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Design and optimization of piezoelectric impact-based micro wind energy harvester for wireless sensor network☆

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ABSTRACT

The purpose of the current study is to design and optimize a piezoelectric impact-based micro wind energy harvester (PIMWEH) as a power source for wireless sensor networks. First, using new PIMWEH design, numerical simulation, and experimental comparison analysis, we determined the most durable PIMWEH shape for application as a power source of WSNs. The experimental results show that the optimized PIMWEH generated 2.8 mW (RMS value) and did not crack within 40 h. Second, to supply power for sensor operation, we performed an experiment using a rectifying circuit, an AC–DC converter, and an electrical charger. The experimental results show a pure DC voltage signal of 3.3 V, and the output power was 1.0 mW (3.1 mW/cm^3). A charging energy of 0.845 J was obtained in 24 min. Third, we calculated the efficiency of the PIMWEH to evaluate its performance. Using a three-step energy conversion process (using wind turbine, PZT, and LTC3588-1), an overall PIMWEH power conversion efficiency of 3.2% was obtained. For one day, the PIMWEH could supply power that is 6263–25055 times the power requirement of a commercialized ZigBee transmission. In addition, transmitting signals at intervals from 3.4 to 13 s was made possible.

1. Introduction

In recent years, wireless sensor networks (WSNs) have been widely used at home, environment monitoring, healthcare, industrial monitoring, structural health monitoring, and traffic control [1–4]. However, because of the size limitation of a WSN module, a WSN battery is very limited and cannot meet the power consumption of a WSN [5]. To solve this problem, self-powered energy harvesters for WSN applications have been actively studied [6–10]. In particular, wind energy harvesters that use ambient air flow have been studied to supply power to wireless autonomous sensors in outdoor and inaccessible locations [11]. Wind energy harvesters that use wind turbines are classified as electromagnetic and piezoelectric types. Electromagnetic wind energy harvesters possess some advantages such as reliable and small mechanical damping. However, the heavy magnet prevents this harvester type from operating at low wind speed [12]. Impact-based piezoelectric wind energy harvesters also possess some advantages such as a compact system, easy operation at low wind speed, higher efficiency, instant starting with no dead time, small size, light weight, extremely low magnetic permeability, and almost no heat dissipation [13,14]. However, it can easily be damaged when pressure is applied to the piezoelectric wind energy harvester because of the brittleness of the piezoelectric device [15]. Therefore, implementing this harvester as a power source for a WSN is difficult. The purpose of the current study is to design and optimize the piezoelectric impact-based micro wind energy harvester (PIMWEH) for application as a power source of WSNs. The first step in this work is to determine the most durable PIMWEH shape to overcome its disadvantage. Then, to supply power for sensor operation, we perform an experiment using a rectifying circuit, an AC–DC converter, and an electrical charger. The final step is the calculation of the PIMWEH efficiency to evaluate the PIMWEH performance.

2. Designing the PIMWEH to determine the most durable PIMWEH shape

2.1. Piezoelectric theory

Piezoelectric effect is defined as the coupling of stress and electrical field in a material. An electrical field strains the material. Conversely, material strain induces an electrical field. In other

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words, the piezoelectric effect is a reversible process, including the direct and reverse piezoelectric effects. Direct piezoelectric effect means that an applied mechanical force generates an electrical charge, and reverse piezoelectric effect means that an applied electrical field generates a mechanical strain. Meanwhile, the piezoelectric effect converts a mechanical strain into an electric current or voltage. This strain can come from many different sources such as human motion and acoustic noise. The governing equation, which is called the mechanical–electrical coupled equation, is expressed in a strain-charge matrix form as follows:

$$\begin{aligned}\{S\} &= [S^E]\{T\} + [d^t]\{E\} \\ \{D\} &= [d]\{T\} + [\varepsilon^T]\{E\}\end{aligned} \quad (1)$$

