International Journal of Automotive Technology, Vol. 13, No. 6, pp. 963−969 (2012)
DOI 10.1007/s12239−012−0098−0

pISSN 1229−9138/ eISSN 1976-3832

A SELF-POWERING SYSTEM BASED ON TIRE DEFORMATION DURING DRIVING

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(Received 23 July 2011; Revised 17 July 2012; Accepted 17 July 2012)

ABSTRACT−Tire intelligence is vital in the improvement of the safety of vehicles because the tire supports the car body and is the contact point between the vehicle and the road. To create an intelligent tire, sensors must be installed to measure the behavior of the tire. However, it is difficult to apply a wired sensor system on the wheel of the tire. Hence, it is necessary to implement a self-powering, wireless system (a type of energy harvesting system) that can be mounted inside the tire. The purpose of this study is to convert the strain energy caused by deformation of the tire while driving into useful electrical energy to supply the sensor system. A flexible piezofiber is utilized for the energy conversion. The variation in strain, due to changes in speed, load, and the internal pressure of the tire, was measured along two axial directions to evaluate the amount of available strain energy. The amount of strain changed from 0.15% to 0.8%. To predict the amount of available energy from a tire, we perform an analysis of the relationship between the strain and the voltage. In addition, experiments for impedance matching between piezofiber and related circuits were conducted to optimize the external loads for transferring energy efficiently. Based on the procedure mentioned above, at least 0.58 mJ of electrical energy can be generated by using the laterally oriented strain (1500 to 2500 micro strain). The result of this study is expected to enhance the potential realization of self-generating wireless sensor systems for so-called "intelligent" tires.

KEY WORDS : Energy harvesting, Piezoelectric, Strain energy, Intelligent tire, Deformation

1. INTRODUCTION

The growth and advancement of the auto industry are prompting customers to focus more on safety and less on the design and performance of cars. Technologies such as ABS (Anti-lock Brake System) and ESP (Electronic Stability Program) have been developed to enhance the stability of vehicles. In addition, information on the unstable braking distance as a function of the variation of the coefficient of friction between the tire and the road under different road conditions is critical because variations in the braking distance cause accidents. Therefore, it is clear that tires are at the core of many safety issues. The rather large effect of tire conditions on fuel efficiency and vehicle safety are largely responsible for the widespread installation of TPMS (Tire Pressure Monitoring System) for continuous monitoring of tire pressure is in the USA. TPMS gives the driver the ability to recognize abnormal conditions of the vehicle by providing information on tire pressure.

In the near future, the technology for improving driving stability will provide information not only on the condition of the tire itself but also the variation in the coefficient of friction with the road. Tires are the most important components in driving safety because they directly contact the outside world and respond quickly to it. According to an experimental report by Yokohama Rubber Company, the response from a tire-mounted sensor was 0.25 sec faster than that from a sensor mounted separately on the vehicle. (The Yokohama Rubber Co., 2005) While the need for tire-mounted sensors is gradually increasing, one must first develop a wireless system to receive the sensor signal from the rotating wheel of the tire. A power source for the wireless system must also be secured: batteries are currently used, but they have limited operation time. Therefore, recent research has focused on SAW (Surface Acoustic Wave), a passive device, to solve the problem of the power source for such sensors. (Pohl *et al*., 1999). However, the main bulk of research on this topic is centered on energy harvesting technologies for replaceable batteries in general systems using active devices. For example, the Apollo project in the EU has performed a study on the generation of energy with PVDF (polyvinylidene fluoride) and on the application of electromagnetic induction on energy generation (The Apollo Consortium, 2005).

This paper presents a self-powering system that supplies tire-mounted sensors with power. In other words, we describe a system in which the mechanical energy generated by deformation of the tire during driving is transformed into electrical energy through piezoelectric

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**Corresponding author.* e-mail: bkchoi@sogang.ac.kr energy transduction. The piezoelectric material produces an electric potential difference due to external loads, which then forces electrons to move. The amplitude of the potential gap and the number of charges is a function of the number of loads. These variables have an effect on the electrical energy produced. An energy harvesting module with a piezoelectric material is attached to the inner lining of the tire, as it is necessary to measure the strain of the tire while driving under various conditions. This information enables one to predict the energy gathered by the energy harvester. In this study, we measure the tire strain and elucidate the relationship between strain and voltage.

