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# Feasibility study of impact-based piezoelectric road energy harvester for wireless sensor networks in smart highways☆

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ABSTRACT

The purpose of this study is designing and examining impact-based piezoelectric road energy harvesters as power sources of a variety of sensors and smart highways. The impact-based piezoelectric road energy harvesters ($15 \times 15 \times 9\,\text{cm}^3$) developed in this research can convert the input energy efficiently into electrical power. The output power of the proposed harvester is significantly higher than that of the existing harvesters. Moreover, in previous studies, simple experiments were performed for measuring the output power of a road energy harvester, with no consideration for the practical road conditions. In this study, the output power is measured using machines that can simulate the practical road conditions. First, the output power of the harvester is measured using a universal testing machine (UTM) that can apply an axial load with a controlled loading frequency. Then, a third-scale mobile loading simulator (MMLS3) that can simulate practical traffic load on a lab scale is used. As a result, the maximum output power of the road energy harvester is 483 mW(21.47 W/m$^2$).

## 1. Introduction

Energy harvesting technologies for different types of applications have been studied for years such as the wind [1], railway [2,3], human movement [4], car tire [5], pavement [6–9] and so on [10–18]. The energy harvesting technology related to roads including bridge has been particularly spotlighted because of its advantages such as applicability and high input energy [19–22]. Moreover, it can be used as a power source for wireless sensor networks [23–25] in smart highways, traffic control [26], structural monitoring [27–29]. A piezoelectric road energy harvester is buried beneath the road, and energy is generated using the axial load from the vehicle moving on the road, as the input. However, most of the existing road energy harvesters have the disadvantage that their output power with less than 10 mW/m$^2$ is too small to be commercialized [19]. This is because large amounts of mechanical input energy cannot be transformed to the equivalent electrical output power because of the ineffective internal structures, especially in cases where the displacement is small and the axial force is high. So, we have conducted a research on mechanism more proper to the under-road condition that has two features: (1) limited working displacement for driving comfort and road sustainability; and (2) a structure exerting large axial force to the piezoelectric material. Then, we have applied both-ends-fixed beams that can transform mechanical input energy into electrical energy effectively more than simple cantilever structures.

In the proposed harvester, both ends of the piezoelectric device in the harvester are fixed, and the center of the device is subjected to the impact. As a result, the harvester generates higher output power compared to the existing harvesters, although both types of harvesters are transformed by the same displacement. An axial force created by a moving vehicle is transferred to the piezoelectric device in the harvester directly; therefore, it can generate higher output power than the existing harvester for the same displacement, because of the large stress and instant force [19,20].

In cases of the established harvesters, the harvesters were manufactured without considering the forces or velocities of the cars on real roads. A piezoelectric road energy harvester that does not consider the conditions of the real roads properly either cannot

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*Abbreviations:* UTM, Universal Testing Machine; MMLS3, Third-scale Mobile Loading Simulator; FEA, Finite Element Analysis.

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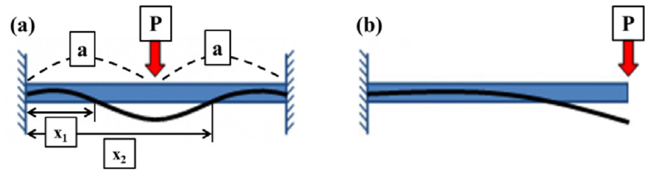

**Fig. 1.** Schematic view of both-ends-fixed beam and cantilever.

generate enough output power because of the lack of stress or can destroy the internal piezoelectric devices owing to excessive stress.

Consequently, lab-scale experiments under conditions of force and velocity similar to those on real roads were conducted to guarantee a high output power and a stable structure beneath the road. First, the output power of the harvester and the weight necessary to obtain a high output power were measured using a UTM, which can apply changeable force and frequency. The derived weight could be used to adjust the structure of the harvester to make it suitable for the required road conditions. Second, an experiment using an MMLS3 was performed for testing under conditions more similar to the road conditions.

The MMLS3 can simulate a moving vehicle with constant weight and velocity, using wheels are built in the MMLS3. Through the experiment using the MMLS3, problems that might occur on a real road can be predicted and preparations can be done. The trends in the output power, with respect to the axial load and weight, are measured using these two types of lab-scale experiments.

