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Laboratory testing and numerical simulation of piezoelectric energy harvester for roadway applications

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HIGHLIGHTS

- The energy output and mechanical failure of piezoelectric energy harvester is studied.
- The predicted voltage and power from numerical simulation match well with experimental measurements.
- The energy output increases with the increase of loading frequency and load magnitude.
- The performance of energy module is affected by fabrication of single transducer and packaging design.

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ABSTRACT

The main objective of this study is to evaluate energy output and mechanical failure of piezoelectric energy harvester for roadway applications. The Bridge transducer with layered poling was designed to have high piezoelectric coefficient and capacitance. An energy harvester module that contains multiple stacked transducers was fabricated and tested under single pulse and cyclic loading events. Forensic analysis was conducted to investigate fatigue failure of piezoelectric transducers after repeated loading. Finite element simulation was used to evaluate output power and mechanical stress of energy harvesters with different layer thicknesses of epoxy adhesive, material types of packing material, and gap design. The predicted voltages and power outputs obtained from numerical simulation match well with experimental measurements. The energy output increased with the increase of loading frequency and load magnitude. This indicates that the energy harvesting performance is affected by vehicle weights, speed, and the embedment location of energy module. On the other hand, the resistive load can be optimized to increase the energy output. The analysis results showed that two different material failure models need to be considered in relation to mechanical failure of Bridge transducer, namely tensile and shear failure. It emphasizes that the optimum design of energy module should consider the balance of energy output and fatigue life that are affected by fabrication of single Bridge transducer and the packaging design of energy module.

1. Introduction

Roadways are one of major civil infrastructures that play important roles in connecting communities and moving people. Traditionally, roadways are regarded as structures that carry traffic loading. Recently, researches have been conducted to explore the potential of energy harvesting from roadways, including solar, thermal, and kinetic energy [1–6].

Vehicle movement on roadways induces mechanical deformation in the pavement system, which produces mechanical energy that can be harvested using piezoelectric material. There are two important types of PZT transducers that can be used to harvest energy from the ambient environment: vibration-based and stress-based. The common design of piezoelectric energy-harvesting devices is based on cantilevers, which utilize vibrations as the source of mechanical input [7,8]. However, this energy harvesting method requires piezoelectric device to be tuned to the source's specific vibration frequency. On the other hand, stress-based piezoelectric transducers were recommended for energy harvesting for low-frequency non-resonant resources [9,10].

Zhao et al. [11] compared different designs of piezoelectric transducers and concluded that the Cymbal and Bridge transducers were recommended configurations for energy harvesting in roadway

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considering the vehicular loading pattern and the stiffness consistency between the transducer and pavement materials. Moure et al. [12] fabricated and tested different configurations of Cymbal piezoelectric sensor to optimize the conversion of mechanical to electric energy. The Cymbal sensors were placed directly in asphalt mixture to evaluate their performance as vibration energy harvesters in roads. The power output of each single sensor was recovered up to 16 μW for one pass of heavy vehicle wheel.

Xiong and Wang [13] investigated the effect of coupling configuration and material selection on energy efficiency of piezoelectric energy harvester. The harvester was built with PZT rods covered by aluminum alloy to distribute the load. They reported that for roadways applications 15% of applied mechanical energy was transferred to transducers under real traffic condition. Roshani et al. [14,15] developed highway sensing and energy conversion (HiSEC) modules using various configurations of boxes containing different numbers of PZT rod elements sandwiched between two copper plates. Through laboratory testing, they concluded that the number and size of piezoelectric disks and the loading magnitude and frequency can significantly the output voltage. Yang et al. [16] designed a piezoelectric energy harvester with multilayer stacked array. The energy harvesters consisted of nine piezoelectric disks (PZT-5H) stacked in parallel inside a 30 × 30 × 6.8 cm (length × width × height) box. After repeated loadings, it was found that the average output of the energy harvester was 174 V (open circuit) and there was no significant reduction in power generation.

Song et al. [17] designed and optimized an energy harvester for roadway applications using piezoelectric cantilever beams. The designed energy harvester had a volume of 30 × 30 × 10 cm^3 containing 48 piezoelectric beams. The developed energy harvester generated output power of 184 mW. Jung et al. [18] demonstrated a piezoelectric energy harvester module based on polyvinylidene fluoride (PVDF) polymer for roadway applications. The module of 15 × 15 × 9 cm (length × width × height) exhibits 0.2 W output with 8 W/m^2 power density. In addition, the stable performance and durability were noticed after over million cycles of loading.

