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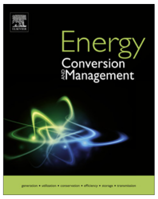

Development of a piezoelectric energy harvesting system for implementing wireless sensors on the tires

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ABSTRACT

The need for energy harvesting technology is steadily growing in the field of self-powered wireless sensor systems for intelligent tires. The purpose of this study is to mount an energy harvester inside the tire. In order to achieve this, we focus on a stable energy source almost independent of vehicle speed. It is ascertained that the use of a strain field is suitable for this purpose. In order to develop the energy harvester for the tire, modeling of tire behavior has been performed and verified through comparing with experimental results. From the results, a piezoelectric energy harvester generates 380.2 μJ per revolution under 500 kgf load and 60 km/h. A self-powered wireless sensor system is manufactured for application and tested during vehicle driving. The result of this study presents 1.37 $\mu W/mm^3$ of power generation from the performance of the energy harvester. This study concludes that the system is applicable to wireless tire sensor systems after making minor improvements.

1. Introduction

With the growth and advancement of the auto industry, customers are focusing more on safety and less on the design and performance of cars. The active safety systems such as ABS (Anti-lock Brake System) and ESP (Electronic Stability Program) have been developed in order to enhance the stability of vehicles. With the enhancement of stability, the information on the unstable braking distance by the variation of the coefficient of friction between the tire and the road according to road conditions is a critical issue because variations in braking distance cause accidents [1]. Tires are the most important components in driving safety because they directly contact the outside world and obtain quick responses from it. The necessity of the sensor mounted on the tire is gradually increasing. Before such a system can be implemented, however, a wireless sensor system must first be developed to receive the sensor signal from the rotating wheel of the tire. Passive type sensors such as SAW sensor and LC resonant sensor do not need any power source for sensing and wireless communication [2], but need an acquisition system separately because of limitation of usable range. However, commercial active type sensors can reduce the limitation of it and thus, do not need the signal acquisition system. Instead, if commercial active type sensors are applied inside the tire, a power source such as battery for the wireless system must be secured. Batteries are currently used, but they are limited in utilization time. Therefore, the main bulk of research is centered on energy harvesting technology to replace batteries in the general system using active devices. This technology focuses on converting otherwise wasted mechanical energy from the surroundings to useful electrical energy. The transformation mechanisms based on the variations of accelerations and strains utilize electromagnetic induction with permanent magnets and coils, capacitance, or piezoelectric materials. Also, thermoelectric devices with thermal gradients are commonly used in energy harvesting [3–8]. The energy harvesting technologies for the application of tires to date are listed in Table 1 [9–12].

The energy harvesting technologies applicable to tires for wireless sensor systems are classified into an acceleration type and a deformation energy type. The main factors for the power generation with the acceleration type are the amplitude of acceleration and the tip mass of a cantilever [9,10,13]. The kinetic energy from the contact between the tires and the road causes the amplitude of acceleration, which is dependent on the velocity of the car. The tip mass of a cantilever is limited to a certain range because of the structural stability due to the centrifugal load. As far as the deformation energy type is concerned, it is affected less by velocity than the acceleration type because electrical charges are generated proportional to the applied strain. However, since the deformation of the tire is large, the mechanical elasticity of the material should be large enough.

This paper presents a self-powered system for measuring the power directly from the tire, which supplies the wireless sensor system mounted inside the tire. The system should ensure

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Table 1
The energy harvesting technologies for the application of tires to date.

Mechanical energy	Conversion mechanism	Critical points and requirement
• Rotation in gravitational field • Vibration	• Piezoelectricity • Electro magnetic converter • Electro static converter	• Necessary to tune resonant frequency • Require overload protection when adopting beam mass model • Difficult to meet requirements of system because of random frequency during driving ➔Robust Design for Beam structure
• Acceleration peaks	• Piezoelectricity • Electro magnetic converter • Electro static converter	• Require overload protection when adopting beam mass model • Applicable to electromagnetic mechanism using spring-mass structure with sufficient energy sources ➔Robust Design of moving parts
• Tire bending	• Piezoelectricity for interdigitated electrodes with transmission of forces	• Overload protection difficult • Necessary for mechanical resistive material ➔Flexible piezo material

performance with lower velocity driving and structural stability with higher velocity driving. Most notably, a non-resonant energy source has been established in order to maintain the high generating efficiency during lower velocity driving [14]. Also, the modeling of energy transduction for the transformation energy of the tire has been executed. Finally, the calculations from modeling were compared to the results from experiments for the verification and the applicability of the proposed energy harvesting system.

