Proceedings of the ASME 2018 Power and Energy Conference
PowerEnergy2018
June 24-28, 2018, Lake Buena Vista, FL, USA

PowerEnergy2018-7496

OPTIMIZATION OF A RAINBOW PIEZOELECTRIC ENERGY HARVESTING SYSTEM FOR TIRE MONITORING APPLICATIONS

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ABSTRACT

Ambient energy harvesting using piezoelectric transducers is becoming popular to provide power for small microelectronics devices. The deflection of tires during rotation is an example of the source of energy for electric power generation. This generated power can be used to feed tire self-powering sensors for bicycles, cars, trucks, and airplanes. The aim of this study is to optimize the energy efficiency of a rainbow shape piezoelectric transducer mounted on the inner layer of a pneumatic tire for providing enough power for microelectronics devices required to monitor tires. For this aim a rainbow shape piezoelectric transducer is adjusted with the tire dimensions and excited based on the car speed and strain. The geometry and load resistance effects of the piezoelectric transducer is optimized using Multiphysics modeling and finite element analysis.

NTRODUCTION

Obviously, the only interface between cars and pavement is tires thus their safety is correspondingly related to passengers and the car itself. To satisfy trending safety requirements, auto industry pioneers are seeking for a comprehensive and cost-efficient monitoring means to better-track conditions of tires. Yokohama Rubber Company tests ascertain that sensors mounted on wheels and within tires can detect vehicle motions 0.15-0.2 seconds faster than sensors mounted on the vehicle body [1]. Regarding that over the past couple of years installing sensors inside tires for measuring and quantifying various properties such as tire pressure, braking distance, contact path length, friction coefficient, slip angle, road condition, and tire wear is grabbing more attention. This direct and in situ information coverage of tire properties leads to development of 'intelligent tires', mostly known as 'smart tires' to improve car safety[2, 3]. A drawback for using passive sensors is that they require a separately implemented data acquisition system. Consequently, active-type sensors excel passive type ones currently being used in tires, however with a bigger price tag. Active-type sensors need a source for power supply, commonly batteries. There is a necessity to replace or recharge batteries used in this type of sensors. In addition, heat generation of batteries is another obstacle to deal with [4-7] which has been always interest of researchers' fields of study to address it efficiently [8]. Nowadays few sensors can be mounted within the tire due to this limitation. However, in order to monitor as many parameters as needed, multiple sensors shall be mounted, leading to need for a bigger power source.

Energy harvesting system is an interesting way for capturing a portion of energy that is being already wasted in tires due to heat and vibration [9]. A review on different sources of excess energy in automotive applications such as light, heat and vibration is available in Ref. [10]. Piezoelectric material use in energy harvesting has taken great attention. Different ways to utilize piezoelectric material for energy harvesting in tires are reviewed in [11]. Usually vibration-based energy harvesting methods by means of resonance piezoelectric cantilever beam are used to harvest energy produced by rotating

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tire vibration [12-16] and can be tested by Hardware In the Loop (HIL) simulation [17, 18]. For vibration based energy harvesting methods, 2.5-349 µW is the maximum output power reported [19]. The big imperfection of this way is that adjustment between resonant frequency of the cantilever beam and the excitation is required [20, 21]. Furthermore, this type can merely harvest the vibration energy on one direction while technically tire undergoes a multi direction deflection. To overcome these challenges, use of strain-based energy harvesting systems can be addressed.

Strain-based energy harvesting systems have an advantage of immense importance: ease of manufacturing and assembly [22] and having structural integrity [23]. The first attempt for harvesting strain energy in tires from tire inner liner was conducted in Apollo project by the use of PVDF (Polyvinylidene Fluoride) [24]. Simulating PZT–Polymer Composites for direct using of strain energy in tires is one of the first studies of this type [25]. Several strain based piezoelectric energy harvesters were studied for tire applications [25-31]. For strain based piezoelectric devices in small scale (not covering a large portion of tire inner layer area) used for tires, 40 µW to 6.5 mW is the maximum output power reported [11].