2. MEASUREMENTS FOR THE BEHAVIOR OF THE TIRE DURING DRIVING

Periodically, the tire is greatly deformed during driving due to contact with the road. Even though the amount of deformation changes according to the various driving speeds, loads, and tire pressures, the periodic strain energy generated remains a suitable source of energy for self-powering. As a starting point, the amount of deformation was measured in a tire test rig with a wireless strain gauge system for various driving conditions.

2.1. Tire Test Rig and Experiment Setup

Figure 1 shows the test rig for measuring the characteristics of a tire in motion and the wireless strain gauge used for the experiment.

2.1.1. Tire test rig

The tire test rig used for the experiment is able to mount a pair of commercial tires with wheels and an applied load of up to 1200 kgf. The size of the mounted tires varies. In addition, it can handle a speed of revolution up to 800 rpm, corresponding to a car speed of approximately 120 km/h. The tire test rig allows one to simulate the behavior of the tire during driving and is designed for use with a pair of tires of the same size for ensured contact with the road.


(a) (b)

Figure 1. Tire test rig for measuring the characteristics of a tire in motion (a) and the strain gauge installed on the inner liner of the tire (b).

(a) (b)

Figure 2. Schematic of the measurement system (a) and a photo of the actual system (b).

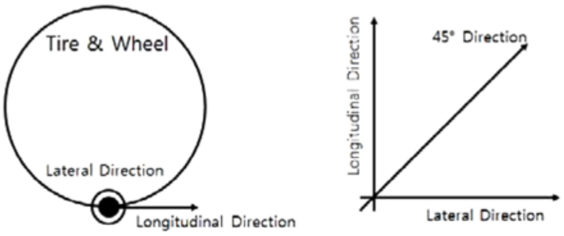


Figure 3. Schematic of the directional strain gauges installed on the tire.

2.1.2. Strain gauge-based measurement system

We adopted a wireless strain gauge system because it is impossible to perform tests with a wired system during driving. Bluetooth was utilized for the data transmission and powered by a battery. The wireless measurement system was mounted on the wheel and fixed in place with 5 bolts. The data acquisition system mounted on the wheel received the signals generated from the strain gauge inside the tire. This signal could be sent to a monitor with a remote. Figure 2 shows a schematic of the measurement system and a photo of the actual system.

2.2. Measurement of Tire Behavior

The experiment for measuring the behavior of the tire was conducted with the strain gauges attached both laterally and longitudinally to the inside of the tire. The tire utilized for the measurement was a commercially available tire (Kumho Co., 235/60 R18). The strain gauges were for a plastic range with 15% of elongation.

Figure 3 shows a schematic of the directional strain gauges installed on the tire. Because many unexpected variables arise during driving, a pre-test that assumed linear road driving was performed before measuring the various variables (e.g., road condition, turning, loading, etc.).

Table 1 lists the conditions for the performed experiments. There were 24 conditions with 2 pressures, 3 rotating speeds, and 4 loads. Figure 4 shows the measured results for a 34 psi pressure, a 500 kgf load, and a 300 rpm rotating speed (approximately 41 km/h). As seen in the figure, both tension and compression occur when the tire contacts the road. The longitudinal strain is larger than the lateral strain, and the strain for the direction at 45° is the

Table 1. Conditions for the experiment of the behavior of tire.

