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A tunable broadband magnetoelectric and electromagnetic hybrid vibration energy harvester based on nanocrystalline soft magnetic film

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ABSTRACT

In this paper, a tunable broadband electromagnetic (EM) and magnetoelectric (ME) hybrid vibration energy harvester (HVEH) employing a hybrid transducer and double cantilever to convert low-frequency vibration energy into electrical energy is presented. The electric output performances of the proposed HVEH have been investigated. Compared to single ME or EM vibration energy harvester (VEH), the experiment results show that the proposed HVEH can simultaneously obtain an enhanced output performance including higher power, voltage, current and wide bandwidth. It is found that the output power and resonance frequency of HVEH can be tuned by controlling the FeCuNbSiB layer thickness, turns number and cantilever length, respectively. When FeCuNbSiB layer thickness, cantilever length and turns number is 30 μm, 5 cm and 750, the optimum output power and effective bandwidth of HVEH achieve 36.8 mW and 5.6 Hz for an acceleration of 0.75 g at frequency of 32 Hz, respectively. Remarkably, the proposed HVEH has great potential for its application in wireless sensor networks.

1. Introduction

With the rapid development of the Wireless Sensor Networks (WSNs), there is a growing interest in scavenging energy from ambient environment to power intelligent wireless sensor systems [1–5]. Compared to the thermal and solar energy, mechanical vibration energy is ubiquitous and high power density, so more and more studies have been focused on vibration energy harvesting [6–9]. There are four main types of Vibration Energy Harvester (VEH), including electrostatic, piezoelectric, electromagnetic (EM) and magnetoelectric (ME) [10–13]. Among them, the EM VEH has the advantages of large current and high output power, but also has the drawback of low voltage. The ME VEH has the virtue of high output voltage but also has the disadvantage of low current. However, in order to make the intelligent wireless sensor systems do a better job, the VEHs should have the advantages of high output power, current and voltage simultaneously [14–16].

To solve this key problem and improve the bandwidth of VEH, a tunable broadband ME/EM hybrid VEH (HVEH) based on the nanocrystalline FeCuNbSiB soft magnetic film and double cantilever has been proposed in this paper. According to the large interface stress-strain coupling effects, the ME coupling characteristics of the heterostructures based on FeCuNbSiB soft magnetic film are significantly improved. Moreover, the electric output performance of the proposed HVEH has also been investigated. The effects of FeCuNbSiB layer thickness, cantilever length, turns number and acceleration on electric output characteristics of HVEH have also been investigated. By comparison with traditional single EMVEH or MEVEH, the experimental results indicate that HVEH obtains a remarkably enhanced output performance and broader bandwidth.

2. Experimental

Fig. 1 shows the schematic diagram of the proposed tunable magnetoelectric and electromagnetic hybrid VEH (HVEH). The HVEH consists of a ME/EM hybrid transducer, magnetic circuits and two cantilever beams. The hybrid transducer and magnetic circuits are placed at the tip of cantilever beam that act as the tip masses, respectively. Furthermore, the tip masses can let the proposed HVEH more available to harvest vibration energy from lower frequency vibration sources, owing to the reduction of the natural frequency of cantilever beams.

The magnetic circuits are composed of four NdFeB permanent magnets which placed symmetrically, which can generate a concentrated magnetic flux gradient. The size of NdFeB permanent magnet is $4 \times 8 \times 12$ mm^3. The ME/EM hybrid transducer is composed of a coil and a five-phase laminate ME transducer, which locates in the working air-gap magnetic field of magnetic circuits. The five-phase laminate ME transducer is FeCuNbSiB/Terfenol-D/PZT/Terfenol-D/FeCuNbSiB (FMPMF) composites, which operated in *L-T* mode. The magnetostrictive layers (Terfenol-D and FeCuNbSiB) are magnetized along the longitudinal direction (*L* mode), while the piezoelectric ceramic (PZT) is polarized in the thickness direction (*T* mode). The sizes of the

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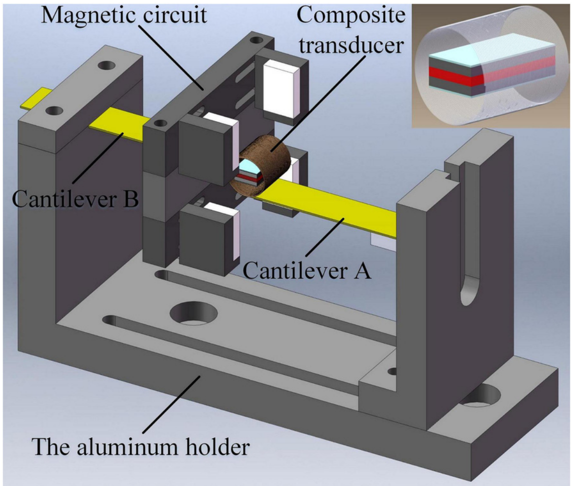

Fig. 1. Schematic diagram of the proposed HVEH.