Among different piezoelectric strain-based energy harvesters, rainbow shape piezo transducer is capable of catching multi-direction deflections [32]. The rainbow shape piezoelectric harvester consists of a flexible metal substrate and piezoelectric material layers as shown in Fig1. The metal base of the energy harvester is deformed by tire deflection thus strain and stress of the piezoelectric films change concurrently. In this paper by the use of COMSOL Multiphysics software a finite element study of a rainbow shape piezoelectric transducer is conducted to convert the strain energy of tire inner layer to the electric energy.

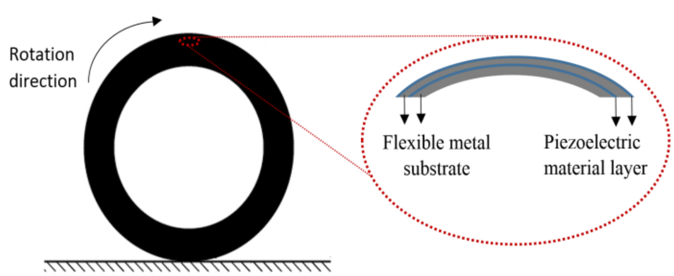

Fig1. A rainbow shape piezoelectric transducer mounted inside the tire

TIRE DEFORMATION

Evaluating the extent of available energy and the portion that is needed to feed sensors is the most important part of energy harvester. For modeling the strain-based piezoelectric energy harvester, the amount of available strain would be the input. Lateral and radial deformations around the contact point of the tire and pavement are present on outer surface of tire while the tire rotates around its axis. There are several sets of studies focusing on measuring tire deformation [33, 34]. The input strain data from Ref. [34] for a tire with a 34 psi pressure, 500 kgf load and 41 km/h speed is used. As mentioned in Ref. [34], total amount of strain increases with increase in applied load also it rises up marginally as the speed increases. Another factor influencing the generated strain is the internal pressure of tire. For constant internal pressure, the longitudinal strain increases as the applied load increases. Apparently, in this case the lateral strain does not have a significant influence on the deflection of the rainbow energy harvester therefore only longitudinal strain is investigated. The strain is converted to the time domain function considering the tire speed 41km/h and the input data is executed for the model in COMSOL Multiphysics software as a piecewise function for prescribe displacement.

Another important parameter for energy harvesting system is the energy harvesting efficiency which depends on the amount of accessible energy. Generally, tire deflection has superior influence, about 90%, on rolling resistance of the tire, which is a representative of total amount of the wasted energy [35]. The total rolling resistance force can be obtained from the following equation [36]:

$$R = f_r N \tag{1}$$

where R is the rolling resistance force, N is Normal force (approximately one fourth of the vehicle's weight for 4-wheel vehicles) and f_r is the rolling resistance coefficient that is related to the tire internal pressure and is well defined in Ref. [36]. Tire vertical forces have roughly 65% effect on the rolling resistance [37] thus the final tire deflection energy can be assumed as 65% of rolling resistance that is the waste of energy of the tire and is obtained by Eq.2.

$$E_d = {}^{65}\!/_{100}\, R V t_r \tag{2}$$

Where V is the car speed and t_r is time needed for one rotation of the tire. The energy efficiency of a system is the useful output energy divided by the total input energy of a system that can be obtained from the following equation:

$$\eta = {}^{E_{out}}\!/_{E_{in}} \tag{3}$$

Here the input energy of the system (E_{in}) is the tire deflection energy (E_d) and the output energy of the system (E_{out}) is the produced energy of energy harvester.

MODELING

Analysis of laminated plates with piezoelectric layers under cylindrical bending has been conducted in several studies [38-42]. The model in this study is a rainbow shape piezoelectric consisting of metal flexible substrates in between the piezoelectric material layers (Fig.1). In addition, homogeneous elastic arches theory is used in this study. According to the dynamics of arches [43, 44], it is assumed that the thickness of piezoelectric layers plus the thickness of metal substrate is much lower than the radius of arch (Eq.4) thus the homogeneous elastic arches theory can be employed.