Pressure	Rotating speed	Load
34 psi	100 rpm	100 kgf
22 psi	200 rpm	200 kgf
	300 rpm	300 kgf
		500 kgf

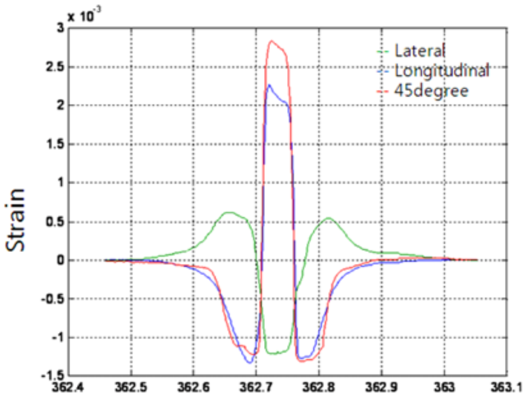
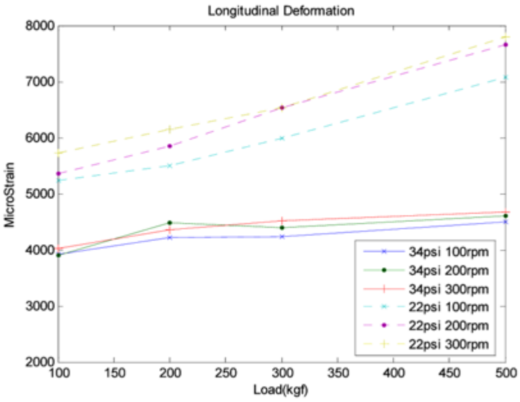


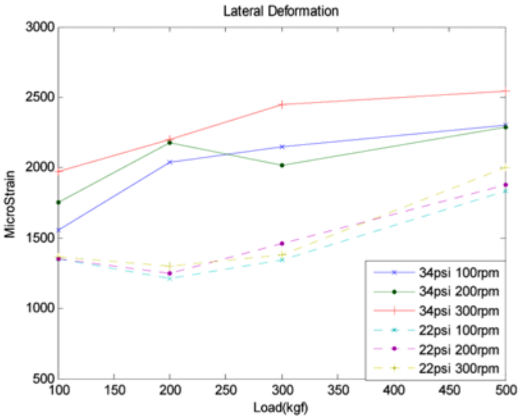
Figure 4. Experimental strain results from an experiment with a 34 psi pressure, 500 kgf load, and 300 rpm rotating speed (approximately 41 km/h).

maximum strain value.

Figure 5 shows the measured results for various conditions. It is noteworthy that the total amount of strain increases as the load applied to the tire increases. It also increases slightly as the speed increases, but the speed does not have much effect on it. The internal pressure affects the strain generated on the tire. For constant internal pressure, the longitudinal strain increases as the applied load increases. However, the increase in rate is different depending on the pressure condition. For low-level internal pressures (22 psi), the lateral strain slowly increases with the applied load but with some variability. Conversely, for normal pressure levels (34 psi), the lateral strain increases with the applied load, but the rate of increase is almost independent of the internal pressure. In addition, the magnitude of the generated lateral strain is generally smaller than that of the longitudinal strain. These measurements lead to the continuous generation of strains in the tire along various directions, enabling the tire itself to serve as a source of energy for the sensor system.



(a) Longitudinal strain



(b) Lateral strain

Figure 5. Measured strains for various conditions (unit: micro strain).

3. THEORY AND EXPERIMENTAL VERIFICATION OF ENERGY CONVERSION FOR A SELF-POWERING SYSTEM

A medium for the transduction of mechanical energy into electrical energy is required to create the self-powering system. Generally, a piezoelectric material is utilized for this transduction (Ciam *et al*., 2008). The mechanism for energy transduction using a piezoelectric material is as follows: the strain generated in the piezoelectric material by the applied external force breaks the equilibrium of the dipole, thereby inducing a potential difference due to poling at both ends of the piezoelectric material. The piezoelectric material possesses a “31 mode” in which the direction of the applied load is perpendicular to that of the electric field. Alternatively, the “33 mode” is a condition where the direction of the load applied is the same as that of the electric field. 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.

Piezofiber is a special material that makes use of the characteristics mentioned above. Piezofiber is favorable because it takes advantage of the material characteristics of both the 33 mode and the 31 mode. For a cantilever or spring–mass system based on vibration energy, the

Table 2. Material properties of the piezofiber (www.advancedcerametrics.com).

