2$ radians when subject to no external force. It includes both mechanical and electrical dampers, representing energy losses due to friction and energy extraction from an ideal energy transducer, respectively. Although the rotational or linear excitation inputs work on the system in three-dimensions, the rotation of the sprung eccentric rotor is constrained to motion in the X-Y plane. Therefore, the governing equation of the rotor motion in the X-Y plane is [37].

$$(ml^2 + I_G)(\ddot{\theta}_z + \ddot{\phi}_z) + (C_m + C_e)\dot{\phi}_z + K_{sp}\left(\phi_z - \frac{\pi}{2}\right) = ml(\ddot{X}sin\phi_z - \ddot{Y}cos\phi_z) \tag{1}$$

where m, l, and I_G are the eccentric mass, eccentric length and moment of inertia of the rotor about the center of gravity, respectively. $\ddot{X}$ and $\ddot{Y}$ are the input accelerations to the system working along X and Y coordinates, respectively. C_m and C_e are the mechanical and electrical damping coefficients, respectively. K_{sp} is the stiffness of the torsional spring. θ_z is the rotational input to the reference frame along Z direction and ϕ_z is the angular displacement of the rotor relative to the reference