2. Theory of the energy generated from piezoelectric energy harvester

The energy harvester proposed here uses the vertical deformation from the car weight and innerliner deformation while driving. The piezoelectric composite, which contains fibers, has been utilized as a material for the transduction of mechanical energy into electrical energy. The mechanism for energy transduction using a piezoelectric material is as follows: Deformation in the piezoelectric material by the applied external force causes a change in charge distribution, thereby inducing a potential difference due to poling at both ends of the piezoelectric material. The piezoelectric material possesses the 31 mode of transduction in which the direction of the applied load is perpendicular to that of the electric field. Alternatively, the 33 mode of transduction is a condition in which the direction of the load applied is the same as that of the electric field [15]. Therefore, the 31 mode condition is generally used for bending a cantilever, and the 33 mode is applied in cases of direct loading, such as during impact. 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.

There are PVDF and PZT ceramic for patch type piezoelectric materials, attachable to interliner of the tire. PVDF, one of the flexible piezoelectric materials, is applicable, but it has lower piezoelectric charge coefficient and durability. PZT ceramic is fragile. However, PZT becomes flexible if it is made of a thin, thread-type ceramic. The material properties of the piezoelectric composite for this study are listed in Table 2 [16]. Piezoelectric composite is a stripe type material with a good characteristic of 33 mode of transduction, which is flexible rather than brittle. The piezoelectric material has a polarity generated by poling as mentioned above. The piezoelectric energy harvester used in this study is composed of the piezoelectric composite with interdigitated electrodes and substrate as shown in Fig. 1. Material properties and dimensions have an effect on the power generated from the piezoelectric energy harvester. The electric field occurred from an external deformation in piezoelectric material is defined as Eq. (1) [17].

$$E = d/(\varepsilon^T s^D)S \tag{1}$$

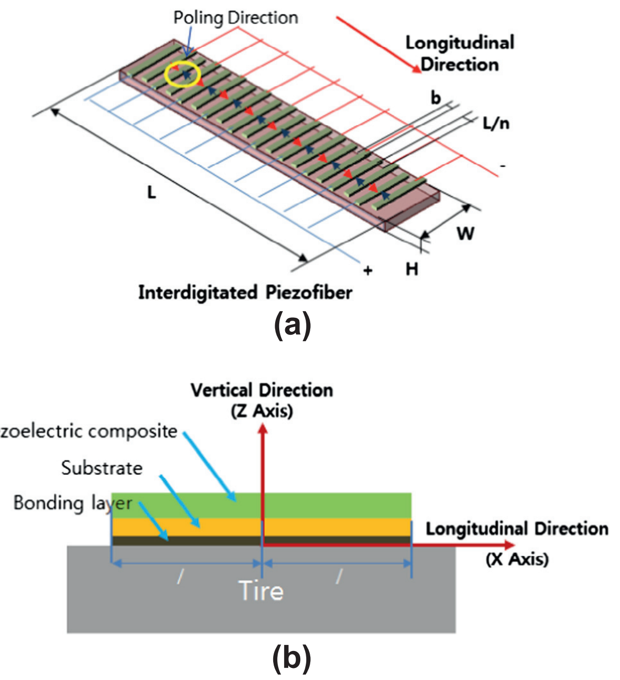
where E, d, ε, s, and S are electric field strength, piezoelectric charge constant, permittivity, compliance, strain, respectively. In addition, the charge generated from the 33 mode of transduction of the piezoelectric composite is represented as Eq. (2) [18].

$$\begin{aligned} Q_{Gen} &= \frac{\partial}{\partial V}\int\int\left(-d_{33}\sigma_3\frac{Vn}{L}\right)dxdA = -d_{33}Y_{33}\frac{WHn}{L}\int S_3dx \\ &= -d_{33}Y_{33}WHnS_3 \end{aligned} \tag{2}$$

Eq. (2) is expressed in terms of the piezoelectric charge coefficient (d_{33}), Young's modulus (Y_{33}), the width of piezoelectric material (W), height (H), the number of unit cells (n), and strain (S_3). With the above mentioned static modeling for the piezoelectric

Table 2
The material properties of piezoelectric composite.

Property	Value
Pizoelectric charge coefficient, d33@1 kV[pC/N]	550
Electromechanical coupling factor, k33	0.67
Elastic compliance, [10–12 m^2/N]	41
Yield strength[Mpa]	157.3



L : length of piezoelectric composite
W : width of piezoelectric composite
H : height piezoelectric composite
b : length of electrode
n : number of piezoelectric cell

Fig. 1. The piezoelectrical composite with interdigitated electrodes (a) and the concept of a piezoelectric energy harvester (b).