where {S}, {T}, {D} and {E} are the mechanical strain, mechanical stress, electrical displacement, and electric field vector, respectively. In addition, [ε] is the permittivity matrix, $[s^E]$ is the elastic compliance matrix, and [d] and $[d^t]$ are the matrices of the direct and inverse piezoelectric effects, respectively. Superscript E represents a zero or constant electric field. Superscript T represents a zero or constant stress field, and superscript t denotes the transposition of a matrix. Equation (1) may be written in detail for the poled piezoelectric ceramic material used in this research as follows:

$$\begin{Bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{Bmatrix} = \begin{Bmatrix} s^E_{11} & s^E_{12} & s^E_{13} & 0 & 0 & 0 \\ s^E_{12} & s^E_{22} & s^E_{23} & 0 & 0 & 0 \\ s^E_{31} & s^E_{32} & s^E_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & s^E_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & s^E_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & s^E_{66} = 2(s^E_{11} - s^E_{12}) \end{Bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{Bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix}$$

$$\begin{Bmatrix} D_1 \\ D_2 \\ D_3 \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{Bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix} \quad (2)$$

where the first equation represents the relationship of the reverse piezoelectric effect and the second equation represents that of the direct piezoelectric effect.

2.2. Design

The maximum stress of a cantilever beam occurs at the fixed end, and the stress is reduced closer to the free end. Thus, when a PIMWEH generates electrical energy, the fixed end of the generator can easily be damaged. To determine the most durable PIMWEH shape, the stress distribution must be uniform. To determine the uniform PIMWEH, we compared six PIMWEH types, as shown in Fig. 1. Piezoelectric devices (PZTs) were installed at the fixed end, middle, and free end of the substrate. Fig. 1(a), (c), and (e) shows the general PIMWEH without an additional device (secondary impacter). On the other hand, Fig. 1(b), (d), and (f) shows the additional device installed to apply a larger stress at the free end [14].

2.3. Numerical simulation

2.3.1. Validation

This section presents the development of a finite element (FE) model for a unimorph piezoelectric energy harvester using the FE code ABAQUS [16]. Then, verification of the developed FE model for a unimorph piezoelectric energy harvester is carried out by two methods. The first method compares the theoretical values and the numerical results, and the second method compares the experimental measurements and the numerical results. The first verification method employs comparison using a closed-form analytical solution originally developed by Erturk and Inman [17]. Fig. 2(a) shows the geometric shape and dimensions of the sample unimorph energy harvester used in this step, and several mechanical and electrical material properties of the harvester are listed in Table 1. Here, E is the Young's modulus, ρ is the density, d is the piezoelectric constant, and ε is the dielectric permittivity. Subscript 1 denotes the direction of the axial strain, and subscript 3 denotes the direction of polarization.

Table 1
Material properties of a harvester for theoretical verification.

	Piezoelectric device	Substrate
E (GPa)	66	100
ρ (g/cm^2)	7.8	7.1
d_{31} (pm/V)	−190	–
ε_{33} (nF/m)	15.93	–

Table 2
First and second modes of the natural frequency.

	First mode	Second mode
Erturk and Inman	48.80 Hz	301.50 Hz
ABAQUS	48.68 Hz	302.28 Hz

Fig. 2(b) and Table 2 show the validation results from the FE model with regard to the output voltage and natural frequency, respectively. The analytical solution for the electro-mechanical frequency response functions (FRFs) from Erturk and Inman [17] is plotted using equation (3). Equation (3) describes the voltage FRF as the ratio of the output voltage to the base acceleration.

$$\frac{v(t)}{-\omega Y_0\, e^{j\omega t}} = \frac{\sum_{r=1}^{\infty}(jm\omega\varphi_r\gamma_r^{\omega}/(\omega_r^2 - \omega^2 + j^2\zeta_r\omega_r\omega))}{\sum_{r=1}^{\infty}(-jm\omega\varphi_r x_r/(\omega_r^2 - \omega^2 + j^2\zeta_r\omega_r\omega)) + (1 + j\omega\tau_c/\tau_c)} \quad (3)$$

$$\gamma_r^{\omega} = \int_{x=0}^{L} \phi_r(x)\,dx \quad (4)$$