THE POTENTIAL OF PIEZOELECTRIC MATERIALS REGARDING PRODUCTION OF ENERGY

MÎNTULEASA Eliza-Nicoleta, MIHAI Claudiu-Andrei, ROȘCA Bogdan,
MARINESCU Marinela Nicoleta, BUȚU Larisa

Faculty of Industrial Engineering and Robotics, Specialization Robotics, Year of study: I-st, e-mail: elizamintuleasa@gmail.com

ABSTRACT: This article presents the possibility of using piezoelectric materials to efficiently produce electric energy by capturing lost energy, such as vibrations and movement, and converting mechanical energy into electrical energy. The article explains the concept of piezoelectricity and shows how piezoelectric materials can be used in the street pavement to collect the micro-energy generated by heavy traffic. Thus, the practical implementation of this concept can lead to reducing the electricity consumption costs of a given structure. This prevents the use of piezoelectric materials as a viable solution for obtaining electric energy from alternative sources, contributing to protecting the environment and reducing energy consumption.

KEYWORDS: piezoelectric materials, piezoelectric generator, energy production, piezoelectricity, piezoelectric roads

1. Introduction

In recent decades, the interest of researchers and enthusiasts of renewable energy towards the problems related to the global energy crisis and the impact on the environment has increased significantly. As a result, the focus on developing solutions with a low environmental impact and optimal energy performance has intensified. Thus, many efforts have been made on finding a viable alternative power source to power energy production technologies. The process of harvesting or capturing energy consists in the conversion of ambient energy (mechanical, solar, thermal, wind, from the movement of fluids, etc.) into electrical energy, by means of various materials or techniques for the transmission and storage of electrical energy, for later use [2]. Research into piezoelectric materials for micro-energy harvesting is constantly developing, with several recent studies exploring new materials and technologies to improve piezoelectric performance.

The piezoelectric effect was first discovered in 1880 by French physicists Jacques Curie and Pierre Curie. Piezoelectricity is electricity generated by applying pressure. Energy harvesting from piezoelectric materials is quite well known and has been studied for the last few decades, but recently, many new advances have been made in using piezoelectric materials in order to produce electricity.

Piezoelectric energy is a type of small-scale energy harvesting based on "lost energy" such as vibration, motion, sound and heat sources. Normally, energy from moving objects, machines that produce vibrations, or other sources that produce mechanical energy is not captured, being dispersed and thus wasted. In order to efficiently use this lost energy, piezoelectric materials can be used as a means to absorb that mechanical energy and convert it into electrical energy. Piezoelectric materials play an essential role because the amount of pressure applied is directly proportional to the electrical energy generated. The practical implementation of the concept of piezoelectricity can have a significant impact, by reducing the cost of electricity consumption of a given structure [3].

In this article we want to highlight the possibility of using piezoelectric materials as a way to generate electricity with the help of increased traffic in heavily populated areas. Incorporating piezoelectric materials into pavements could lead to higher efficiency when it comes to micro-energy harvesting.

2. The concept of piezoelectricity

By definition, the piezoelectric effect is the electric charge that accumulates in certain solid materials under the action of mechanical stress. Applying a strain to a piezoelectric material causes a voltage to appear between the electrodes. Piezoelectric materials can be configured so that the mechanical stress is perpendicular or parallel to the electrodes. As a result of compressive and tensile forces, stresses of opposite polarity can be produced, proportional to the applied force [3].

The piezoelectric effect converts mechanical stress into electrical stress. In general, there are two effects that manifest piezoelectricity, namely the direct piezoelectric effect and the reverse piezoelectric effect. When it comes to the direct piezoelectric effect, materials have the ability to convert mechanical stress into electrical charge (these materials can be used as sensors or energy transducers), while in the reverse piezoelectric effect, materials have the ability to convert an applied electrical charge into voltage energy mechanics. The direct and inverse piezoelectric effects can be mathematically expressed by two linearized equations [1,3].

