Energy Conversion and Management 106 (2015) 393–404

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Design and experiment of a human-limb driven, frequency up-converted electromagnetic energy harvester

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A R T I C L E I N F O

Article history:
Received 11 July 2015
Accepted 25 September 2015

Keywords:
Non-resonant
Frequency up-conversion
Helical compression spring
Human-limb motion
Electromagnetic energy harvester

A B S T R A C T

We present a frequency up-converted electromagnetic energy harvester that generates significant power from human-limb motion (hand-shaking). Because the power generated by a vibration energy harvester is proportional to the operating frequency, the proposed energy harvester has been designed to up-convert the applied low-frequency vibration to a high-frequency vibration by mechanical impact. Upon excitation, a freely moveable ball (non-magnetic) within a cylindrical structure periodically hits two magnets suspended on two helical compression springs located at either ends of the cylinder, allowing these to vibrate with higher frequencies. The relative motion between the magnets and coils (wrapped around the outside of the cylinder) induces e.m.f. (voltage). High-frequency oscillators have been designed through the design parameters (i.e., frequency, spring stiffness, mechanical, and electrical damping), to minimize the power loss. A prototype was fabricated and tested both using a vibration exciter and by manual hand-shaking. The fabricated device showed non-resonant behavior during the vibration exciter test. At optimum load condition, the frequency up-converted generators (FUGs) delivered 0.84 mW and 0.96 mW of average power. A maximum 2.15 mW of average power was obtained from the device with series connected FUGs while it was mounted on a smart phone and was hand-shaken. The fabricated device exhibited 0.33 mW cm^{-3} of average power density, which is very high compared to the current state-of-the-art devices, indicating its ability in powering portable and wearable smart devices from extremely low frequency (~5 Hz) vibration.

1. Introduction

Over past few decades, clean and regenerative energy sources have become more important due to the increasing global warnings on environmental issues. Meanwhile, advances in technologies of micro-electromechanical system technology and electronics industries mean that wireless sensors and portable and implantable smart devices are being manufactured with miniaturized, low-power consumption, and low-cost features that allow their wide potential applications and accessibility in hostile environments [1]. However, one of the major challenges is the energy source. The power required for these devices to be operated is mainly generated by conventional electrochemical batteries and micro fuel cells. Although these power sources can provide more power, they require periodic charging; they also need to be replaced due to their limited lifetime. Sometimes these power sources are inconvenient, expensive, tedious, and even impossible to recharge or replace. Moreover, disposal of the expired batteries and cells exacerbates environmental pollutions. Therefore, energy harvesting from environmental sources such as light, wind, ambient heat, acoustic noise, radio waves, and vibrations has attracted considerable research interest as an alternative power source for these devices [2–4]. Among these energy sources, kinetic energy in the form of vibration or motion is more attractive due to its versatility, ubiquity, inexhaustibility, and abundance in nature [5,6]. The well known techniques for harvesting energy from vibration or motion are piezoelectric, electromagnetic, electrostatic, and magnetoelectric transduction mechanisms, which have already been published extensively in the literature [7–14]. The electromagnetic mechanism has been chosen in this study.

Generally, vibration harvesters are utilized by resonant systems that prolong the vibration displacement and preserve kinetic energy which is then transferred to electrical energy by any of the transduction mechanisms mentioned above. A vibration energy harvester must be customized for a specific operating condition and application because the operating conditions (e.g., the available vibration characteristics, required output voltage and power, overall harvester dimension, mass, and volume) will differ for different applications. In the work presented here, we developed

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http://dx.doi.org/10.1016/j.enconman.2015.09.065
0196-8904/

a frequency-up converted electromagnetic energy harvester based on an application-oriented operation through the optimization of design parameters. Following the introduction, Section 2 will discuss the design choices regarding the vibration environment and intended applications, from which system architecture will be developed. The theory behind the working of the proposed system along with the parameters design will be analyzed in Section 3. The fabrication of a prototype will be discussed in Section 4. Subsequently, the realistic performance of the fabricated prototype based on the proposed system architecture and the parameter design process will be verified by carrying out a series of experiments in Section 5. Finally, a conclusion will be drawn in Section 6.

2. Motivation and system architecture

2.1. Challenges in low frequency energy harvesting

Typically, most vibration energy harvesters are resonant devices employing one or more spring-mass-damper systems. These devices must be operated at their resonant frequencies in order to harvest maximum energy because they generate maximum voltages and power at their resonances. It has been observed that the average power of a vibration energy harvester decreases dramatically as the resonant frequency decreases [15]. Unfortunately, most ambient vibration sources have peak vibration amplitude at low frequencies (<100 Hz) [16]. The ambient vibration frequencies for human-body-induced motion and machine-induced motion range from 1 to 10 Hz and from 10 to 100 Hz, respectively [17]. The kinetic energy within vibration or motion varies unpredictably with cyclic movements in different directions from time to time within the environment [18]. A number of studies on the characteristics of ambient environmental vibrations generated by various sources in various locations and conditions have been published in the literature [19–23].