$$t_p + t_m << r \tag{4}$$

In Eq.2, t_p and t_m are thicknesses of piezoelectric layers and metal substrate, respectively, and r is the mean of radius of the arch. Since the energy harvester is going to be installed on the inner layer of the tire, this assumption will be always fulfilled because the radius of the tire is much larger than the total thickness of the harvester. In addition, another assumption is the lack of imperfection within interlayer bonding; i.e. piezoelectric layers are perfectly bonded to the elastic layer. Consequently, rainbow shape material is equivalently looked at as a single-layer arch. The input data for the modeling and materials properties are given in Table 1. The amount of output electric energy is related to the stress distribution of the metal flexible substrate. Based on the constitutive equation of piezoelectric materials and the mechanical analysis of the flexible substrate, the generated charge and voltage of every piezoelectric film is calculated as follows [32]:

$$Q_i = \frac{E_p R^2 d_{31} b_p}{2h^2}\left[-\phi_{4,i} + (-1)^i \frac{1}{2}(t_p + t_m)\phi_{5,i}\right] \qquad ,(i=1,2) \tag{5}$$

$$V_i = \frac{\dfrac{E_p R^2 d_{31} b_p}{2h^2}\begin{bmatrix}-\phi_{4,i} + \\ (-1)^i \dfrac{1}{2}(t_p + t_m)\phi_{5,i}\end{bmatrix}}{\dfrac{E_p R^2 d_{31} b_p l_p}{2h^2}\begin{bmatrix}2\phi_{1,i} + \dfrac{1}{2}(t_p + t_m)^2\phi_{2,i} + \\ (-1)^{i+1}(t_p + t_m)\phi_{3,i}\end{bmatrix} + \dfrac{l_p}{t_p}\left(\varepsilon_{33} - d_{31}{}^2\right)}, (i=1,2) \tag{6}$$

$$h = c^2 - ae \tag{7}$$

$$a = 2E_p b_p t_p + E_m b_m t_m \tag{8}$$

where i=1,2 is inside and outside piezoelectric layer respectively, E_p and E_m are Young's modulus of piezoelectric and metal layer, ε_{33} is the relative permittivity of the piezoelectric at constant stress, d_{33} is the constant element of piezoelectric strain coefficient. In addition c and e is defined in Ref. [32].

Table1, The input data for the modeling and materials

Material	Aluminum substrate	Ceramic Lead Zirconate Titanate (PZT)
Young's modulus (GPa)	69	66
Density (kg m^{-3})	2700	7800
Piezoelectric coefficient, d33 (m V^{-1})	N/A	3.74e-10
Load resistance(kΩ)	N/A	10
Radios(mm)	337	N/A
Thickness(mm)	1	0.2
Width(mm)	2.5	2.5

VALIDATION

Xiangjian et al. [32] have studied the mathematical analysis and finite element analysis on energy conversion efficiency on the basic idea of rainbow energy harvester with specific dimensions. A 1N constant excitation force is applied to a rainbow shape piezoelectric actuator with PVDF and steel thicknesses of 0.2 mm and 0.1 mm, respectively. For validation, the Ref. [32] geometry and boundary conditions of the rainbow shape is simulated on COMSOL. The geometry of the basic rainbow shape piezoelectric energy harvester used for validation is shown in Fig.2.

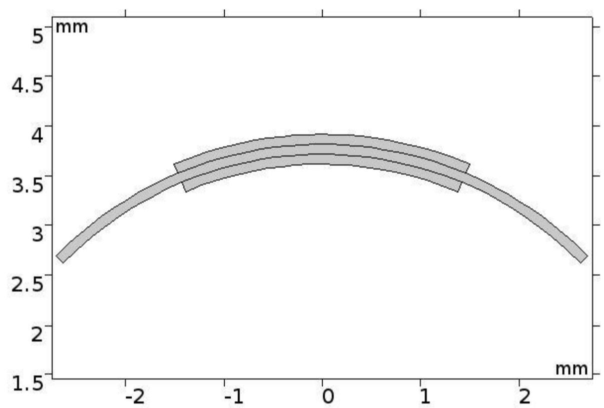

Fig.2: Initial rainbow energy harvester geometry used for validation

Xiangjian et al. [32] study on output voltage dependency to piezoelectric layers thickness is compared with developed model and Fig. 3 represents a thorough consensus between reference data and developed model output voltage. The maximum statistical error is 1% occurred with piezoelectric layers of 0.2 mm thickness that is an acceptable error.