The direct piezoelectric effect:

$$D_i = e_{ij}^{\sigma} E_j + d_{im}^{d} \sigma_m \tag{1}$$

The reverse piezoelectric effect:

$$\varepsilon_k = d_{jk}^{c} E_j + S_{km}^{E} \sigma_m \tag{2}$$

In these equasions Di is the dielectric displacement, measured in N/mV or C/$m2$ and εk is the stress/solicitation vector. Ej represents the electric field applied in volts per meter and σm is the tension expressed in N/$m2$. The piezoelectric constants are piezoelectric coefficients d_{im}^{d} and d_{jk}^{c}, measured in m/V or C/N, the permittivity of dielectric materials e_{ij}^{σ} in N/$V2$ or F/m, while S_{km}^{E} represents the elastic compliance of said materials, measure in $m2$/N. The exponents c and d denote the reversed effects, respectively direct and the exponents σ and E highlight the subjection of the coefficients to continuous stress and to a continuous electric field respectively.

2.1. Piezoelectric materials

Piezoelectric materials are a type of materials with unique properties that allow them to convert mechanical energy into electrical energy and vice versa, making them valuable in a wide range of technological applications. Some materials exhibit piezoelectric properties, including synthetic and natural materials such as natural crystals, ceramics, or synthetic crystals, piezoceramics, polymers, and organic nanostructures. They are divided into three categories according to their structural characteristics: inorganic piezoelectric materials, bio-piezoelectric materials, and piezoelectric polymers.

Inorganic piezoelectric materials can be divided into ceramics and single crystals. These ceramics are composed of small, irregular collective grains, and piezoelectricity occurs when a large electric field is applied to align the orientations of the crystals in a polarization process. Piezoelectric crystals, such as quartz film and ZnO, have a simple crystal structure and exhibit natural piezoelectricity. The stability and mechanical quality factor of quartz crystals are relatively higher than that of ceramics.

Bio-piezoelectric matter consists of some microorganisms and biological tissues such as silk, bones and certain viruses.

In comparison to inorganic piezoelectric materials, a piezoelectric polymer such as PVDF can carry a much higher load due to its intrinsic flexibility, having a lower electromechanical coupling constant than that of inorganic piezoelectric materials. However, the piezoelectric strain constant of piezoelectric polymer is relatively small, which has limited its application in transducers [1].

3. The concept of energy production utilizing piezoelectic materials

Energy recovery by means of piezoelectric materials represents a promising field of research, based on the ability of these materials to transform mechanical energy into electrical energy. This transformation is achieved by means of piezoelectric converters, which are composed of thin plates or piezoelectric crystals, subjected to mechanical deformation. The generated electrical voltage can be stored in batteries or other storage devices, having a variety of practical applications. These include powering monitoring and measurement devices in environments where an electrical power source is not available, powering sensors and smart devices for health and environmental monitoring.

One area of research where this technology is especially promising is harvesting energy from road traffic. The vibrations generated by vehicles traveling on the roads can be converted into electricity by means of piezoelectric plates, without using fossil fuels and without producing harmful emissions to the environment. This electricity could be used to power traffic lights, billboards and other roadside devices.

Global research has evaluated the performance of different types of piezoelectric materials, conversion technologies, and strategies to improve system efficiency and reliability. These studies aimed to identify current trends, challenges and opportunities in this field [3,6,7].

4. The operating principle of piezoelectric generators embedded in asphalt

A study by Najini et al. presents various analyses of existing piezoelectric elements and shows why PZT-5H is the most adaptable material in the process of power generation with the help of road traffic. The article presents two ways of implementation, one of which is in direct correlation with our own research, an implementation based on embedding piezoelectric transducers in asphalt to produce energy directly, with the help of vehicles (Fig. 1).

