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Modeling and experiment of a handy motion driven, frequency up-converting electromagnetic energy harvester using transverse impact by spherical ball

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ABSTRACT

Power generation from human-body-induced vibration faces the challenges of low frequency and high amplitude with random excitation. In such cases, employing spring-mass structure as the low frequency oscillator is unrealizable and also unreliable. Impact based frequency up-conversion mechanisms have extensively been using to overcome the challenges. Random and direct impacts on the power generating element raise the questions on reliability, as well as efficiency of the energy harvesters. In order to meet these shortcomings, we have presented a handy motion driven electromagnetic energy harvester that also uses impact based frequency up-conversion mechanism; but instead of direct impact, it utilizes transverse impact by a freely movable spherical ball. Upon handy motion excitation, the ball vibrates along a fixed–fixed cantilever beam and pushes (by transverse impact) it at right angles while comes in contact with the parabolic top surface of a proof-mass attached to the beam, allowing it to vibrate at its higher resonant frequency. Relative motion between a magnet attached to the cantilever and a coil (placed below) induces voltage. A prototype energy harvester has been fabricated and characterized. At a periodic handy motion excitation of ~2 g peak amplitude and frequency 5.8 Hz, it is capable of delivering maximum 103.55 μW average power (5.4 μW cm^{-3} power density) to 85 Ω matched load resistance. Experimental results reveal feasibility and reliable operation of the proposed frequency up-converting energy harvester in harvesting power from handy motion vibration. Further optimized design would be able to offer higher power density to be used efficiently for portable and wearable smart devices applications.

1. Introduction

Extracting energy from mechanical vibration has drawn much attraction over the last few decades due to its abundance in nature and unlimited lifetime [1,2]. Different vibration sources, such as human and machine motion [3,4], water and wind flow [5,6], rotary motion [7] etc. generate vibrations of different frequencies and amplitudes, but most vibrations are of low frequencies and large amplitudes with various cyclic movements in different directions. Widely used techniques for harvesting energy from mechanical vibrations are piezoelectric, electromagnetic and electrostatic mechanisms [1]. Generally, these mechanisms are employed by spring-mass systems using cantilever beam structures having a specific resonant frequency. Harvested energy (power) is maximum when harvester's resonant frequency matches the applied vibration frequency. But, the power output decreases dramatically as the frequency decreases [8]. Moreover, implementing cantilever beam in order to couple low frequency vibration to the harvester makes the harvesting device larger in size, especially when the harvester is to be operated below 10 Hz, either by increasing its length (to reduce the stiffness) or by attaching a heavy mass on it. This is why, efficient energy harvesting from extremely low frequency vibration (below 10 Hz) for miniaturized hand-held and wearable smart electronics applications is challenging.

A number of efforts have been exerted to overcome low frequency energy harvesting challenges by using mechanical frequency up-conversion mechanism that allows the transduction element (in the form of a spring-mass system) to actuate at its own resonant frequency (considerably high) by a low frequency oscillatory system that responds to the external low frequency vibration, no matter how low it is [9,10–16]. Mechanical impact, magnetic attraction/repulsion, plucking etc. are the commonly used mechanisms to accomplish frequency up-conversion. Basic human activities such as walking, running, shaking limbs, jumping,

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breathing etc. also generate vibration which are recently being interesting for energy harvesting [17–19]. Frequency up-conversion mechanisms have also been used in human motion based energy harvesting. For examples, a plucked beam rotational knee joint piezoelectric energy harvester for human walking or running motion was presented in [16,20]. An impact driven piezoelectric energy harvester for walking motion was investigated in [21]. A piezoelectric energy harvester with rotating proof mass for human body applications was proposed in [22] which harvests energy by magnetic plucking from the motion of upper arms during walking, running or exercising. All those devices are wearable on different places of human body which are quite uncomfortable. Besides, people walk, run and do physical exercise occasionally; also vibration generated by these activities are random. However, vibration energy harvesters perform better in harmonic excitation rather than random excitation. This is why, an impact based piezoelectric generator for energy harvesting from the motion of human limbs was designed and analyzed in [23] where two piezo-benders were struck consecutively by a free sliding mass, referred to as 'missile'. A direct impact based electromagnetic energy harvester was employed in [24] for hand-shaking vibration that used helical compression spring as high frequency oscillators. However, direct force mechanisms (impact or plucking) cause damage to the transducer element of the harvester, especially in case of piezoelectric devices. Moreover, higher stiffness of the piezoelectric beam increases the damping in its vibration and its large source resistance decreases the output power. As a result, the average power decreases considerably.