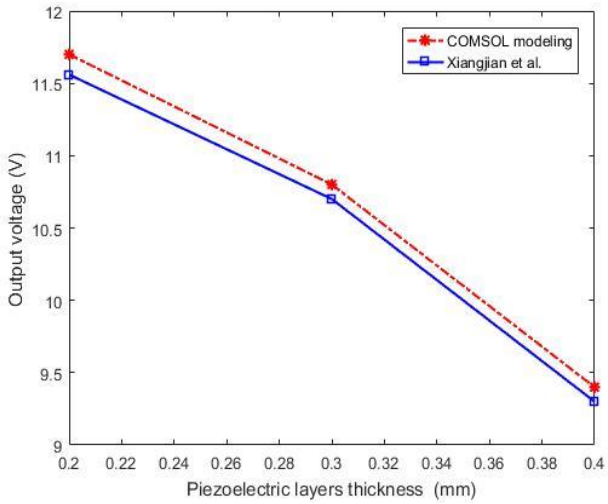

Fig.3: Comparison of the developed model with Xiangjian et al results[32]

RESULTS AND DISCUSSION

An arch shape metal base with the dimension given in Table.1 is modeled in COMSOL 5.3 and the geometry and generated mesh is shown in Fig.4. Extremely fine mesh is used and the model have 3075 mesh elements. Length of 23mm and width of 2.5mm is chosen for the energy harvester that is less than 0.01% of the tire inner surface and thickness of piezoelectric film is 0.2 mm. For adjusting energy harvester design for tire application, two flexible metal substrate layer is used thus there is metal layer in contact with the tire to protect piezoelectric material.

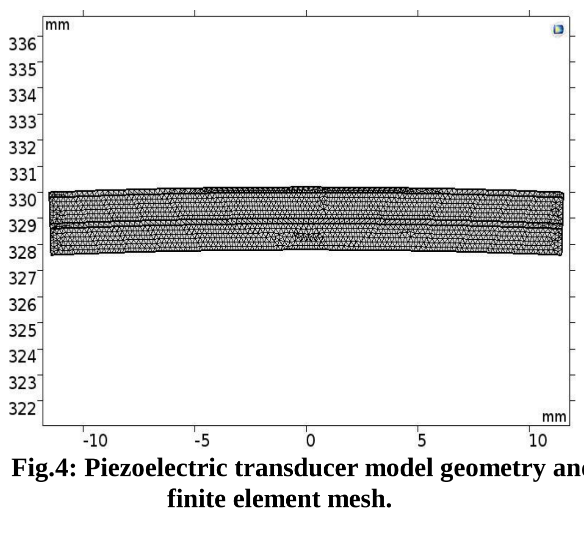

Fig.4: Piezoelectric transducer model geometry and finite element mesh.

The one rotation of the strain of 235/60R18 tire with the speed of 41 km/h of Ref. [34] is converted to the time domain and in Fig.5 the input piecewise function for prescribe displacement is shown. Just before the tire contact the pavement a compression happened in the inner layer of the tire and during the tire pavement contact the inner layer strained and again after the contact it compressed and in the other locations there is not any strain happened.

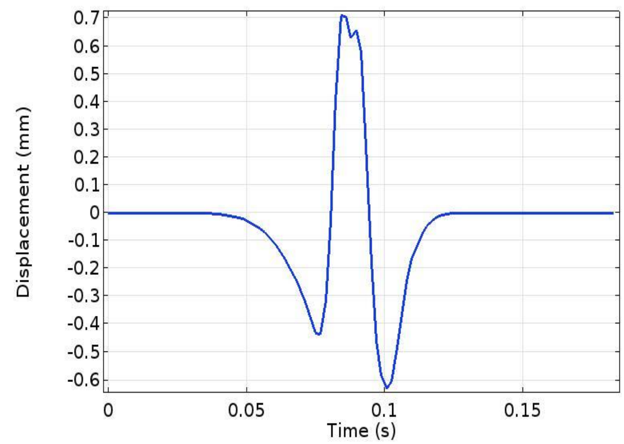

Fig.5: Displacement of the rainbow piezoelectric energy harvester for one complete rotation of tire (360°).

