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Optimization design and experimental investigation of piezoelectric energy harvesting devices for pavement

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HIGHLIGHTS

- A energy harvesting device with a group of piezoelectric transducers is designed.
- Optimal device dimensions for light and heavy traffic loading are identified.
- Device material configurations are optimized by mechanic-electric responses test.
- The 15 cm × 15 cm device achieves output power of 50.41 mW with the loading of 4 kΩ.

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ABSTRACT

This study designs a compression-based pavement energy harvesting device with a group of piezoelectric transducers and investigates the selection of the component materials based on four technical device requirements for enhanced the electric energy output of power-generation pavements. The external dimensions of the proposed devices are optimized based on vehicle wheelpath distribution, tire trace patterns, and vehicle roller compaction conditions. The array pattern of the piezoelectric device is designed based on the driving characteristics. Various device material configurations are examined using different cover plates, rubber pad thicknesses, protective pads, and transducer specifications for optimal mechanic-electric response characteristics. A 150 mm × 150 mm type device is tested as an example and its electrical output performance is evaluated under typical road loading environments. Subsequently, a comparative analysis of various disclosed piezoelectric harvesting device technology were conducted and further research plan was developed. The selected modified polypropylene or aluminum plate, steel plate, modified polypropylene bar, and fiber heat insulation plate are suitable for the device which meets the application demands. The optimum device dimensions under light and heavy traffic conditions are 100 mm × 100 mm and 150 mm × 150 mm, respectively. The optimum configuration of the device includes a modified polypropylene upper cover plate, 1 mm rubber pad, ball-type protective pad, and eight laminated transducers. In addition, parallel connection of stacked transducers is more suitable for energy collection and reuse from traffic-induced pavement vibrations. Under the loading of 0.7 MPa and 15 Hz, the 150 mm × 150 mm device with nine parallel transducers achieves a maximum output power of 50.41 mW, and the corresponding optimum loading is 4 kΩ. Under the loading of 0.2 MPa and 10 Hz, the device achieves a maximum output power of 2.92 mW, and the corresponding optimum load is 10 kΩ. The performance of piezoelectric device designed in this paper excels that of many other available devices.

1. Introduction

With increasingly prominent environmental issues, such as energy shortages and pollution, the development and utilization of clean and renewable energy have been receiving significant community attention. New environmental energy-harvesting technologies can convert various environmental energy sources that exist in nature, such as solar [1–3], wind [4–6], thermal [7,8], vibration [9–11], and ocean [12], into electrical energy by means of energy-convertible materials, structures, or systems. Through these methods, energy utilization is realized

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without producing pollution. Piezoelectric vibration energy-harvesting technology is extensively used in vibration energy harvesting because of its high electrical conversion coefficient and no external power supply being required, among other factors. Vibration energy can easily be obtained in our surroundings; for example, from different types of mechanical equipment, buildings, roads, railways, and biological system movements [13], of which vibrations in road structures may be the most significant. Furthermore, with increased global motor vehicle ownership and highway mileage, road vibration energy will continue to grow. If this technology and road engineering can be combined to create a safe, clean, and reliable intelligent road piezoelectric power generation system, transformation and upgrading of energy structures may be effectively promoted, thereby alleviating the energy and environmental problems that have long plagued human development.

The concept of converting vibration energy into electrical energy was first proposed by Williams and Yates in 1996 [14]. Since then, research into the electrical conversion of vibrating micro-energy has become important. At present, piezoelectric power generation technology for pavements includes two methods: piezoelectric material composite power generation pavement technology and transducer-embedded pavement piezoelectric power generation technology. The former is used in road paving to harvest vibration energy by compounding pavement and piezoelectric materials. The California State Government used piezoelectric material in road power generation to convert their state highway into smart highway [15]. Guo et al. designed an energy-harvesting pavement system consisting of two conductive asphalt layers and one piezoelectric material layer and verified its feasibility [16]. Tan et al. prepared piezoelectric asphalt composites by compounding piezoelectric material and asphalt, and achieved an output voltage of up to 7.2 V [17]. Wang et al. compounded piezoelectric, conductive, electrode, and pavement materials in order to prepare d_{31} and d_{33}, two forms of piezoelectric asphalt concrete, with an output voltage of up to 2.4 V [18]. The latter technology refers to the asphalt pavement being embedded with piezoelectric transducers in order to harvest and convert road mechanical energy. Numerous road experts and scholars have carried out relevant research in this area. Najini and Cafiso et al. optimized piezoelectric material and used finite elements to compare the energy outputs of different transducers in the road environment [19,20]. Collin et al. systematically analyzed the feasibility of road energy harvesting and constructed an LED traffic signal guidance lamp based on piezoelectric cantilever beam transducers [21]. Jung et al. demonstrated a piezoelectric energy-harvesting module based on polyvinylidene fluoride, which exhibited instantaneous output power of up to 200 mW across 40 kΩ [22]. Wang et al. proposed a compact piezoelectric vibration energy harvester and adjusted the resonant frequency using multiple nonlinear techniques [23]. Huang et al. tested the energy output effect of stacked piezoelectric transducers under different conditions by simulating the typical road load, and the power output could reach 0.46 mW [24]. Wang et al. explored the feasibility of transducer-embedded piezoelectric power generation pavement, preliminarily studied the single piezoelectric element buried directly into the pavement and tested the energy output effect of a single piezoelectric element in a typical surface layer structure. A maximum voltage of 14 V and an effective output power of 0.44 mW were obtained [25], which lays the foundation for the research team's subsequent integration of piezoelectric transducers and the development of piezoelectric devices.

