Hybridized thermal energy harvesting mechanism

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Abstract. This work demonstrates a moving beam thermal energy harvesting mechanism for use adjacent to a heat source with modest temperature variation at low frequency (below 0.1 Hz). We investigate the coupling between the piezo- and pyro-electric effects to improve output power. The phase relationship between two effects was studied under different beam end conditions, i.e. fixed-free and fixed-fixed. A model to estimate the output is given and experimentally validated. Experimental result at 0.05 Hz shows that the output voltage in the fixed-fixed configuration is about 53% higher than the fixed-free configuration.

1. Introduction

Energy harvesting, a technology to generate electrical energy from natural or man-made sources, has attracted attention as a substitute for batteries for wireless electronic devices as well as for low-power devices [1, 2]. Among the different sources of energy, thermal energy is abundant and ubiquitous on the planet in a technologically advanced society. Large amounts of thermal energy are released in waste heat, which is a by-product of industrial processes, heat engines and electronic devices. A thermoelectric generator, a typical thermal energy harvester, requires a temperature gradient; however a pyroelectric harvester requires a time-varying temperature condition. Self-oscillating harvesters with a static heat source have been presented by several research groups [3, 4]. On the other hand, time-varying temperature heat sources have also been applied directly to harvesters [5, 6].

In this work, a simple structured hybridized thermal energy harvesting mechanism is presented based on a time-varying heat source with small and slow temperature variations. We evaluated two methods: one is increasing piezoelectricity in the same condition, and the other is decreasing the phase shift between the two effects. This relationship was studied in a model. The mechanism shows the capability to couple the two effects at low frequencies of less than 0.1 Hz and temperature differences of less than 3 K. It can be applied to electronic devices utilizing the heat produced by chips on a circuit board.

2. Harvester Design and Operating Principle

The device is a simple mechanism consisting of a bimetallic beam with an attached lead zirconate titanate (PZT)-5H layer over the central portion of its length. The beam is mounted either as a cantilever (fixed-free) or with both ends fixed. The bimetallic beam consists of two layers (Ni-Cr-Fe and Ni-Fe) with a large difference in coefficients of thermal expansion (CTE), and induces deformation due to temperature change. As a heat source, a heating element of 95 °C was used. Figure 1 illustrates the basic heat cycle. The temperature variation is achieved by
mounting the fixed heat source on a position-controlled slider oscillating laterally beneath the beam.

3. Modelling

3.1. FEM simulation

The heat transfer and distribution feature are critical to the performance of this mechanism. Finite element method (FEM) simulation was performed using Comsol Multiphysics 5.3. Figures 2 and 3 show example stress and heat distribution obtained by Comsol at 0.02 Hz, which is the lowest frequency in this study. The meshing around the objects is particularly important for studying the time-varying heat transfer behavior by conduction and convection. Dynamic simulation was conducted for 600 seconds to reach thermal equilibrium.

3.2. Modelling

Based on heat transfer from Comsol, a model has been built to estimate the output voltage. Figure 4(a) illustrates the equivalent circuit of the PZT layer, which can be modeled as two current sources in parallel. The phase shift between piezo- and pyro-electric effects was

| Symbol | Description | Value |
|--------|-------------|-------|
| \( L_p \) | length | 35 mm |
| \( b_p \) | width | 10 mm |
| \( h_p \) | thickness | 0.127 mm |
| \( d_{31} \) | piezo-coeff. | \(-320 \times 10^{-12} \) m/V |
| \( p \) | pyro-coeff. | \(-400 \) \( \mu \text{C}/(\text{m}^2\text{K}) \) |
investigated to compare the two configurations. The temperature oscillation of the heat source is of the form

\[ T(t) = T_0 + \Delta T \cos(\omega t) \]  

where \( T_0 \) is the mean temperature, \( \Delta T \) is the amplitude of the sinusoidal temperature, and \( \omega \) is the angular frequency. In the fixed-free configuration, the total output voltage is given by

\[ \vec{V}_{fr} = V_{fr}^{pi} \cos(\omega t + \pi) + V_{fr}^{py} \sin(\omega t + \phi) \]  

where \( \phi = \tan^{-1}(\omega C_p R) \) \[^7\], \( C_p \) is the capacitance of PZT, 90 nF, and \( R \) is the total resistance, 50 M\( \Omega \). \( V_{fr}^{pi} = (\vec{F}d_{31}L_p)/(h_0 C_p) \) is the amplitude of piezoelectricity, where \( \vec{F} \) is the beam load. \( V_{fr}^{py} = \rho A \Delta T/C_p \) is the amplitude of pyroelectricity, where \( A \) is the surface area of the PZT. The total output voltage in the fixed-fixed configuration is given by

\[ \vec{V}_{ff} = V_{ff}^{pi} \cos(\omega t) + V_{ff}^{py} \sin(\omega t + \phi). \]  

The superscripts \( fr \) and \( ff \) stands for the fixed-free and fixed-fixed configuration, respectively.

4. Experimental Validation

Figure 4 (b) shows the experimental set-up. Experimental results at 0.05 and 0.1 Hz are shown in Figure 5: deflection measured at the center of the beam by a laser sensor; temperature \( T \), measured by K-type thermocouple; \( dT/dt \); and output voltage (open circuit). Figure 6 shows the beam deflection and output voltage amplitude as a function of frequency. As frequency increases,
deflection and output voltage drop significantly, although maximum rate of temperature change decreases by a lower factor, indicating that both piezo- and pyro- effects contribute significantly.

Figure 6: Output as a function of frequency.

Figure 7: Comparison of results.

Figure 7 illustrates a comparison of experimental and modelling results as a function of frequency. The total output voltage of the model is the sum of pyro- and piezo-electricity values with the phase between them. In fixed-free, piezoelectricity counteracts pyroelectricity. In fixed-fixed, the greater piezoelectricity and the phase relationship between two effects leads to a greater total output voltage than in fixed-free. The relatively large difference between the experiment and model at low frequencies is due to the discharge during the heat cycle. The sum of the piezo- and pyro-electric effects are in phase under the fixed-fixed configuration, giving a peak output voltage of 2.8 V at 0.05 Hz, 53 % above the fixed-free configuration.

5. Conclusions

This paper presents a hybridized thermal energy harvesting mechanism harnessing low frequency of heat cycle. A simple structure was shown using a bimetallic and PZT beam. Comsol simulation was performed on the heat transfer characteristics, and a model was built to evaluate the output. This was validated experimentally. As is to be expected, pyroelectricity is dominant, and piezoelectricity is an additional factor to improve the output voltage. At 0.05 Hz, for an optimal load resistance of 30 MΩ, the peak output powers were 63 nW and 137 nW for the fixed-free and fixed-fixed cases respectively. Future work will involve design optimisation of mechanism in order to improve output power.

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