The amount of electric energy and voltage is shown in Fig.6 and 7. The maximum output voltage and electric power is about 9.7V and 5.85mW, respectively. A load resistor in the electric circuit was used to demonstrate the electrical power output. Compare to the vibration based energy harvesting methods with maximum output power 2.5-349 µW [19], the output power of rainbow shape energy harvester studied here is 16 times greater.

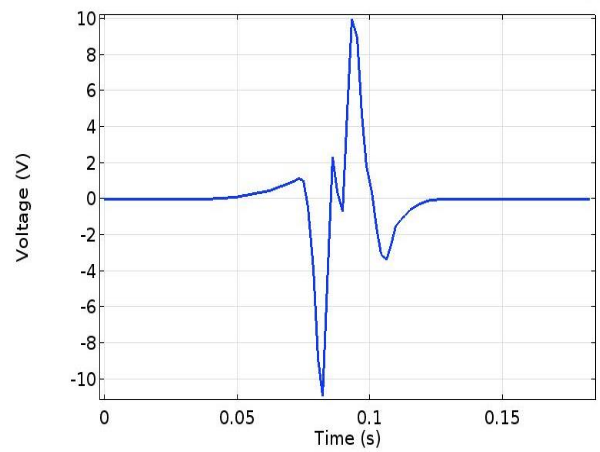

Fig.6: The output voltage of the rainbow piezoelectric energy harvester for one complete rotation of tire in Fig. 5

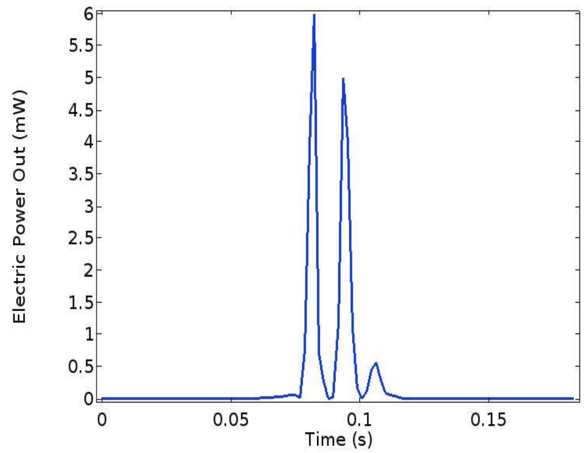

Fig.7: The output electric power of the rainbow piezoelectric energy harvester for one complete rotation of tire.

It is reported that the average energy requirement for commercial tire pressure monitoring system (TPMS) is 10 µJ/rev [45]. In addition it is reported that the amount of energy requirement for TPMS is a function of sensor transmission per minute and car speed, for this study condition (vehicle speed 41km/h and tire pressure 35 psi) it is about 10-80 µJ/rev for 0.1-60 s/min transmission speed [27]. The harvested energy achieved in this paper (Fig.8) is 95 mJ/rev and it is higher than the energy needed for a sensor like TPMS with the highest transmission speed of 60 s/min. Also it could be sufficient for more than 3 sensors with 30 s/min transmission speed. In addition, for more energy demand it is possible to have more than one energy harvester in a tire.

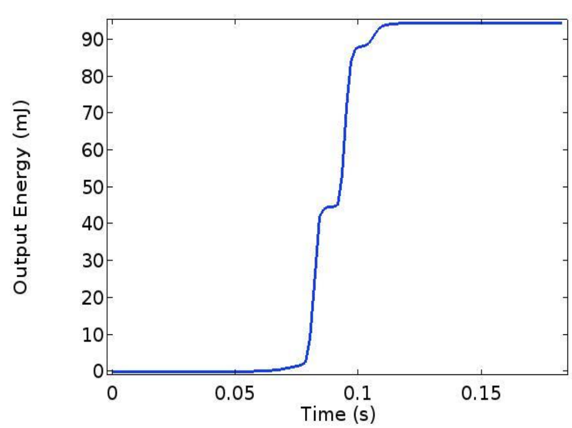

Fig.8: The accumulative output electrical energy from the rainbow piezoelectric energy harvester for one complete rotation of tire.