In summary, many countries have actively carried out research on developing pavement piezoelectric power generation technology. In particular, piezoelectric material composite power generation pavement technology demonstrates to have better material integrity and convenient laying process. However, its major disadvantages include complex material preparation, difficult polarization, low energy output and lacking of continuous energy supply for real-world applications. Comparing with piezoelectric material composite power generation pavement technology, the transducer-embedded pavement piezoelectric power generation technology can obtain higher and more controllable power output. Therefore, modern pavement piezoelectric power generation technology is mainly based on transducer-embedded pavement piezoelectric power generation technology. It is convenient to install the piezoelectric transducer directly into the pavement structure. However, it is facing several problems such as damaging of piezoelectric transducer unit, low reuse rate and unsatisfactory energy output. In order to improve the survival rate, reuse rate, and power output level of transducer units, research has been shifted to the development of piezoelectric devices for pavement piezoelectric power generation technology. Piezoelectric devices that have been publicized at the present stage usually depend on laboratory simulation analysis during the design process. Some piezoelectric devices have considerable energy output effects, but lack of considering environmental factors such as road coupling, waterproof, temperature insulation, durability, and array patterns. Its practicality needs to be improved.

In order to overcome the barriers of practical application of piezoelectric power generation pavement, this study designs the corresponding piezoelectric power-generation device and selects the materials based on four technical device requirements. The array pattern of the piezoelectric device is designed based on the driving characteristics. The device power response is used as the evaluation index for optimizing the detailed material configuration and confirming the transducer connection mode through rolling and loading tests. The electrical output of the 150 mm × 150 mm-type device is evaluated under typical road loading environments. It is anticipated this research can lay the foundation for gradual application of piezoelectric devices in urban roads, highways, service areas, toll stations and warning windows.

2. Design device

A transducer that is directly embedded in the pavement structure will face numerous problems, such as structural damage and difficulty in ensuring power-generation performance. Therefore, a carrier device should be developed in combination with road traffic characteristics in order to meet the application requirements of power generation pavements.

2.1. Fundamentals of piezoelectric devices

Piezoelectric device relies on the piezoelectric effect of the piezoelectric transducer for mechanic-electric conversion. At this stage, the three common types of mechanic-electric conversion modes of piezoelectric transducers are: d_{31}, d_{33}, and d_{15}. In d_{31} mode the electrical energy generated by the transducers mainly comes from horizontal compressive stress, while in d_{33} mode the electrical energy mainly comes from vertical compressive stress. In d_{15} mode it requires the transducers to obtain the effect of shear stress to generate electrical energy [26], however, it is difficult to obtain the shear stress effect in the road environment. Therefore, the d_{15} mode is rarely used piezoelectric transduction for pavements. Compared with d_{31}, the d_{33} mode has a higher piezoelectric coefficient [27]. Under the same conditions, the d_{33} mode can obtain a larger energy output and the force requirements are more in line with the road environment. Therefore, this paper mainly uses the d_{33} mode stacked piezoelectric transducers.

When piezoelectric device loaded with the piezoelectric transducers is embedded in pavement structures, vehicle loading is realized to the convert of mechanical energy into electric energy. according to various theoretical calculation methods for different connection modes. The theoretical calculation formula of transducers in series is shown as follows [28].

$$U_{os} = \frac{d_{33} F_m \omega n h R}{\sqrt{nh^2 + \omega^2 A^2 (\varepsilon_{33}^T)^2 R^2}} \tag{1}$$