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Scavenging energy from ultra-low frequency mechanical excitations through a bi-directional hybrid energy harvester

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HIGHLIGHTS

- The harvester can scavenge energy from ultra-low frequency excitations.
- The harvester can capture energy from two orthogonal directions.
- Simultaneous energy extraction from one excitation through two mechanisms is achieved.
- The bandwidth is expanded under the ultra-low frequency ($<$ 10 Hz) operation.
- The frequency up-conversion is realized through the magnetic coupling.

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ABSTRACT

A bi-directional hybrid energy harvester (HEH) is presented in this paper to scavenge energy from ultra-low frequency mechanical excitations. The proposed HEH consists of two piezoelectric cantilever beams, a suspended magnet, and a set of coil. Specifically, the two piezoelectric beams work as a conventional piezoelectric energy harvester (PEH), whereas the suspended magnet and the coil constitute an electromagnetic energy harvester (EMEH). The two energy-harvesting units (PEH and EMEH), which are sensitive to excitations coming from different directions, are coupled by the suspended magnet, through which the PEH and EMEH are coherently integrated. The suspended magnet not only induces the coil to generate electricity but also actuates the PEH to work, achieving the simultaneous energy extraction from one excitation through two conversion mechanisms. The dynamic model of the HEH is established. Theoretical simulations and experimental measurements under the sinusoidal excitation indicate that the nonlinear interaction between the PEH and EMEH actuates the two energy-harvesting units to oscillate either chaotically or periodically with large amplitudes, which can improve both the PEH and the EMEH power outputs at ultra-low frequencies, not only expanding the HEH working bandwidth but also making the HEH suitable for ultra-low frequency energy harvesting. Moreover, the hand-shaking test shows that the HEH has a better charging performance than an individual energy-harvesting unit for charging a capacitor. Under the hand-shaking induced excitation, the fabricated HEH prototype can also light up tens of light-emitting diodes (LEDs), demonstrating its potential application for powering some portable electronics.

1. Introduction

With low-power electronic devices becoming smaller and more pervasive in an increasingly mobile world, the development of long-lasting power systems has attracted growing attention in recent years with intent to increase the devices' functional duration and even implement self-sustained devices [1–3]. Realization of such a goal has been considered to rest upon the progress in energy harvesting technologies, which convert the renewable energy available in the environment into useful electrical energy to power some electronic devices such as sensors, wireless transceivers, and wearable electronics [4–6]. Among various energy sources, the mechanical energy, mainly in the form of vibration, is omnipresent in the environment and human bodies, and then the mechanical energy harvesting technologies have become the subject of a large number of studies [7–10]. As promising alternatives to life-limited electrochemical batteries, the mechanical energy harvesting technologies make the sustainable powering of low-power devices possible.

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In general, the mechanical energy can be scavenged through piezoelectric [11–14], electromagnetic [6,15–17], triboelectric [18,19], and electrostatic [20] conversion mechanisms, among which the piezoelectric conversion has attracted great interests owing to the simple structure and high output voltage. The conventional piezoelectric energy harvester (PEH) is composed of a uni-morph or bimorph cantilever beam with a proof mass attached at the free end, which behaves as a linear resonator and works effectively within a narrow bandwidth [21–27]. To remedy this issue, several strategies have been proposed to expand the PEH's operating bandwidth, including tuning the PEH's natural frequency to match the excitation frequency [28,29], integrating multiple cantilevers with different but close resonant frequencies in one device [30,31], adopting multi-degree-of-freedom (MDOF) PEH configurations [32,33], or introducing nonlinearities into the conventional PEH [34–38]. Although the aforementioned broadband PEHs can work in larger frequency ranges than the conventional PEH, their high resonant frequencies make them perform poorly when capturing energy from low-frequency excitation sources, such as vehicle motion, machine vibration, and wind-induced vibration, which usually occur at comparatively low frequencies [14,39–41]. This weakness is usually tackled by what is called frequency up-conversion techniques [16,42–44], in which a low-frequency oscillator absorbs energy from low-frequency excitations and transfers part of the absorbed energy to a high-frequency oscillator either by mechanical impact or by magnetic coupling.

Although various broadband strategies and frequency up-conversion techniques have enhanced the PEH's performance, the uni-directional sensitivity, meaning that PEHs can only extract energy from the excitation coming from their sensing directions, still impedes the practical applications of PEHs since the ambient excitations may come from various directions [41,45–49]. In order to achieve multi-directional energy harvesting, Audò et al. [45] reported a two-dimensional bistable PEH that consists of two piezoelectric beams coupled by magnets to harness vibration energy from two orthogonal directions. Fan et al. [48] presented an improved two-dimensional PEH, in which one beam encloses the other one to attain a more compact structure. Su and Zu [46] proposed a new bi-directional PEH configuration that is comprised of a cantilever beam and a spring-mass oscillator instead of two cantilever beams. Their bi-directional PEH was further upgraded to a tri-directional PEH [47] by adding an extra cantilever beam to collect vibration energy distributed in the third orthogonal direction. Fan et al. [11,14] also designed two multi-directional PEHs by magnetically coupling a ferromagnetic ball with piezoelectric beams, in which the ball captures energy from multi-directional and low-frequency excitations and triggers the beams to vibrate freely and produce power output.