Based on the Ref. [36] for the tire with the inflation pressure of 34 psi and car weighing 2500 kg, the rolling resistance coefficient is calculated as 0.016, using Eq.1 the rolling resistance force would be 10 lb, consequently the tire wasted energy in each rotation of the tire would be 13.31J/rev regarding to the Eq.2. The energy efficiency of the one rainbow shape piezoelectric energy harvester system based on Eq.3 and Fig.8, would be 0.69% that is a satisfactory amount for tire piezoelectric energy harvesters and by having an additional identical energy harvester in another location of the inner layer of the tire, the energy efficiency would be 1.38%.

The parametric study on the effect of energy harvester width on the output power and accumulative output electrical energy for one complete rotation of tire is shown in Figs. 9 and 10. By increasing the energy harvester width; i.e. increasing the interacting area, the amount of output electric power is increased. So as far as limitations do not hinder the fabrication process there is an opportunity to increase the width of the energy harvester to have higher output electric power energy efficiency of the system. With an increase of width from 2.5 to 8.5 mm a significant and favorable increase in energy efficiency of the system from 0.69% to 8.3%. will occur as a result.

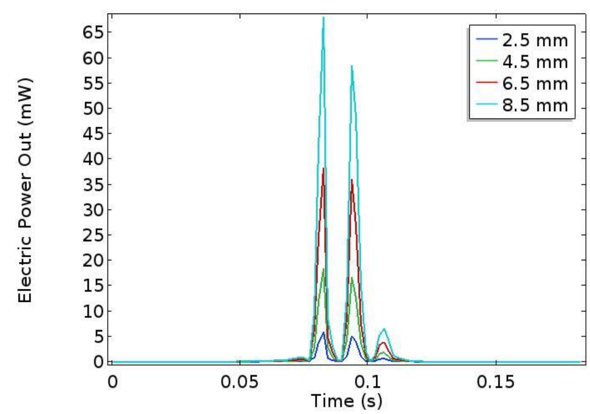

Fig.9: The effect of the piezoelectric width on the output electrical power generated in one rotation of tire.

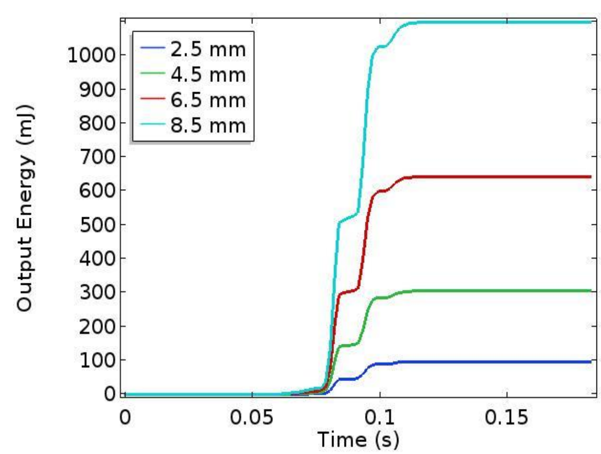

Fig.10: The effect of the load resistance on the accumulative output electrical energy for one complete rotation of tire.

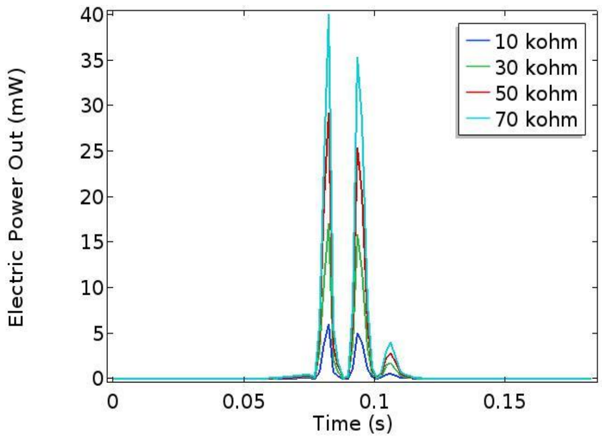

Fig.11: The effect of the load resistance on the output electrical power generated in one rotation of tire.