Property	Value
Dimensions [mm]	132 × 14 × 0.3
Pizoelectric charge coefficient, d_{33}@1kV[pC/N]	550
Electromechanical coupling factor, k_{33}	0.67
Elastic compliance, s_{33}^{E} [10^{-12} m^2/N]	41
Yield strength [Mpa]	157.3
Blocking force, F@1kV[N]	1.0

Table 3. Characteristics of the piezofiber and PVDF (Swallow *et al*., 2008).

	Piezofiber	PVDF
Piezoelectric charge coefficient [pC/N](d_{33})	550	33
Relative dielectric constant	495	12
Young's modulus [10^{10}N/m]	2.44	0.25

maximum deformation at resonance is normally applied for energy transduction (Chang and El-gindy, 2005). However, for the tire system proposed in this study, a flexible material attachable to the surface inside the tire via patch is easier to utilize than vibrational energy. Hence, while the Apollo consortium made use of PVDF, our team used piezofiber, which possesses a better piezoelectric coefficient. While ceramic PZTs are typically fragile, which may be problematic for external loads, piezofiber is very flexible because it is made of a thin, thread-type ceramic. The material properties of the piezofiber for this study are listed in Table 2. Table 3 lists a comparison of the characteristics for piezofiber and PVDF.

3.1. Theory of the Energy Transduction of the Self-powering System

The piezoelectric material has a polarity generated by poling, as mentioned above. The piezofiber proposed in this study has interdigitated electrodes, meaning that a cantilever made of piezofiber contains many pairs of electrodes, as shown in Figure 6.

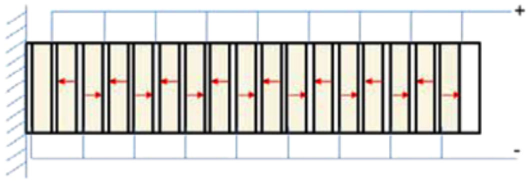


Figure 6. Piezofiber with interdigitated electrodes.

All electrodes are connected in parallel, as shown for the cantilever in Figure 6. Each pair of electrodes has the structure of the 33 mode, and the relevant constitutive piezoelectric equation is as follows (Mo *et al*., 2009):

$$\varepsilon_1 = s_{33}^{E}\sigma_1 - d_{33}E_3 \quad D_3 = -d_{33}\sigma_1 + \varepsilon_{33}^{T}E_3 \tag{1}$$

where ε, σ, s_{33}^{E}, d_{33}, E_3, D_3, and ε_{33}^{T} represent the strain, stress, elastic compliance, piezoelectric charge coefficient, electric field strength, charge density, and dielectric constant, respectively. The subscripts 1, 2, and 3 represent the x, y, and z axes, respectively. The subscripts *p* and *E* refer to the piezoelectric structure and electrical energy, respectively. With the assumption that the strain generated on the surface of the tire is equal to the strain generated in the piezoelectric material attached to the tire (i.e., the piezofiber is perfectly attached to the surface of the tire), the stress of the piezoelectric material can be expressed as

$$\sigma_p = \frac{1}{s_{33}^{E}}(\varepsilon_1 + d_{33}E_3) \tag{2}$$

Then, the energy in the interdigitated piezoelectric structure can be described as

$$\begin{aligned} dU_p &= \frac{1}{2}\varepsilon_1\sigma_1 + \frac{1}{2}D_3E_3 \\ &= \frac{1}{2}s_{33}^{E}\sigma_p^2 - d_{33}\sigma_pE_3 + \frac{1}{2}\varepsilon_{33}^{T}E_3^2 \end{aligned} \tag{3}$$

where dU_p represents the internal energy of the piezofiber.

