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Linear stiffness compensation using magnetic effect to improve electro-mechanical coupling for piezoelectric energy harvesting

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ABSTRACT

Piezoelectric transducers have been widely used in vibration-based energy harvesting. The efficiency of piezoelectric energy harvesting depends to a large extent on the electro-mechanical coupling of the harvester. Improvement of the coupling effect is possible through a variety of means from the transducer material-level to the device-level. At the device-level, the coupling effect of a cantilever-type energy harvester is inversely proportional to its mechanical stiffness which consists of the stiffness of the cantilever beam and that of the piezoelectric transducer. The mechanical stiffness, however, cannot be easily reduced because of the necessary inclusion of the cantilever beam and the inherent stiffness of the transducer. Both the beam and the transducer cannot be made arbitrarily thin due to typical design considerations. This paper reports a device-level approach for improvement of energy conversion efficiency by directly compensating the effective stiffness of a cantilever-type vibration energy harvester through magnetic effect. Specifically, two sheet-type permanent magnets are placed in the vicinity of the piezoelectric composite beam, and another slender magnetic bar is attached onto the beam together with an iron proof mass where one of its poles is located between the two magnetic sheets. It is shown analytically and experimentally that, under such configuration, a linear magnetic field yielding linear force pointing toward the magnetic sheets can be produced, which results in the reduction of the effective stiffness of the energy harvester to improve the electro-mechanical coupling. The experimental case studies demonstrate that the electro-mechanical coupling coefficient can be increased by 65% with 44.1% stiffness compensated. Both the open-circuit voltage and the power output are enhanced.

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1. Introduction

Due to the rapid advancement in portable and wireless devices, harvesting energy from ambient sources to prolong power supply to these devices has received significant attention [21,25,18]. As vibration energy is virtually ubiquitous, utilizing piezoelectric transducers for energy harvesting, i.e., converting vibration energy into electrical energy, has emerged as one of the primary methods [1,22,12]. Piezoelectric transducers are compact, have high bandwidth, and maintain good linearity within functional range. Design and optimization of piezoelectric transducer-based energy harvesters have been addressed in several aspects [17]: (1) absorbing mechanical energy from vibration source [8,27,10]; (2) converting mechanical energy into electrical energy [3,32]; and (3) storing electrical energy [7]. Among these aspects, the conversion of mechanical energy into electrical energy is generally characterized by the electro-mechanical coupling coefficient of the device, i.e., the ratio of the energy converted to that imposed [30,24,14].

The effect of electro-mechanical coupling on energy harvesting has been analyzed in a number of studies. Roundy [25] suggested that the power generated by a piezoelectric harvester was in general proportional to the electro-mechanical coupling. Lefeuvre et al. [14] indicated that the power output at resonance was proportional to the coupling in low coupling condition. Shu and Lien [28] modeled and analyzed the power output of a piezoelectric energy harvesting system, and concluded that better performance could be achieved with larger coupling and quality factor. Meanwhile, Kim et al. [13] derived an optimal value for maximum power when the coupling coefficient was greater than a certain threshold value. While saturation of power output may exist [26], the maximum power output envelop could be increased with the increase of electro-mechanical coupling [7,28]. Tang and Yang [29] further pointed out that a large coupling coefficient boosts power output of a system with standard circuit even more than that with synchronized charge extraction technique (SCE). The electro-mechanical coupling coefficient is directly related to the transducer material property, predominantly the piezoelectric coupling constant

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at the material-level. For example, one of the most commonly used piezoelectric transducers, PZT5H, has limited piezoelectric coupling constant of 0.44 in the 31 direction and 0.75 in the 33 direction, respectively (when attached to a beam, the 1 coordinate of the transducer is along the length direction, the 2 coordinate the width direction and the 3 coordinate the transversal direction) (IEEE Standard). Choosing transducers with larger piezoelectric coupling constant may certainly help. Rakbamrung et al. [23] compared the performance of two energy harvesters with the same configuration but two different transducers, PMN-PT and PZT. The one with PMN-PT showed higher power output, but this type of material is more expensive.

At the device-level, a number of studies have defined an electro-mechanical coupling coefficient of an energy harvester, and indicated that this coefficient is related to not only the material property of the transducer, but also the specific design features of the harvester. For example, the harvester in general stores a significant portion of energy through its mechanical stiffness throughout the energy harvesting process, which reduces the energy conversion efficiency [24,11,17]. It is worth emphasizing that the mechanical stiffness of the energy harvester includes contributions from both the host beam and the piezoelectric transducer. A significant portion of the mechanical stiffness in the harvester comes from the piezoelectric bending stiffness, which cannot be easily reduced. In the unimorph case, a host beam is required, which shifts the beam-shaped transducer's neutral line so the charges generated by the top and bottom halves of the transducer during bending vibration will not offset. The host beam thus has to possess certain thickness, yielding considerable mechanical stiffness. Many investigations have been carried out to explore manipulating the mechanical behavior as well as the circuitry dynamics of the harvester in order to enhance the electro-mechanical coupling. Chen and Wang [5] investigated the increase of the electro-mechanical coupling of a piezoelectric cantilever by thickness ratio optimization, and identified a maximum coupling under a proper thickness ratio. Alberto and Paolo [2] studied the optimal positioning of piezoelectric transducer. These investigations are in the category of mechanical tailoring, and therefore are subject to the limitation of the material-level coupling constant.