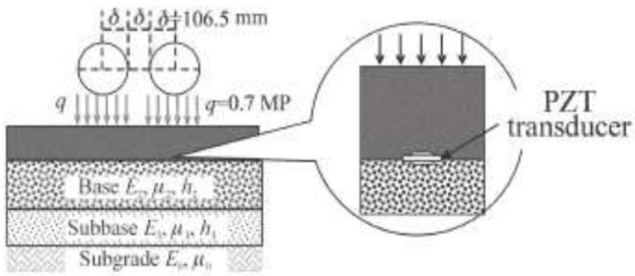

Fig. 1. The transducer's placement in the asphalt [7]

While the piezoelectric effect is observed in various materials such as quartz, tourmaline and Rochelle salt, synthesized polycrystalline ferroelectric materials usually produce more electricity [7]. Therefore, Najini et al. used lead zirconium titanate (PZT) because it is the most robust commercially produced crystal compared to naturally occurring crystals. They have found PZT-5H (a ceramic material) to be the most suitable element of used in the process of energy recovery by the piezoelectric method (Fig. 2).

This ceramic exhibits increased tolerance to applied pressure with high piezoelectric properties. Thus, the properties presented in the study denote it as the most viable option for conducting research by introducing piezoelectric transducers into the pavement surface.

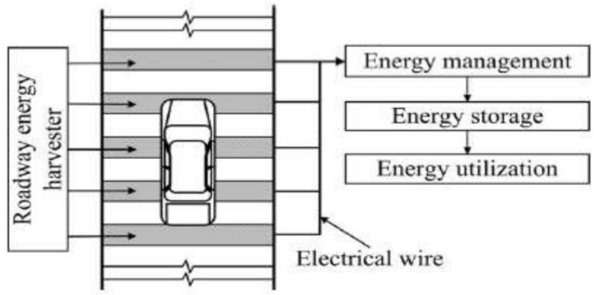

Fig. 2. Overview of the piezoelectric generator's placement [7]

The work of Yang et al. put this concept into practice, aiming to design a piezoelectric energy generator (PEH) for use in pavement and asphalt, with the goal of creating a sustainable and reliable energy source that can withstand the millions or billions of load cycles that it will experience during its lifetime. The PEH was designed to be 30 cm x 30 cm with a thickness of 8 cm and contains 12 piezoelectric units, an internal rectification circuit and two cables for the electric current. The core component of the PEH is the PZT-5H piezoelectric ceramic, with three strips overlapped and connected in parallel to form each unit. The protective structure of the PEH includes three layers: an upper layer that directly supports the vehicle load, an intermediate layer that contains the piezoelectric units, and a lower layer that withstands the ground reaction force. The intermediate layer also includes channels for the wires and the internal circuit board, as well as holes for the piezoelectric units.

After connecting the piezoelectric units to the circuit board, the generated power is drawn by the cables. The rectifier bridge is sealed with electronic glue to prevent water leakage and short circuit. This design ensures that PEH will have fatigue resistance, waterproofing and a good performance when subjected to compression (Fig. 3). During installation in the previously prepared pavement, the PEH positions were recorded and marked to facilitate the core extraction process. The process involves cutting the pavement, creating PEH pits and wire slots, levelling the bottom of the pits, installing the PEH, placing the wires along the slots, and filling the joints with modified asphalt mixed with diatomite [6].

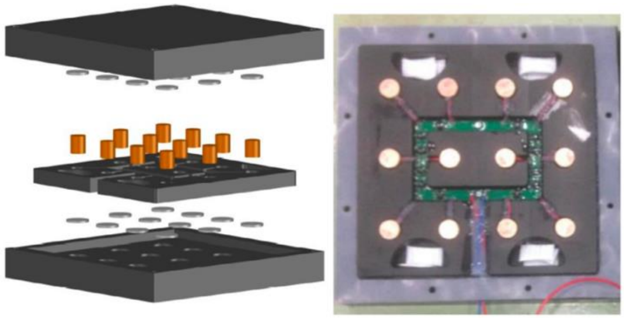

Fig. 3. The interior structure of the PEH [6]

In practice, the generators made by Yang et al. were tested by installing twenty of them on a section of about 50 meters long in the Ma-Zhao highway (Yunnan Province) and evaluating the performance under the action of real traffic (Fig. 4.). The test results concluded that the generator had an excellent performance in producing electricity with an open circuit voltage of more than 250 V under real road traffic conditions. The output voltage of the generator increased with the speed of the vehicle, thus providing a reliable solution for supplying electricity to street lighting. The electrical energy generated by the vehicles was supplied to the road facilities, the solution being in accordance with the concept of sustainable development [6].

