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Broadband dual phase energy harvester: Vibration and magnetic field

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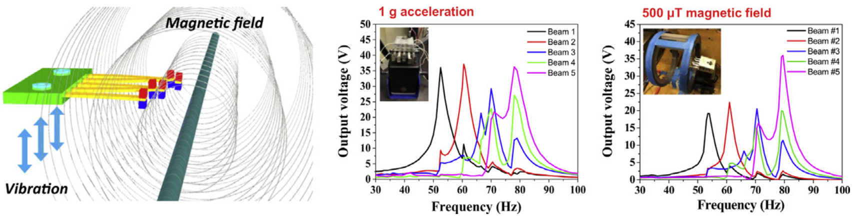
HIGHLIGHTS

- Magnetically coupled energy harvester array is demonstrated for broadband operation.
- Energy harvester provides dual mode energy harvesting in magnetic field and vibration.
- Energy harvester exhibits 243 μW/cm^3 g^2 power density and over 30 Hz bandwidth.
- Energy harvester is implemented in practical environments of a rotary pump, power cable, and car engine.

GRAPHICAL ABSTRACT



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ABSTRACT

Broadband mechanical energy harvesting implies stable output power over a wide range of source frequency. Here we present a cost-effective solution towards achieving broadband response by designing a magnetically coupled piezoelectric energy harvester array that exhibits a large power density of 243 μW/cm^3 g^2 at natural frequency and bandwidth of more than 30 Hz under 1 g acceleration. The magnetically coupled piezoelectric energy harvester array exhibits dual modes of energy harvesting, responding to both stray magnetic field as well as ambient vibrations, and is found to exhibit the output power density of 36.5 μW/cm^3 Oe^2 at 79.5 Hz under the ambient magnetic field while maintaining the broadband nature. The magnetically coupled piezoelectric energy harvester array was demonstrated to harvest continuous power from a rotary pump vibration, an automobile engine vibration and a parasitic magnetic field surrounding a cable of an electric kettle. These demonstrations suggest that the magnetically coupled piezoelectric energy harvester array could serve the role of a standalone power source for wireless sensor nodes and small electronic devices.

1. Introduction

In the past decade, energy harvesting technology has been extensively investigated to realize self-powered low power consuming devices such as transceivers, sensors and MEMS components [1–4]. There are several mechanisms for converting ambient energy into

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electricity including photovoltaics [5], thermoelectrics [6], magneto-thermoelectric [7,8], electromagnetics [9,10], magneto-mechano-electric (MME) conversion, and various types of mechanical energy harvesters [11–15]. Mechanical energy harvesters utilize many different energy conversion phenomena and materials including piezoelectric, magnetic, electrostatic, electrets, triboelectric, dielectric elastomer, ionic polymer, etc. Among this large number of candidates, piezoelectric energy harvesting has been extensively studied as it can provide high electromechanical energy conversion efficiency, energy density, and high voltage [4,16–20]. Mechanical energy is attractive due to its availability in a variety of scenarios such as vehicles, aircrafts, industrial machines, household appliances, and human motion. In some scenarios, mechanical energy is parasitically supplemented by the stray magnetic field generated from surrounding power cord in electronic devices and transmission cables. Simultaneous dual phase energy harvesting of mechanical and magnetic energy provides an attractive opportunity to amplify the power density and thereby strengthen the argument for self-powered devices [21–23].

Traditionally, electromagnetic generators have been utilized for harvesting magnetic energy, but they are bulky in size and difficult to be integrated with low force – low frequency oscillations [9,21,24,25]. An example of constant oscillation frequency source would be stray magnetic field generated from A/C power cords on electronic devices. The electric power transmission cables can generate low magnetic fields (< 1 mT = 10 G at a distance of 10 mm from 50 A cable) at fixed frequency of 50/60 Hz (depending upon the geographical region). The available stray magnetic fields can be higher in the vicinity of electric equipment/machines. Recently, a magneto-mechano-electric (MME) energy conversion mechanism has been proposed that allows the combination of piezoelectric energy harvester and magnets to simultaneously harvest this magnetic energy and mechanical energy [26–29]. In contrast to magnetic fields, vibration frequency is seldom constant rather it varies over a band depending upon the mass and operating environment. Thus, the challenge lies in capturing this wide range of vibrations while also optimizing the power production at specific frequencies.