It is worth noting that there actually has been a stream of efforts to improve the electro-mechanical coupling coefficient and to tune the system dynamics in a device by resorting to external elements. For example, Tang and Wang [30] indicated that adding an operational amplifier-based negative capacitance, which offsets the inherent capacitance of the piezoelectric transducer, could increase the electro-mechanical coupling. Since the negative capacitance element itself consumes power, such an approach is more suitable for control/damping applications. For another example, it was found that compressive axial forces could reduce the mechanical bending stiffness of the cantilever [15,16,20]. This type of methods is generally effective when the vibration amplitudes are small. To introduce favorable dynamic effects to energy harvesters, conservative forces due to permanent magnets, because of the non-contact nature, recently emerged as an attractive option. Challa et al. [4] attached magnetic blocks on the top and bottom of the cantilever, and created attractive and repulsive forces to adjust the harvester's resonant frequency to match the frequency of the ambient vibration to improve the bandwidth of energy harvesting. As the force by the magnetic blocks exhibits nonlinearity, the system is essentially nonlinear. Cottone et al. [6] placed magnets on the cantilever tip and in the vicinity to generate nonlinearity which was then used to improve the bandwidth of energy harvesting. One challenge in these nonlinear methods is that the system behavior is usually amplitude-dependent, which may limit the effectiveness of the respective methods to a certain operating range.

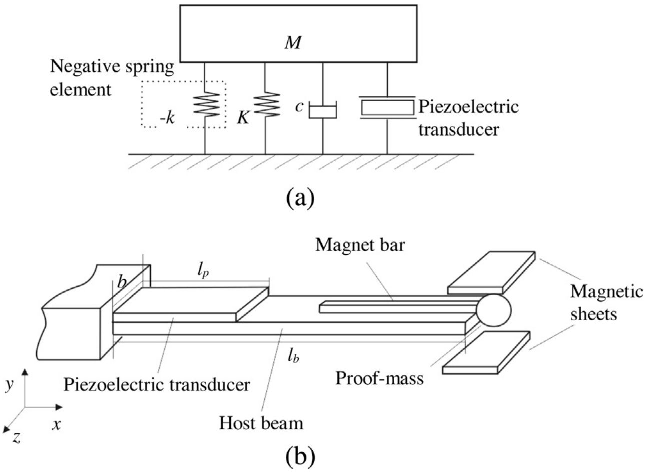

Fig. 1. (a) Schematic of stiffness compensation; (b) Schematic diagram of the proposed new piezoelectric energy harvester.

One ideal solution would be to add a negative spring element to a harvester to reduce its bending stiffness while maintaining the linearity. As mentioned, reducing the mechanical stiffness can increase the electro-mechanical coupling at the system level, and maintaining linearity can ensure that the performance enhancement can be realized within the entire operating range. Such a negative spring element should be non-contact with no additional damping. Inspired by the recent explorations in incorporating magnets into energy harvester design [4,6,33], in this research we develop a design scheme that enables the compensation of the effective stiffness of the energy harvester by utilizing magnetic effects. In particular, a linear magnetic field effect is synthesized by placing properly configured magnetic elements in the vicinity of the piezoelectric cantilever. The magnetic field produced by these elements yields a linear force with respect to the cantilever displacement that is equivalent to the negative spring element effect, thereby reducing the portion of energy stored in transducer and host structure and improving the electro-mechanical coupling of the system. As the additional force induced is linear, the electro-mechanical coupling improvement is effective throughout the entire operating range of the harvester, and is not amplitude-dependent. Another potential advantage of this design scheme is that adding the aforementioned magnetic elements does not exclude the usage of other design optimization methods proposed previously [8,3,7,27,4,6,32].

The rest of this paper is organized as follows. In Section 2, the concept of the new design is outlined first, followed by the analysis of the magnetic field to demonstrate the benefits to electro-mechanical coupling improvement and energy harvesting performance. In Section 3, experimental studies are reported that validate the analytical predictions. Finally, concluding remarks are provided.

2. Design concept and system analysis

2.1. Schematic of design

Fig. 1a illustrates the concept of stiffness compensation, where a fictitious negative spring element is included. Fig. 1b shows the schematic diagram of the new piezoelectric energy harvester system proposed, which is a conventional piezoelectric cantilever incorporated with specially arranged magnetic elements to improve the electro-mechanical coupling coefficient. The piezoelectric cantilever consists of a cantilevered steel beam bonded with a piezoelectric transducer near the fixed-end. The poling axis

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