## 2. Determination of the generation method

### 2.1. Comparison of the cantilever and both-ends-fixed beam using stress formula

Fig. 1(a) and (b) show the schematic views of the both-ends-fixed beam and the cantilever, respectively. $P$ is the input pressure, and $a$ is the distance from one fixed end of the beam to the half point. $x_1$ and $x_2$ are the locations of two random points with respect to one fixed end of the beam. In Fig. 1(a), when $P$ is applied to the half point, moments $M_1$ and $M_2$ are generated at $x_1$ and $x_2$, respectively. Their relationships are shown in the following equations [30]:

$$M_1 = \frac{P}{2}x_1 \tag{1}$$

$$M_2 = \frac{P}{2}x_2 - P(x_2 - a) = \frac{P}{2}(2a - x_2) \tag{2}$$

The moment $M$ is dependent on the vertical displacement $V$, the young's modulus $E$, the moment of inertia $I$ and the location $x$ as follows:

$$\mathrm{M} = \mathrm{EI}\frac{d^2V}{dx^2} \tag{3}$$

The following boundary conditions can be used to solve the differential equations.

$$\mathrm{At}x_1 = 0, V_1 = 0 \tag{4}$$

$$\mathrm{At}x_2 = 0, V_2 = 0 \tag{5}$$

$$\mathrm{At}x_1 = x_2 = a, \frac{dV_1(a)}{dx_1} = \frac{dV_2(a)}{dx_2} \tag{6}$$

Therefore, the curvature $dV/dx$ and the displacement $V$ can be derived as follows:

$$\frac{dV_1}{dx_1} = \frac{P}{4EI}x_1^2 - \frac{Pa^2}{4EI} \tag{7}$$

**Table 1**
Material properties of the piezoelectric cantilever beam.

| Stainless steel | Value |
|---|---|
| Density (g/cm$^3$): ρ | 8 |
| Young's modulus (GPa): E | 193 |
| Piezoelectric material (PZT-PZNM ceramic) | Value |
| Density (g/cm$^3$): ρ | 7.60 |
| Dielectric constants ($\varepsilon_{33}{}^{T}/\varepsilon_0$) | 2300 |
| Piezoelectric charge constants ($\times 10^{-12}$ m$^2$/V): $d_{33}$, $d_{31}$ | 450, −200 |
| Piezoelectric voltage constants ($\times 10^{-3}$ V·m/N): $g_{33}$, $g_{31}$ | 22.1, −11.1 |
| Elastic constants ($\times 10^{-12}$ m$^2$/N): $S_{11}{}^{E}$,$S_{11}{}^{D}$ | 13.8, 11.8 |

$$\frac{dV_2}{dx_2} = \frac{P}{EI}x_2 - \frac{P}{4EI}x_2^2 - \frac{3Pa^2}{4EI} \tag{8}$$

$$V_1 = \frac{P}{12EI}x_1^3 - \frac{Pa^2}{4EI}x_1 \tag{9}$$

$$V_2 = \frac{Pa}{2EI}x_2^2 - \frac{P}{12EI}x_2^3 - \frac{3Pa^2}{4EI}x_2 + \frac{Pa^2}{6EI} \tag{10}$$

To find the displacement at the half point, we substitute $x = a$ in Eqs. (9) and (10). Finally, the displacement $V$ at the half point can be expressed as shown in Eq. (11).

$$V = \frac{Pa^3}{12EI} - \frac{Pa^3}{4EI} = -\frac{Pa^3}{6EI} \tag{11}$$

Through Eqs. (1)–(11), the relationship between the vertical displacements $V$ and the input pressure $P$ on the both-ends-fixed beam is derived.

On the other hand, when input pressure is applied to the end of the cantilever in Fig. 1(b), the displacement $V$ of the cantilever is as follows:

$$V = -\frac{Pa^3}{3EI} \tag{12}$$

Comparing the displacements of the both-ends-fixed beam and the cantilever with the Eqs. (11) and (12), we could find that the displacement of the cantilever is found to be larger than that of the both-ends-fixed beam when the same input pressure is applied to the structure. However, the input pressure of the cantilever is less than that of the both-ends-fixed beam in case of the displacement of the road energy harvester is same in both cases. Thus, the output electrical energy, which increases with the input pressure, is higher in the both-ends-fixed beam.

### 2.2. Comparison of the cantilever with the both-ends-fixed beam using FEA

To determine a suitable generation method for the piezoelectric road energy harvester, we compared a cantilever used in an established road energy harvester, with the both-ends-fixed beam proposed in this work, with respect to various aspects like stress distribution, output voltage, and charge. The properties of the piezoelectric device used in this work are displayed in Table 1.

The piezoelectric device consists of stainless steel and piezoelectric ceramic. The size of the steel and the ceramic are 40 × 60 mm$^2$ and 38 × 38 mm$^2$, respectively, and the ceramic is fixed to the center of the steel. The input force is applied to the center of the both-ends-fixed beam and the end of the cantilever, with a displacement of 2 mm and a frequency of 10 Hz.

To verify the structure of the road energy harvesters, a finite-element analysis (FEA) program ABAQUS is used [31]. The results of the simulations for the stress distributions of the both-ends-fixed beam and the cantilever beam are displayed in Fig. 2. In case of the cantilever beam, the stress is concentrated at the fixed and free