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A mathematical model for piezoelectric ring energy harvesting technology from vehicle tires

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ABSTRACT

A theoretical model for a dual-mass piezoelectric ring tire harvester is developed by an iteration method to determine the energy harvested from excitations of vehicle tires by rough roads. The piezoelectric ring harvester is made of a series of discrete PZT4 patches in a square shape circumferentially embedded in a polymer ring evenly. The harvester is placed between two the steel belts tightly pasted in the inner liner of tires for the harvesting process. The influences of some practical considerations, such as the central angle θ of the tire sector to measure the contact section of a tire, the width of patches, the number of piezoelectric patches in the direction of the tire width, the thickness of patches, the radius of the piezoelectric ring, the speed of a vehicle and the road roughness, on the root mean square of the generated electric power are discussed. The results show that a power up to 42.08 W can be realized from a harvester with the central angle of θ, the radius of the piezoelectric ring, the width, the thickness, and the number of the PZT4 patch in the direction of the tire width being 30°, 0.25 m, 0.01 m, 0.01 m and 3, respectively. The research on the theoretical model develops a novel technique for an efficient and practical energy harvesting from vehicle tires.

1. Introduction

Intelligent tires that have abilities of monitoring forces at the tire-road interface, the contact patch length, the friction coefficient, the slip angle, the road condition, and the tire wear in real time, have been developed to avoid traffic accidents. Anti-lock Brake System (ABS) and Electronic Stability Program (ESP) have been developed to enhance the stability of vehicles. A wirelessly interrogated passive surface acoustic wave (SAW) sensor for measurements of the torque, speed of revolution on transmission shafts, and air pressure in tires was introduced (Pohl & Steindl, 1997; Pohl, Steindl, & Reindl,1999). Erdogan, Alexander, and Rajamani (2011) proposed a novel wireless piezoelectric tire sensor inside a tire that can provide good estimation of both slip angle and tire-road friction coefficient through decoupling of the lateral carcass deformations from the radial and tangential deformations. The Yokohama Rubber Co., Ltd. (2005) announced the development of its Intelligent Tire Pressure Monitoring System (Intelligent TPMS), which not only gauges the air pressure of tires, but also accurately identifies road conditions and tire motion across the road surface. All these sensors equipped in all vehicles are expected to improve safety and reliability of tires and also improve the performance of vehicle control systems.

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However, sensors in a tire require sufficient power to function all the measurements. For example, when applying wireless sensor nodes with battery powered inside tires, a sensor has to be retrieved and the battery has to be replaced after the battery is drained of all its power. However, it is noted that the battery replacement is not feasible, especially for a remote placement of these devices within the tire carcass. Hence, although batteries are able to provide a stable voltage supply, their limited total energy availability, temperature dependency and relatively short life span call for a challenge in developing new science and technology of energy harvesting to provide feasible power for electronic components of sensors. Nowadays, a number of novel energy harvesting systems have been proposed for the purpose. Harvesting vibrations or strain energy of tires to power the sensing and wireless communication devices is one of the important research areas. The high vibration or strain level inside a tire has a potential to generate electrical power based on energy harvesting techniques.

Galchev, Kim, and Najafi (2009) provided a fabrication and testing of a miniature electromagnetic inertial power generator for scavenging low-frequency non-periodic vibrations. The fabricated device generated a peak power of 288 μW and an average power of 5.8 μW from an input acceleration of 9.8 m/s^2 at 10 Hz. Lee, Kimi, Oh, and Choi (2012) presented a piezoelectric composite energy harvester attached to the inner of a tire to transfer the longitudinal tire strain into the electric power. The harvester ($60 \times 10 \times 0.3$ mm) can generate a power density of 1.37 μW/mm^3 to supply a wireless sensor. Hatipoglua and Urey (2009) developed a FR4-based electromagnetic energy harvester to scavenge mechanical vibrations in tires due to tire-road contact for wireless tire sensor nodes. A power of 0.4 mW was obtained by using tangential acceleration waveforms of the typical tire rotation for an amplitude of 15 g peak-to-peak at 22.83 Hz. Manla, White, and John (2012) proposed a non-contact piezoelectric energy harvester to generate power from magnetic forces owing to the effect of the centripetal force. An output power ranging from 0.2 μW to 3.5 μW can be generated when the rotating speed changes from 3 rps to 5.55 rps through a prototype with an off-axis distance of 75 mm, a volume of approximately 17.74 cm^3, and a weight of 46 g. Singh, Bedekar, Taheri, and Priya (2012) presented an onboard vibration energy harvesting system for a tire. The harvester element is a bimorph piezoelectric cantilever with a proof mass fixed on the harvester casing, which is disposed on the inner liner of the tire, along a plane orthogonal to the radial direction. The bimorph energy harvester with a tip mass of 11.45 g can generate a maximum power of 15 μw and 31 μw with a root mean square of radial excitation acceleration of 0.4 g at frequencies of 62.5 Hz and 80 Hz, respectively.