FeCuNbSiB, Terfenol-D and PZT layers are $12 \times 6 \times 0.06$ mm^3, $12 \times 6 \times 0.8$ mm^3 and $12 \times 6 \times 1$ mm^3, respectively. The five layers are bonded together by the insulated epoxy adhesive which has an average thickness of 0.01 mm. The samples of laminate composites are cured at 80 °C for 2 h for good mechanical coupling. In order to saving space, the laminate ME transducer is placed in the copper coil. The coil is mainly characterized by the proportion of the coil that passes through the magnetic field and the turns number N. The second order effects such as inductance can often be ignored due to the low-frequency of many applications. The turns number N of the coil range from 250 to 750.

Therefore, when there is a small vibration in the external environment, it will excite the HVEH work immediately. Additionally, the ME/EM hybrid transducer will cut the magnetic lines of flux in the working air-gap of magnetic circuits. For coil, based on the Faraday's law of electromagnetic induction, the coil will induce an electromotive force and electrical power (large current and high power), owing to the relative motion between the coil and the magnetic circuit. For the five-phase laminate composites, based on the magnetoelectric (ME) effect, the magnetostrictive layers will induce stresses, which will transmit to the piezoelectric layer and finally result in the generation of electrical power (high voltage). Ultimately, the proposed HVEH has the advantages of large current, high voltage and high power simultaneously, which are very suitable for the wireless sensor networks.

In the measurements, as shown in Fig. 2, the fabricated HVEH is fixed on a mechanical vibration shaker. A functional generator is used to create and transmit a sweeping sinusoidal signal to the power amplifier and obtain an input acceleration into the vibration shaker, which supplies mechanical vibrations to the proposed hybrid energy harvester. The working frequency of vibration shaker is equal to the output signal frequency of signal functional generator. The vibration strength of vibration shaker is measured by an accelerometer which mounted on the vibration shaker. As the vibration energy harvester is excited by the mechanical vibration shaker, the output voltages are measured and stored by a Tektronix TDS1012B digital storage oscilloscope. Furthermore, to investigate the relationship between electric output characteristic of the proposed HVEH, the cantilever length L, the acceleration of vibration shaker A and the number of turns N are controlled from 3 cm to 5 cm, 0.25 g to 0.75 g and 250 to 750, respectively.

3. Results and discussion

For the purpose of a contrast analysis, the ME VEH and EM VEH have also been prepared. Compared with HVEH, the only difference of EM VEH is the transducer, which is only coil (not has FMPMF), the other parameters are the same as HVEH. Similarly, in ME VEH, the transducer is only Terfenol-D/PZT/Terfenol-D (MPM) composites, the other parts of energy harvester are exactly the same as HVEH. Fig. 3(a) illustrates the open-circuit voltages and currents as a function of frequency for HVEH, ME VEH and EM VEH, respectively. Owing to the proposed HVEH has two energy acquisition unit at the same time, it's electric output include a current of coil and a voltage of ME transducer. As illustrated, the HVEH demonstrated two resonance peaks overlap, which can expand the working bandwidth in ambient low frequency vibration. The effective bandwidth (3 dB) of the HVEH is about 4.96 Hz, which is much larger than VEH with one cantilever beam, primarily attributed to the multi-cantilever beams and nonlinear behavior of the magnetic force.

As also can be seen from Fig. 3(a), the peak current of coil and the peak voltage of ME transducer in HVEH reach 85.9 mA and 37.9 V at a frequency of 38 Hz, respectively. In addition, Fig. 3(b) shows the output power as a function of frequency for the proposed HVEH, ME VEH and EM VEH, respectively. As shown, the maximum value of output power for the HVEH achieves 12.6 mW, which is about 1.4 times higher than

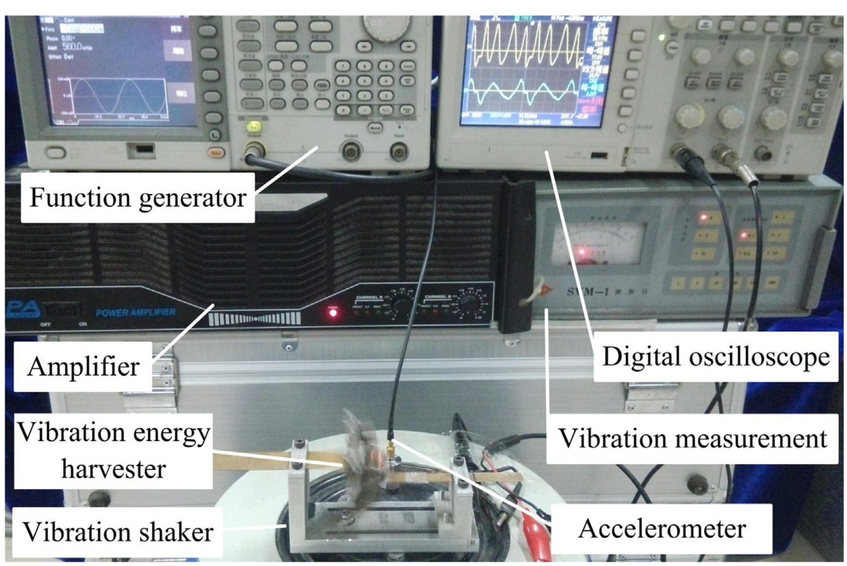

Fig. 2. Experimental setup.