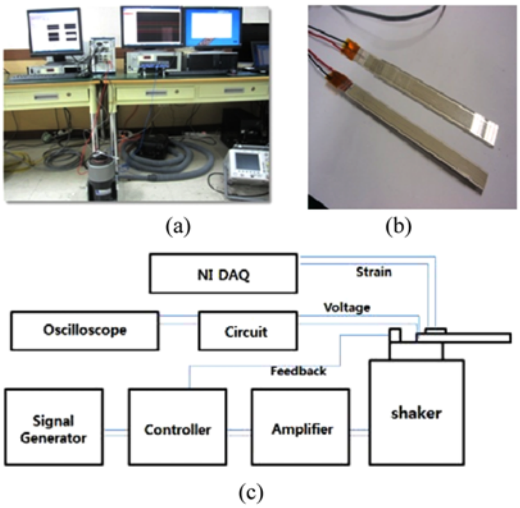
The transduction energy in Equation (3) represents the total energy of the deformed beam, which consists of pure mechanical energy, pure electrical energy, and coupled terms. The actual transformed energy for generating power consists of the electrical energy and the coupled energy. Therefore, one can obtain the generated energy by substituting an expression for electric field in terms of voltage, $E_3 = V/l$. This produces

$$dU_{pE} = -d_{33}\sigma_p V/I_d + \frac{1}{2}\varepsilon_{33}^{T}(V/I_d)^2 \tag{4}$$

where dU_{pE}, V, and l_d, are the electrical energy of the piezofiber, the voltage, and the length between interdigitated electrodes, respectively. It is known from the equations above that the strain generated due to the external load is proportional to voltage and that the square of the electrical energy is also proportional to voltage.

3.2. Energy Transduction Experiment on the Piezofiber to Study Tire Behavior

The experimental setup to measure the energy transduction of the piezofiber is composed of a shaker (Labworks Co.) and shaker controller (M+P Co.). Figure 7 shows photographs of the experimental setup, the piezofiber module and a schematic of the experimental setup.



(a) (b)

(c)

Figure 7. Photographs of the experimental setup (a), piezofiber module (b), and a schematic of the experimental setup (c).

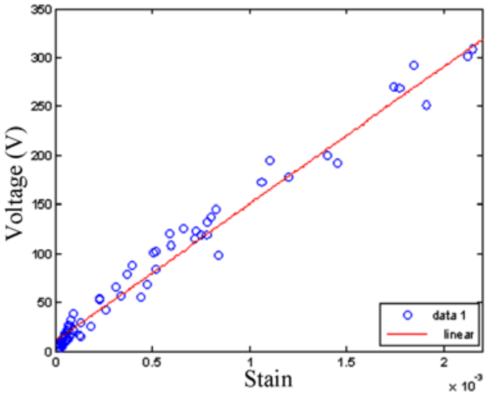


Figure 8. Measured strain versus generated voltage.

3.2.1. Relationship between the strain and the generated energy

An experiment for measuring strain due to external loading and the transformed electrical energy was performed. Because the piezoelectric material generates a voltage in response to the application of an external load, the strain and the voltage for continuous change induced by a shaker were measured with a cantilever composed of piezofiber. Figure 8 shows the measured strain and voltage generated from the experimental setup. As seen in the figure, the generated voltage changes linearly with the strain of the piezofiber. This generated voltage is expected to be an AC signal, and thus, a rectification device is necessary to store the electrical energy generated by the voltage. In addition, impedance matching between the circuitry and the piezoelectrical material is necessary for efficient flow of energy. Therefore, the optimal resistance for matching the impedance between the piezofiber and the circuit was measured to determine the maximum efficiency of the piezofiber.

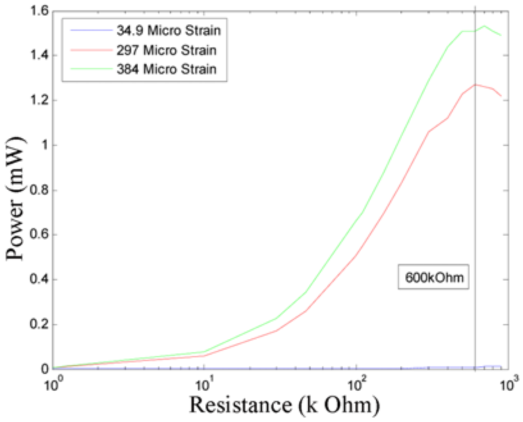


Figure 9. Graph of the generated power as a function of resistance.