In order to maximize the generated electrical power from mechanical vibrations, the piezoelectric energy harvester should be operated at resonance frequency [12,27]. However, piezoelectric structures typically exhibit narrowband resonance frequency and thus it is difficult to couple with broadband vibrations. In particular, it is difficult to harvest sufficient power from continuously varying frequency conditions such as an automobile and airplane engine vibrations. In order to harvest energy from vibrations, ideally piezoelectric harvesters should have broadband response or ability to automatically tune the resonance frequency in accordance with ambient vibration source. There are several ways to implement the broadband energy harvesting including nonlinear technique, self-resonance frequency tuning, and energy harvester array etc.

One of the most investigated techniques for the wide bandwidth energy harvesting is exploiting nonlinear behavior of the structure. The nonlinearity can arise from the nonlinear strain-deflection relationships under large deformations. The most common approach towards the design of nonlinear system is to introduce nonlinear restoring forces such as magnetic or mechanical forces [30]. Cottone et al. [31] and Erturk et al. [32] realized the bistable configurations by employing permanent magnets. The bistability improved the bandwidth under sinusoidal excitation. Stanton et al. [33] demonstrated the monostable piezoelectric energy harvester, describing both the hardening and softening responses by tuning the magnetic interactions. However, the nonlinearity does not appear and can be reduced under low-energy vibrations and random excitations.

Most of reported studies on resonant frequency auto tuning techniques require additional power input from the outside to adjust the natural frequency of the energy harvester and thus cannot be used for variant-frequency oscillations due to slow response time. In some active tuning methods, even the energy required for tuning frequency may be larger than the harvested power [34]. Only two types of self-resonant frequency tuning without additional energy have been reported. Jo et al. [35] introduced resonance frequency switching scheme through a pair of movable cantilevers connected in the opposite direction with difference length. Since the energy harvester closer to the resonant frequency oscillates more vigorously, the resonant phase can be converted by the movement of the connected harvester by the horizontal inertial force. No additional power is required for resonance tuning, but only two resonance phases can be switched. Gu and Livermore [36] presented the design that can automatically tune the resonance frequency of the cantilever energy harvester in rotational motion. Since the stiffness of cantilever changes proportional to the centrifugal force, the resonance frequency of the energy harvester can be automatically adjusted in accordance with rotation speed. However, this device is only applicable to the rotating environment.

One of the simpler and trustworthy methods for achieving the broadband response is arraying piezoelectric bimorph/unimorph type energy harvesters with different natural frequencies. Shahruz [37] proposed energy harvester array that comprises of piezoelectric cantilevers of varying lengths and tip masses and Xue et al. [38] designed a broadband energy harvester using multiple piezoelectric bimorphs with different thickness of piezoelectric layers. Both energy harvester arrays showed wider bandwidth and faster response time with frequency variation. However, in these cases, the energy density dramatically decreases because only one of the energy harvester generates electric power at a specific resonance frequency. In addressing this problem of low power density in the broadband energy harvester arrays, we demonstrate a magnetically coupled piezoelectric energy harvester array (MaCoPEHA) that couples each harvester in the array through interaction of magnetic proof masses. If one of the harvesters in the MaCoPEHA is vibrating at resonance, the next neighboring harvester will be excited to a quasi-resonance state through the magnetic interaction. Thus, in varying vibration conditions, the generated power and bandwidth will increase significantly in comparison with to a normal (non-magnetically coupled) harvester array. The MaCoPEHA shown in Fig. 1(a) uses the MME mechanism, where piezoelectric bimorph cantilevers are mounted with magnetic proof masses such that they can also function as a magnetic field energy harvester while maintaining the broadband nature. The MaCoPEHA can respond to both mechanical vibrations and magnetic fields through the oscillation of the cantilever through bending stresses or through the coupling of magnetic proof mass displacements in neighboring beams. This is the first demonstration of the harvester with simultaneous broad bandwidth and operational tunability. Further, this study provides a comprehensive understanding of harvester response under broadband vibration input signal and stray magnetic field. The MaCoPEHA was also successfully demonstrated on practical platforms comprising of rotary pump vibrations, automobile engine vibrations and parasitic magnetic fields surrounding a power cable of an electric kettle.

2. Design of MaCoPEHA

The design of the MaCoPEHA is depicted in Fig. 1(c) and (d), where the use of magnetic poof masses on arrayed energy harvesters allows coupling between them and a subsequent broadband response. Each harvester in the array can have multiple resonance frequencies because the harvester not only responds at its own fundamental frequency but also at the coupled frequencies corresponding to the response of other harvesters in the array. The maximum output voltage can be obtained at the fundamental resonance frequency and it decreases as the frequency varies, while still maintaining a significant magnitude over the wide range of frequency corresponding to f_{long}–f_{short}, where f_{long} and f_{short} are the fundamental resonance frequencies of the longest beam and the shortest beam in the array, respectively.

Fig. 1(b) shows the schematic configuration of each piezoelectric