The tire harvesters mentioned above can be classified into three main categories: (1) harvesters with piezoelectric composite patches attached to the inner liner of a tire to transfer the longitudinal tire strain into electric power; (2) electromagnetic energy harvester to scavenge mechanical vibrations in tires owing to the steep leap of the tangential acceleration during the contact of tires on roads, and (3) harvesters with piezoelectric beams fixed on a tube or a casing to absorb vibration energy caused by the change of the radial acceleration of tires. The aforementioned researches are mainly on practical realizations of harvesting systems but lack fundamental and theoretical framework of the energy harvesting process of the piezoelectric technology for a better scientific understanding of the harvesters in designs. Especially, a scientific description and model for the harvesting process by piezoelectric materials from tire radial excitements caused by rough roads has been unavailable. In addition, the above-mentioned energy harvesters usually have a little volume to avoid dynamic imbalance of the highly rotating tires caused by the centrifugal force of the harvesters fixed in inner tire. Hence the power generated by these harvesters is only in a range of μW. Besides, these applications only use electromagnetic effect or the "31 mode" in piezoelectric transductions to generate electric powers. In fact, it is well known that in mostly available vibration-to-electric conversion mechanisms, the energy density of the piezoelectric transduction is three times higher than that of the electromagnetic and electrostatic transductions (Priya, 2007; Williams & Yates, 1996). Piezoelectric materials possess both a "31 mode" and a "33 mode". The "31 mode" suffers from lower efficiency because the piezoelectric charge coefficient and coupling factor are low. In contrast, the "33 mode" exhibits superior material characteristics.

Piezoelectric generators with an optimal design based a fundamental and scientific modeling can produce electric power at watt and even kilowatt. Many research works have been conducted on applications of piezoelectric materials for energy conversion from ambient environmental vibrations (Wang & Quek, 2000; Wang & Quek, 2002; Wang, Quek, Sun, & Liu, 2001; Wang & Wang, 2000). Xie, Wu, Yuen, and Wang (2013) introduced an optimal design based on a newly proposed model of a piezoelectric coupled cantilever structure with a proof mass to achieve a higher efficient energy harvesting from high-level buildings. Xie, Wang, and Wu (2014b, 2014c) introduced sea wave piezoelectric energy harvesters to harvest electric energy from longitudinal or transverse wave motions of water particles. Their results show that the harvesters can generate a power up to 55 W and 30 W for a practical longitudinal and transverse wave motions, respectively. Xie, Wang, and Wu (2014a) developed a ring piezoelectric energy harvester excited by magnetic forces and found that a power up to 5274.8 W can be realized for a harvester with a radius around 0.5 m. The above researches show that applications of piezoelectric harvesters can generate up to thousands of watts of electric power by absorbing ambient vibration energy if a scientific model can be developed, verified, and applied in designs of the newly proposed harvesters.

It is hence expected to develop a mathematical model for building a novel technique for an efficient and practical energy harvesting from vehicle tires. The new piezoelectric ring technique is proposed to generate electricity by using the "33 mode" to fully absorb the tire radial excitements from road surfaces and avoid dynamic imbalance of the highly rotating tires to main their central symmetry even if they have a large volume. Correspondingly, a dual-mall piezoelectric ring tire harvester would be introduced to provide sufficient power to electronic components of sensors in vehicles, and the harvested power is from the tire excitations from rough roads for a more efficient energy harvesting rather than the techniques discussed before that only benefit the strain energy or mechanical vibration in limited tire area in harvesting.