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Road energy harvester designed as a macro-power source using the piezoelectric effect

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ABSTRACT

While energy harvesting is commonly used for micro-power sources, it could be applied in macro-power sources using a large-scale harvester in a spacious area. We designed and optimized an energy harvester for a busy roadway using piezoelectric cantilever beams. Using the road vibrational frequency under vehicle speeds of 60–80 km/h, we tuned the natural frequency of the beams by attaching a tip mass. Considering the typical vehicle wheel width and the depth of pavement, the designed energy harvester with a volume of $30 \times 30 \times 10$ cm^3 contained 48 piezoelectric beams. To optimize the harvester circuit, we rectified the output current from each piezoelectric beam and connected the beams in parallel to avoid phase difference interruptions. Finally, we conducted impedance matching to maximize the output power. As a result, we realized an output power of 736 μW with a power density of 8.19 mW/m^2.

Introduction

As climate change becomes more significant, the use of fossil fuels will lose popularity, and therefore, researchers are currently focusing on renewable energy sources such as wind, solar, geothermal, and tidal power [1,2]. Moreover, there has been some interest in recycling ambient waste energy such as undesirable mechanical vibration and abandoned heat. This process is called energy harvesting, and it has been considered for low-powered electronic devices.

In particular, energy harvesting is ideal for wireless systems as it can eliminate the electrical wires connected to conventional AC power outlets or reduce the use of built-in batteries [3]. For example, for microelectromechanical systems (MEMS) designed for applications in human veins or artificial organs, energy harvesting could be very useful because changing batteries in these systems is very difficult. Further, energy harvesting is favorable in building technologies if wireless switches are powered by harvested energy because eliminating complex electrical wires inside the walls of the building can reduce building costs. Given these advantages, energy harvesting must be used effectively for smart home automation systems or the Internet of things, because it can make them batteryless and self-powered [4].

Although the nature of energy harvesting makes it readily applicable for micro-power sources, it could be potentially used for macro-power sources by installing large-scale

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harvesters in a spacious area. For example, an energy harvester installed under a road may be useful for macro-power sources. Such a system does not require any additional installation space because it can be located under an existing road, and this system could constantly harvest energy as long as vehicles are moving on the road. However, it is not desirable for vehicles to expend unnecessary energy by driving over a mattress-like road owing to the installed road energy harvesters. The displacement of the harvester must be minimized in order to properly harvest naturally-abandoned energy from moving vehicles.

To collect the ambient energy from the vehicles on a road, we need to convert road vibration, i.e., mechanical energy, into electrical energy. There are three possible methods for performing this conversion: electromagnetics, electrostatics, and piezoelectricity [5–8]. An electromagnetic energy harvester generates electricity from induced current in magnetic fields. It uses permanent magnets and coils of electrical wire, which require a spacious room in the harvesting module and a complex mechanical structure [3,9]. The electrostatics energy harvester captures sudden static electricity, which is difficult to store and has limited application owing to its low current [3].

On the other hand, piezoelectric energy harvesters have the widest range of output power density as well as the simplest structure among the three methods of harvesting mechanical energy [3]. This piezoelectric energy harvesting technology is gaining significant research interest [10], and has been applied for harvesting energy from human bodies [11–14], energy harvesting shoes [15,16], and sidewalk tiles [17].

Thus, using the piezoelectric effect to harvest energy from road traffic could be a new and reliable macro-energy source. Many studies have considered different types of road energy harvester designs [18,19]. Most studies have used a bulk piezoelectric ceramic owing to its structural simplicity and high output power; however, bulk ceramic is very fragile and expensive, which must be considered when implementing harvesters under a road.

In this study, we designed and optimized a piezoelectric energy harvester for a busy roadway using piezoelectric cantilever beams, which comprise piezoelectric ceramic layers and substrate layers. The substrates provide increased durability to the ceramic beams, and therefore, the piezoelectric beams are more appropriate for use in road energy harvesters. We constructed the piezoelectric energy harvester by considering important environmental conditions and design constraints and maximized its output power by conducted impedance matching to optimize the piezoelectric circuits.

Materials and methods

Fig. 1 shows the piezoelectric cantilever beam used in this research. A well-known piezoelectric material, namely PZT-PZNM ceramic (TIOCEAN, Korea), with dimensions of $38 \times 38 \times 0.2$ mm^3 was attached on an AISI Type 304 stainless steel plate with dimensions of $40 \times 60 \times 0.2$ mm^3. The specific material properties are listed in Table 1.

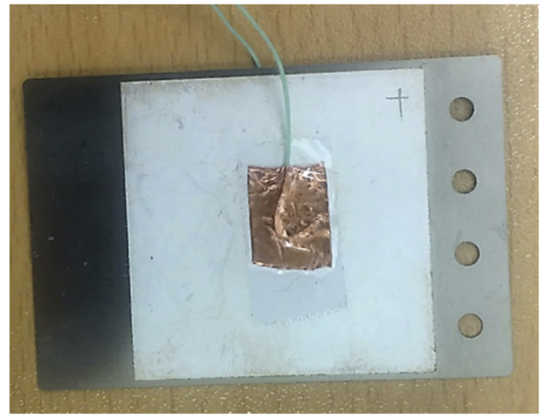

Fig. 1 – Piezoelectric cantilever beam.

Table 1 – Material properties of the piezoelectric cantilever beam.

Stainless steel (304SS)	Value
Density (g/cm^3): ρ	8
Young's modulus (GPa): E	193
Piezoelectric material (PZT-PZNM ceramic)	**Value**
Density (g/cm^3)	7.60
Dielectric constants ($\varepsilon_{33}T/\varepsilon_0$)	2300
Piezoelectric charge constants ($\times10^{-12}$ m/V): d_{33}, d_{31}	450, −200
Piezoelectric voltage constants ($\times10^{-3}$V·m/N): g_{33}, g_{31}	22.1, −11.1
Elastic constants ($\times10^{-12}$ m^2/N): S^E_{11}, S^D_{11}	13.8, 11.8

Frequency analysis

A piezoelectric cantilever beam vibrates at its natural frequency when subjected to external impacts, and electricity is generated from its deformed perovskite structure. As the deformation increases, the power generated by the cantilever beam increases. Therefore, it is important to match the natural frequency of the cantilever beam to the frequency of the input source to maximize the deformation causing the resonance effect. Many previous studies have proven that a piezoelectric energy harvester shows a considerably effective mechanical–electrical power conversion at its resonance frequency [20,21]. In our case, the input source will be the road vibration.

Because vehicles move at random speeds, the road may vibrate with different frequencies. We analyzed existing studies to determine the road vibration caused by car movements under the most common car speeds of 60–80 km/h [22–25].

Frequency matching for a piezoelectric cantilever beam

We need to generate the resonance effect for our energy harvester, and it must show resonance at the most common road vibration frequency. The frequency of the beam can be described by

$$f_o = \frac{1}{2\pi}\sqrt{\frac{K_{beam}}{m_{eff}}}, \quad (1)$$