Generally, a mass loaded cantilever beam is used as the spring element where the loaded-mass works as the proof-mass. The undamped angular resonant frequency of a cantilever in transverse motion is

$$\omega_r = \sqrt{\frac{k_{eq}}{m_{eq}}} = \sqrt{\frac{Ewh^3/4L^3}{(33/140)m_b + m_t}} \tag{1}$$

k_{eq} is the equivalent spring stiffness of the beam expressed with the length L, width w, thickness of the beam h, and Young's modulus E of beam material; m_{eq} is the equivalent mass composed of the beam mass m_b and the tip mass m_t [24]. According to Eq. (1), lowering the resonant frequency increases the dimensions of the resonating element either by reducing the stiffness of the compliant spring or by introducing a heavy mass on the spring, or both. Explicitly, either decreasing k_{eq} by any of (i) increasing L, (ii) decreasing w, (iii) decreasing h or increasing m_t makes the system impractical (either large or weak, or both) for any desired application. Moreover, reliability of the cantilever beam must be taken into consideration while decreasing its k_{eq} or increasing m_t. Therefore, it is not easy to ensure that a typical straight cantilever beam can meet the low-frequency energy harvesting requirement.

While the resonant system is subjected to a periodic base vibration of amplitude Y_0, the magnitude of proof mass deflection Z_0 can be expressed as $Z_0 = QY_0$; where Q is the quality factor related to the dimensionless damping ratio ζ as $Q = 1/(2\zeta)$ [25]. Vibrations are commonly referred to in terms of acceleration amplitude A_{peak} rather than displacement amplitude Y_0 related as $A_{\text{peak}} = \omega_r^2 Y_0$. Therefore, the magnitude of proof mass deflection can be re-written as

$$Z_0 = \frac{QA_{\text{peak}}}{\omega_r^2} \tag{2}$$

Eq. (2) shows that at the resonance, for a given acceleration amplitude, the magnitude of proof mass deflection depends on the quality factor of the resonant generator. All the resonant generators reported to date are under damped ($\zeta < 1$), which have higher quality factor ($Q > 1$). Therefore, a relatively large proof mass deflection is obtained from a resonant generator with a high quality factor than that with a low quality factor, at a certain A_{peak}. In addition, the amplitude of proof mass deflection increases with the decrease in resonant frequency. For this reason, designing a small scale low frequency resonant generator with high quality factor is a challenge.

2.2. Frequency up-conversion

To address the low frequency environmental energy harvesting challenges, mechanical frequency up-conversion techniques have been suggested and demonstrated by many researchers over the past few years [26–35]. A mechanical frequency up-converted energy harvester uses at least two oscillating structures, one of which (low frequency oscillator) absorbs kinetic energy from low frequency environmental vibration and transfers it to the second one (high frequency oscillator) either by mechanical impact or by non-mechanical interaction such as magnetic attraction/repulsion. The kinetic energy transferred to the high frequency oscillator is then converted into electrical energy by any of the transduction mechanisms mentioned earlier. Being excited by the first oscillator, the second oscillator oscillates freely with its damped resonant frequency, resulting in an exponentially decaying motion with time. The periodic motion of the low frequency oscillator re-excites the high frequency oscillator in each of its cycles. As the kinetic energy of the low frequency oscillator is periodically removed by the high frequency oscillator, the larger amplitude of the proof mass motion in the low frequency oscillator is restricted within an allowed geometry.

A number of prototypes of mechanical frequency up-converted energy harvesters have been designed and presented in the literature. In their design, Rastegar et al. [27] presented a two stage system in which a proof mass absorbs very low frequency vibration energy and triggers the high frequency vibration of two piezoelectric cantilever beams to convert the vibration energy to electrical energy. Lee et al. [28] suggested a comb slider with low resonant frequency that excites a high resonant frequency piezoelectric cantilever beam by means of a sharp probe touching the ridges of the comb slider. Kulah and Najafi [17] and Galchev et al. [30] proposed magnetic attraction force in order to achieve frequency up-conversion. Unfortunately, each of the proposed structures mentioned above has been designed to operate at a specific resonant frequency of the low frequency oscillator. The unpredictably varying characteristics (frequency and amplitude) of the ambient vibration limit their efficient energy harvesting in low frequency vibration environments. In order to overcome this limitation, a number of research groups have proposed frequency up-converted wideband energy harvesters. Jung and Yun [31] demonstrated snap-through bulking for mechanical frequency up-conversion and the bi-stable behavior of buckled bridges in the proposed device offers wideband operation at an ambient vibration frequency. Tang et al. [32] demonstrated a broadband, bi-stable frequency up-converted energy harvester driven by non-contact magnetic repulsion. Liu et al. [33] and Halim and Park [35] investigated wideband frequency response of an impact driven piecewise linear energy harvester with mechanical stoppers. Table 1 summarizes the frequency up-conversion methods used in some of the aforementioned references and their operating