In the meanwhile, the electromagnetic harvester/generator, which currently works as a dominant way to provide commercially significant quantities of electric power, has also been retrofitted and miniaturized to increase the mobility [50]. Saha et al. [17] designed a monostable electromagnetic energy harvester (EMEH), which consists of a center magnet magnetically levitated in a hollow tube by two endmost magnets and a set of coil wrapped around the outer surface of the tube, to convert human motion energy into electricity. Mann and Sims [51] conducted a systematic study on the monostable EMEH and their investigation revealed that engaging the system's nonlinear response could result in better energy harvesting performance. Wang et al. [15] proposed a tunable monostable EMEH to scavenge energy from the impact between the shoe and the ground as well as the swing motion of the leg during walking or running. Mann and Owens [52] transformed the monostable EMEH into a bistable EMEH by adding four magnets around the tube's midpoint to repel the center magnet away from the midpoint; theoretical and experimental studies indicated that the harvester's frequency response can be enlarged by the potential well escape phenomenon. Daqaq [53,54] evaluated the output power of a bistable EMEH under white and exponentially correlated Gaussian noise. Halim et al. [16] developed a frequency up-converted EMEH to scavenge energy from human limb motion through the mechanical impact between a non-magnetic ball and two spring-mass structures. Ylli et al. [55] reported a multi-coil topology EMEH that exploits the swing motion of the foot to engender the relative motion between a magnet stack and a set of coil.

Based on the stand-alone conversion mechanism, the aforementioned nonlinear harvesters or frequency up-converted harvesters have demonstrated better performance than the conventional harvester. However, their output power is still not high enough to drive some low-power electronics when the excitations feature ultra-low frequencies. A case in point is the human motion induced vibration, which occurs at around 5 Hz under the normal human activity [10,11,55]. A possible solution to this problem is using two kinds of conversion mechanisms to simultaneously scavenge energy from one excitation source [18,19,56,57]. The challenge is how to design the two energy-harvesting units with different conversion mechanisms to simultaneously and effectively work under the same excitation. The frequency up-converted PEHs proposed by Fan et al. [11,14,41] use a movable ball or cylinder to capture the low-frequency mechanical energy and then trigger the piezoelectric beams to function, and the EMEHs can also work from the relative motion between a cylindrical magnet and a set of coil. By integrating the piezoelectric beams, spherical or cylindrical magnets, and the coil, it is possible to utilize the PEH and EMEH to simultaneously capture energy from the same excitation.

In this paper, we report a bi-directional hybrid energy harvester (HEH) that is composed of two piezoelectric cantilever beams, a suspended magnet, and a set of coil with intent to scavenge energy from ultra-low frequency (< 10 Hz) mechanical excitations. Specifically, the two piezoelectric beams constitute a PEH, whereas the suspended magnet and the coil work as an EMEH. The PEH and EMEH capture energy from two orthogonal directions, and coupling of the two energy-harvesting units (PEH and EMEH) is realized through the suspended magnet, which not only induces the coil to generate electricity but also triggers the PEH to work, achieving the simultaneous energy harvesting from one excitation using two conversion mechanisms and up-converting the excitation frequencies. Theoretical and experimental studies are carried out to reveal the performance of the proposed HEH under a sinusoidal excitation. The HEH's potential application as a portable energy device is demonstrated by charging a capacitor and lighting up tens of light-emitting diodes (LEDs) when actuated by the hand-shaking induced excitation.

2. Design and modeling

2.1. Design and working principle

The proposed HEH consists of two piezoelectric cantilever beams, a set of coil, a tube, and a series of magnets, as schematically illustrated in Fig. 1. The two piezoelectric beams, which deflect along the x direction, are respectively fixed at the two ends of the tube with their longitudinal direction aligned with the z direction (tube's axial direction). Two cylindrical magnets (endmost magnets) are attached at the two ends of the tube, respectively, and another cylindrical magnet (center magnet) is placed between the two endmost magnets and oriented to repel them, thereby suspending the center magnet within the tube. The coil is formed by a varnished wire wrapped around the outer surface of the tube.

The working principle of the HEH can be divided into two parts: the piezoelectric part (PEH) and the electromagnetic part (EMEH). The PEH is composed of two piezoelectric beams and operates under the x-directional excitations. The center magnet, which has the same magnetization direction as the cuboidal magnets attached on the piezoelectric beams, moves along the tube's axis and triggers the two piezoelectric beams to vibrate and generate electricity through the magnetic coupling in response to the z-directional excitation, upgrading the uni-