In this paper, we have presented the theoretical modeling and experimental results of a frequency up-converting electromagnetic (EM) energy harvester from human handy motion, which employs frequency up-conversion strategy by transverse impact on the parabolic tip of a mass (loaded on a cantilever beam) by a freely movable metallic (non-magnetic) ball. As a result, a magnet attached to the cantilever vibrates in a direction perpendicular to that of the ball movement. A pick up coil placed at the bottom of the magnet induces e.m.f. voltage due to the relative motion between magnet and coil according to Faraday's law of electromagnetic induction. Use of transverse impact mechanism in an impact based harvester meets the reliability challenge from its quick damage. Besides, as the spherical ball is freely-movable, the device can be operated efficiently at any frequencies (at low frequency range with sufficiently large amplitude), meaning its non-resonant behavior [24]. This frequency up-conversion feature of the proposed device can be a reliable approach in supplying meaningful power to the portable and wearable smart devices from handy-motion vibration.

2. Harvester design and modeling

2.1. Device configuration and its operation

The schematic structure of the proposed frequency up-converted EM energy harvester is shown in Fig. 1. It consists of a rectangular channel having an opening at the center of its bottom wall. A freely moveable non-magnetic ball is placed inside the channel. A proof-mass with parabolic top surface is attached at the center of one side of a fixed–fixed cantilever beam that works as the spring-mass-damper system. The beam is assembled in such a way that the parabolic top surface of the proof-mass can be positioned through the opening at the bottom of the rectangular channel. A cylinder magnet is attached to the cantilever, opposite to the mass and a pick-up coil is also placed below the magnet, on the bottom cover of the device structure.

When the device is excited, the ball inside the channel, vibrates along the cantilever beam sliding over the parabolic surface of the proof-mass, giving rise to a transverse impact on the proof-mass. As shown in Fig. 2, when the ball slides over the parabolic surface of the mass, it pushes the proof-mass downward which, in turn, pushes the cantilever away from its neutral axis in the vertical direction allowing it to vibrate freely with its own resonant frequency. The magnet attached to the cantilever beam also vibrates at the same frequency, relative to the coil that induces electromotive force within the coil. The vibration frequency (resonant frequency) of the cantilever beam, as well as the magnet, is much higher than the applied vibration that can be determined by material and structural parameters of the cantilever beam. In every vibration cycle of its back and forth motion, the ball impacts on the proof-mass twice. Theory states that when an under-damped system undergoes an impulse excitation, its response will be an oscillatory motion with exponential decay [25]. So is the case for the proposed system; the output response decays exponentially between two consecutive impacts.

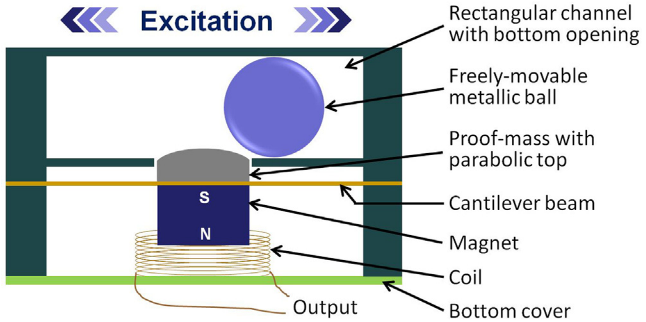

Fig. 1. Schematic structure of the proposed handy motion driven, frequency up-converting electromagnetic energy harvester.

2.2. Transverse impact model

The proposed impact energy harvester could be modeled as a single-degree-of-freedom (SDOF) forced spring-mass-damper system excited by a periodic force $F(t) = F_0\sin(\omega_0 t)$, where F_0 is the amplitude of the applied force and ω_0 is the angular frequency, with the governing equation of motion

$$m\ddot{u}(t) + cu(t) + ku(t) = F(t) \tag{1}$$

where $u(t)$ is the mass displacement, m is the overall mass (includes masses of attached proof-mass and magnet), c is the damping coefficient, and k is the spring stiffness of the cantilever beam. Eq. (1) is valid only if the force F_0 is applied in axial direction. But, in this case, as the ball moves back and forth along the cantilever beam, it hits the parabolic surface of the proof-mass and slides over it. The collision between the ball and cantilevered proof-mass is relevant the low-velocity transverse impact of a rigid body on a flexible element, as stated in [26]. The impact process occurs in two distinct phases: first, when the proof-mass and the ball come in contact, they tend to interpenetrate each other and a local compression force F develops in their interface [23], as shown in Fig. 3. As the ball slides over the parabolic surface, the compression force increases, resulting in larger bending of the cantilever beam. When the compression force is large enough, the ball and the proof-mass repulse each other or the ball just passes through the proof-mass before the force becomes large enough. The either situations depend on the curvatures of both the ball and parabolic surface as well as overlap (δ) between them. Finally, the ball and the proof-mass gets separated and each vibrates independently until the next impact occurs.

As we see in Fig. 3(a), when the ball impacts on the parabolic surface of the proof-mass, the force F_0 is applied to the proof-mass in the direction perpendicular its contact plane and a counterforce