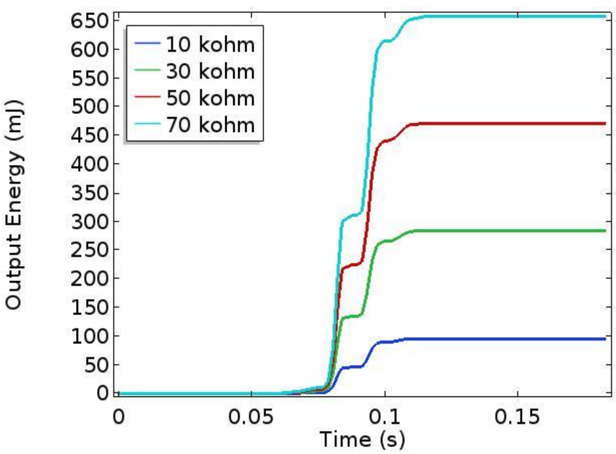

Fig.12: The effect of the load resistance on the accumulative output electrical energy for one complete rotation of tire.

The effect of connected load resistance on the output power and accumulative output electrical energy for one complete rotation of tire is shown in Figs.11 and 12. It is obvious that by increasing the load resistance the output electrical energy and accumulative output electrical energy is increased. By increasing the load resistance from 10 to 70 kΩ the energy efficiency of the system will increase from 0.69% to 4.9%.

Sham[46] reach the maximum power levels of 6.5 mW with the load resistance of 42 kΩ that is the maximum power among the strain based energy harvesters in small scale. Here we can get from Fig 11 that with the load resistance of 30 kΩ and 50 kΩ the maximum output power would be 17mW and 27mW respectively.

CONCLUSION

An optimized rainbow shape piezoelectric energy harvester mounted inside the tire for power generation from deflection energy of tires for microelectronic devices such as TPMS was presented in this paper. This piezoelectric that consists of two flexible metal substrate and two piezoelectric material layers was studied through computer simulation. The energy harvester geometry was adjusted with the tire dimensions and finally the model predicted that maximum output voltage, electric power and electric energy is about 9.7V, 5.85mW and 95 µJ/rev, respectively. This amount of output electrical power is sufficient to feed a TPMS with high data transmission speed of 60s/min or more than 3 sensors with 30s/min transmission speed. The calculation of the energy loss due to rolling resistance in tire deflection was used to obtain tire deflection energy loss. That is about 13.31J/rev for a four-wheel car weighing 2500 kg moving with the speed of 41 km/h and the tire inflation pressure of 35 psi. Thus the energy efficiency of one rainbow energy harvester system would be about 0.69% and with two harvesters it would be 1.38%. Finally, with the aim of optimization of the energy harvester the effect of width and load resistance on the output electric power was studied. The results indicated that by increasing the width from 2.5 to 8.5 mm an increase in energy efficiency of the system from 0.69% to 8.3%. will occur, in addition increasing the load resistance from 10 to 70 kΩ results in the increase of the system energy efficiency from 0.69% to 4.9%.

ACKNOWLEDGMENTS

This work has been supported by NSF-CenTiRe fund.

NOMENCLATURE

Ep	Piezoelectric Young's modulus
Em	Metal Young's modulus
Ed	Tire deflection energy
fr	Rolling resistance coefficient
i	Inside and outside piezoelectric layer indicator
N	Normal force
R	Rolling resistance force
r	Tire radius
t_m	Metal substrate layers thicknesses
t_p	Piezoelectric layers thicknesses
tr	Time needed for one rotation of the tire
V	Speed
ε_{33}	Relative permittivity of the piezoelectric
d_{33}	piezoelectric strain coefficient element
η	Energy efficiency

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