Chen et al. [19] developed mechanical harvesting energy (MEH) device made of two square-shaped thickness-polarized PZT bimorph of parallel type. The MEH device was embedded in the asphalt mixture specimen at a depth of 10 mm and found that the output power depended on the loading period, location, and size of the piezoelectric device. In addition, the researchers concluded that selecting appropriate material and geometry parameters for practical traffic conditions are very important for energy harvesting system.

Guo and Lu [20] introduced the energy harvesting pavement system (EHPS) that consisted of one piezoelectric material layer in the middle of two conductive asphalt layers. The prototype was tested in the laboratory and compared to the results from three-degree-of-freedom electromechanical model. It was found that more piezoelectric elements with higher piezoelectric stress constant and more flexibility of conductive asphalt mixtures can improve the energy harvesting performance of EHPS.

Most previous researches have investigated different piezoelectric energy harvester designs for stress-based energy harvesting from roadway, including disk or rod shape, cantilever beam, bimorph, Cymbal, and Bridge. Among different designs, disk- or rod-shape PZT transducers were most commonly used due to its easy fabrication, although its energy harvesting performance may not be as significant as other transducer designs. On the other hand, the generated energy output is usually small for single piezoelectric transducer. Thus, multiple arrays of piezoelectric transducers are usually stacked and packaged to generate the energy under repeated traffic loading. However, the effects of packaging material and fatigue loading on the durability of piezoelectric materials have not been studied. Therefore, further investigation is needed to evaluate energy output and long-term performance of energy harvester with different transducer types and packaging designs.

2. Objectives

The main objective of this study is to evaluate energy output and fatigue behavior of piezoelectric energy harvester using laboratory testing and numerical simulation. The new Bridge transducer with layered poling was designed to have high piezoelectric coefficient and capacitance. An energy harvester module that contains multiple stacked transducers was fabricated and tested under single pulse and cyclic loading events. Forensic analysis was conducted to investigate fatigue failure of piezoelectric transducers after repeated loading. Finite element simulation was used to evaluate output power and mechanical stress concentration of energy harvesters with different layer thicknesses of epoxy adhesive, material types of packing material, and gap designs.

3. Bridge transducer with layered poling

3.1. Theoretical background

Piezoelectric materials like lead zirconate titanate (PZT) contain dipoles that naturally randomly orient. When mechanical stress is applied to PZT material, the dipoles rotate from original orientation, causing electric and mechanical energy to store in the dipole [21]. The constitutive equations for linear piezoelectric material under low stress levels can be written as shown in Eqs. (1)–(3).

$$x = s^D X + gD \tag{1}$$

$$E = -gX + \beta^X D \tag{2}$$

$$g = \frac{d}{\varepsilon_o \varepsilon_r^X} \tag{3}$$

where, X is the stress; x is the strain; D is the electric displacement; E is the electric field; s is the elastic compliance; β is the dielectric susceptibility which is equal to the inverse dielectric permittivity tensor component; g is the piezoelectric voltage coefficient; d is the piezoelectric charge constant; ε_r^X is the relative dielectric constant of PZT in the 3rd axial direction; and ε_o is the dielectric constant of vacuum (8.85×10^{-12} Farad/m).

Under an applied force, the open circuit output voltage of the piezoelectric ceramic can be calculated from Eq. (4).

$$V = E \cdot t = -g \cdot X \cdot t = -\frac{g.\ F.\ t}{A} \tag{4}$$

where, V is the voltage; t is the thickness of piezoelectric ceramic; F is the applied force; A is the area of piezoelectric ceramic element; and X is the stress.

The charge (Q) and capacitance (C) generated on the piezoelectric ceramic can be determined from Eqs. (5) and (6).

$$D = \frac{Q}{A} = \frac{E}{\beta^X} = \frac{V.\ \varepsilon_o.\ \varepsilon_r^X}{t} \tag{5}$$

$$\frac{Q}{V} = \frac{\varepsilon_o.\ \varepsilon_r^X.\ A}{t} = C \tag{6}$$

where, Q is the charge of piezoelectric ceramic; and C is the capacitance of piezoelectric ceramic.

The above relationship shows that at low-frequency loading, the piezoelectric ceramic can be assumed to behave like a parallel plate capacitor. Hence, the electric power available under the cyclic excitation is given by Eq. (7).

$$P = 1/2CV^2.\ f \tag{7}$$

where, P is the electric power; and f is the frequency of cyclic loading.

The electrical power is dependent upon the capacitance of piezoelectric material. The increase of capacitance will generate high power when the piezoelectric ceramic is directly employed for energy