Figure 9 shows the results of an experiment to find the optimal external resistance for achieving the maximum converted power for constant micro strain values of 34.9, 297, and 384 micro. In all cases, sinusoidal loading was applied to the piezofiber cantilever. The optimal resistance

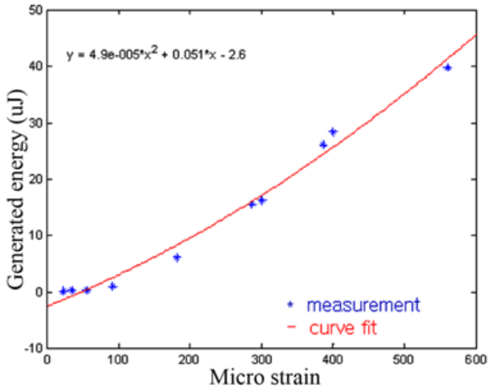


Figure 10. Plot of the generated energy for various strains.

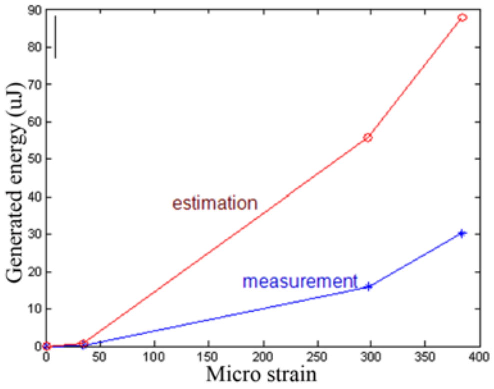


Figure 11. Comparison of the theoretical with experimental results.

was utilized for impedance matching between the piezoelectric material and the circuit for collecting the self-generated power. The voltages generated in the piezoelectric material for various resistances were measured. We found that the maximal power was generated at 600 kΩ of resistance.

Figure 10 shows the measured transduction energy as a function of strain along with a quadratic curve fit to the data. Based on the theory mentioned above, the square of the electrical energy is proportional to strain, which yields a reasonably close fit to the quadratic curve based on the measured results. The difference between the theory and measured results is approximately 30%.

Figure 11 shows a comparison of the theoretical and experimental results. The reason for the difference is likely due to the fact that some of the generated voltage in the piezofiber is lost to the rectification device even when the maximum voltage is obtained with the optimal choice of external resistance, leading to a discrepancy in the amount of energy generated.

3.2.2. Estimation of the generated energy

To estimate the minimum energy generated from the behavior of the tire, the weight of a tire with an 18 in. diameter was determined to be 500 kgf for a vehicle with a weight of 2 tons. At the normal tire pressure of 34 psi, the lateral strain was estimated to be between 700 to 900 micro strain under tension and between 1300 to 1500 micro strain under compression. The corresponding voltage range was 100 to 200 V. Given these conditions, the generated energy for various rotation speeds can be estimated, as shown in Table 4.

The generated electrical energy under lateral application of the strain gauge is 0.58 mJ for one rotation of the tire of a vehicle moving at 40 km. For the cases of the longitudinal or 45 strain gauge measurements, three times more energy could be generated. The amount of generated energy is predicted to increase when multiple piezofiber modules are applied.

3.3. Application of the Generated Energy from the Behavior of the Tire

In this study, we explored the potential use of tire deformation as a source of energy to power the analysis of the tire behavior. To achieve this, we compared the energy consumption of the sleep and active modes of the wireless sensor system to monitor tire behavior. Because the different duties of the sensor system vary widely during different modes (e.g., sleep, processing) and require different amounts of power and time to execute, the power consumed by the wireless sensor system also varies with the duty cycle. Table 5 describes the different modes and their corresponding power consumption. For Table 5, the wireless sensor system used was the Zigbee compliant EM2024 transceiver in conjunction with an 8-bit Atmega 28L microcontroller.