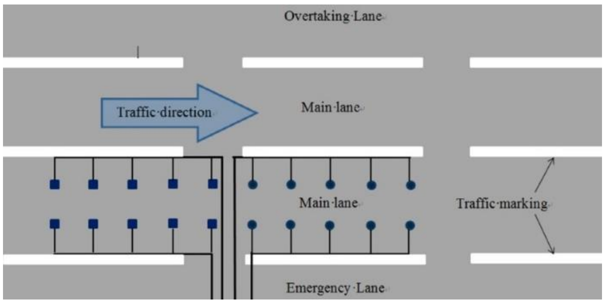

Fig. 4. The mounting area of the piezoelectric generators [6]

Another such trial was carried out by Nyamayoka et al, who analyzed the feasibility of using a piezoelectric generator on the N1 highway in South Africa (specifically at the Pumulani Plaza toll station). Various parameters such as vehicle mass, axle load and rolling resistance force were considered in the study to estimate the average power output of the generator (Fig. 5.). The generated mechanical energy, energy conversion efficiency and charging time are also calculated. According to the study, the total average electrical energy generated by a piezoelectric generator on the N1 highway would be 1.576587613 kWh. This energy can be used to power six High Pressure Sodium (HPS) streetlights for one hour. The article also discusses the need for an energy storage system to be able to store the energy generated during the day [3].

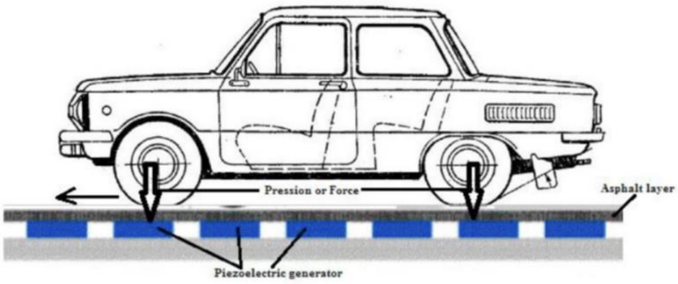

Fig. 5. Method of testing the piezoelectric generators [3]

5. The advantages and disadvantages of using piezoelectric materials for energy harvesting

The use of piezoelectric materials for energy harvesting is a technology that possesses advantages such as long lifespan, high reliability, and relatively low installation costs. They can be used in various applications, such as harvesting energy from traffic, human movement or the vibrations of machinery and industrial equipment. However, their use may be limited by the size and shape of piezoelectric devices, sensitivity to vibration frequency, ambient temperature, and data security issues. Research in this field and the development of new materials and technologies can help overcome these obstacles and improve the performance of piezoelectric materials for energy harvesting [4,5]. Combining piezoelectric converters with other energy harvesting technologies, such as solar cells and wind generators, can increase efficiency and ensure a constant supply of electricity.

In terms of energy harvesting from traffic, there is significant progress in the development of piezoelectric converters, but there are still challenges to be overcome. The high cost of piezoelectric materials and conversion technologies may be a major obstacle to their large-scale implementation, but researchers continue to work on developing new materials and more efficient production technologies to reduce costs and make the technology more accessible [4 ,5].

6. Conclusions

In conclusion, piezoelectric materials are a promising option for energy harvesting due to their advantages such as long lifespan, high performance, and relatively low installation costs. However, the use of piezoelectric transducers in practical applications faces several challenges, including relatively low efficiency and sensitivity to external factors such as vibration frequency and ambient temperature.

Current and future research in this area could help overcome these obstacles and develop more efficient and versatile piezoelectric transducers that can be used in a wide range of applications. In particular, the development of new materials and advanced manufacturing technologies, together with the integration of piezoelectric converters into multiple energy harvesting systems.

Finally, energy harvesting with piezoelectric materials is an important component of current efforts to develop renewable technologies and reduce dependence on fossil energy sources. Although further research and development is still needed in this area, it is clear that piezoelectric materials have significant potential in this regard and deserve to be considered as an important option for the future of energy harvesting.

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