Table 5. Power consumption of various modes of the wireless sensor system.

Operation mode	Time (ms)	Power (mW)
Sampling (Temp.)	0.2	1.2
Sampling (Pressure)	100	5.2
Sampling (Acc.1.5 g~6 g)	1	1.15
Sleep mode	-	0.054
Transmitting	3.9	83.127
Receiving	0.4	91.476
Processing	150	19.983

When utilizing the TPMS MPXY8000 model to monitor tire behavior, the temperature measurement requires 1.2 mW of power and the pressure measurement requires 5.2 mW (Freescale Semiconductor, 2006). Due to standardization of the comprehensive model, the TPMS model also includes an acceleration sensor. This acceleration sensor necessitates 0.345 mW~1.15 mW of power (Kionix, 2007). The energy required for measurement and data transmission is 3.88 mJ. As mentioned before, for tire rotation at 300 rpm, each rotation potentially produces 0.58 mJ of energy. Therefore, it will require approximately 7 rotations to create enough energy for one complete temperature and pressure measurement, including for wireless transmission of this data. After factoring the total energy lost to storage and transformation of the circuit to be approximately 50%, we estimate that 15 rotations will

Table 4. Generated energy for various tire rotation speeds.

RPM	Loading	Micro strain	Generate voltage (V)	Energy before rectifica-tion (mJ)	Energy after rectifica-tion (mJ)
100	Tensile compress	771.25 -1528.75	137 240	1.59	0.478
200	Tensile compress	932.5 -1357.50	159 217	1.63	0.488
300	Tensile compress	956.25 -1583.75	162 248	1.93	0.580

be required for each transmission. Although this study utilized a commercially common sensor and wireless module, even lower predicted powers will be needed if the energy harvesting technique previously introduced (e.g., with a low power TPMS) is employed: the predicted power needed for a 10kbit/s data rate is approximately 200 μWs (Lohndorf *et al*., 2007). With this technique at the center of power consumption for data transmission, each TPMS data transmission would require a single rotation.

These results confirm that the renewable energy generated from tire deformation during driving has great potential to become the power source of choice for a self-powering tire behavior monitoring system, depending on the intended usage.

4. CONCLUSION

This paper presents a self-powering system that powers a sensor mounted inside the tire to assess tire intelligence to improve the stability of vehicles. The system transforms mechanical energy generated by the deformation of the tire during driving into electrical energy using a piezoelectric material.

(1) Several experiments for measuring the strain in the tire of a vehicle during driving were performed. The resulting range in longitudinal strain was 5,000 to 8,000 micro strain, and the lateral strain ranged from 1500 to 2500 micro strain.

(2) The relationship between the strain and voltage for was analyzed for a flexible piezofiber that served as the medium of energy transduction. The optimal resistance was utilized for impedance matching between the piezoelectric material and the circuit for collecting the self-generated power. The maximum power was generated at a resistance of 600kÙ.

(3) The minimum energy generated from the behavior of the tire was estimated using the relationship between strain and voltage. For a weight of 500 kgf and a normal tire pressure of 34 psi, the generated electrical energy with a lateral strain gauge was estimated to be 0.58 mJ for one rotation of the tire of a vehicle travelling at 40 km. For the cases of a longitudinal strain gauge or a 45 strain gauge, three times more energy could be generated. With the application of many piezofibers modules, it is estimated that the generated energy would increase by a factor equivalent to the number of modules applied.

This study also provides simulation results for a tire test rig before installing the system inside the tire. Further research should explore what happens to the measured energy generated during actual installation of a piezofiber system. An optimally designed module applicable to real vehicles could increase, in the long-term, the possibility of fabricating a self-powering wireless sensor system inside the tire.

ACKNOWLEDGEMENT–This research was supported by the Converging Research Center Program of the National Research Foundation of Korea (NRF) which is funded by the Ministry of Education, Science and Technology (No. 2010K000986) and the grant from the Industrial Source Technology Development Program (10033705) of the Ministry of Knowledge Economy (MKE) of Korea, the U-Eco City project in the program year of 2009.

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