STRAIN-BASED PIEZOELECTRIC ENERGY HARVESTERS FOR INTELLIGENT TIRE SENSORS

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STRAIN-BASED PIEZOELECTRIC ENERGY HARVESTERS FOR

INTELLIGENT TIRE SENSORS

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Dissertation

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ABSTRACT

Nowadays, the automotive industry is paying more attention to autonomous vehicles; as a result, the importance of tire safety is increased. Since tires are the only contact between the vehicle and the road, monitoring the parameters such as tire pressure and temperature, friction between tire and road, and tire wear is essential to ensure vehicle safety. These parameters are monitored with the sensors embedded in intelligent tires. These sensors need electric power for operation. To provide the electric power for the intelligent tire sensors, piezoelectric energy harvesters (PEHs) can be used to harvest a part of tire deflection waste energy to provide electric power to the sensors.

Two new shapes of piezoelectric energy harvester inspired from Cymbal piezoelectric energy harvester were designed. It has been proven that the Cymbal piezoelectric energy harvester is effective in vibration energy harvesting. Two new shapes are inspired by cymbal energy harvester, and they are developed to harvest strain energy from rolling tires. It is the first time this type of energy harvester based on the Cymbal geometry is used for the intelligent tire application. To ensure that these new designs will be safely and effectively embedded on the inner surface of tires, some modification on the shape, size, and design was made. The output voltage, power, and energy of the designed PEHs were evaluated through the developed Multiphysics model and experimental analysis. In order to run the experimental analysis, a wireless measurement system is developed. The

PEH will be undergoing cyclic loading in the tire application. Therefore, the fatigue failure of the piezoelectric material is also considered in the design stage. The PEH is designed to be used in autonomous vehicles tire to provide power to the tire sensors. Due to this application, the PEH is subjected to temperature change, tire inflation changes, vehicle speed changes, and tire load changes due to this application. Therefore, in this study, some parametric analysis is done to investigate the effect of these changes on the PEH performance. The parametric study with the use of the COMSOL Multiphysics model is done. In this study, the effect of vehicle speed, PEH depth, piezoelectric material thickness, and temperature on the output of the PEH is investigated. The parametric experimental study is done to study the effect of tire inflation pressure and tire load on the output voltage of the PEH. The model output showed that the harvested energy from each new design is sufficient to power up several sensors in intelligent tires. These new designs showed several advantages, such as high performance and ease of manufacturing.

Dedicated

to

The beloved families of 176 victims of Flight PS752, which was shot down shortly after taking off by Iranian IRGC surface-to-air missiles

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CHAPTER I

INTRODUCTION

In recent years, autonomous vehicles have been at the forefront of the vehicle industry's attention. As autonomous vehicles do not have drivers thus their safety is paramount [1]. Tires are the only connection that the vehicle has with the pavement; as a result, the safety of tires is critical to maintaining the safety vehicle and passengers. In order to monitor the tire condition and the tire-road conditions for autonomous vehicles, intelligent tires are presented. Intelligent tires use sensors embedded on them to monitor the tire and tire-rad condition and send these data to the vehicle computer center to be processed. The sensors embedded on the tire need power to collect the data and transmit it to the vehicle computer center. Usually, batteries are the primary power source for intelligent tire sensors, but they need replacement or recharging. In addition, taking care of the intelligent tire batteries increase the tire maintenance intervals. Therefore, energy harvesting systems are suggested to be used in intelligent tires as a sustainable source of energy [2]. Energy harvester systems convert a portion of ambient waste energy into valuable energy [3-5].

In this study new shape of PEH is designed, and with the use of the developed Multiphysics model, the output power, voltage, and energy are studied. The new shape of the PEH is inspired by the Cymbal energy harvester [6]. There are few studies on the PEH for the tire application that is the inspiration to design new shapes of the PEH that are applicable and are not complicated to manufacture. The developed PEH in this study is never used before. The proposed designs have several advantages, such as ease of manufacturing compared to the designs presented in the literature.

1.1. Dissertation overview

The introduction section briefly discusses the importance of tire and vehicles safety, autonomous vehicles, and the necessity of energy harvesting for autonomous vehicles. This work is focused on designing a new strain-based piezoelectric energy harvester (PEH) for monitoring the tire. For this purpose, in Chapter 2 a background of the energy harvesting piezoelectric effect is given. In addition, in Chapter 2, The available approaches of energy harvesting for tire application is studied. Finally, in the research gap section in Chapter 2, the drawbacks of the vibration-based energy harvesters for tire application are given.

Chapter 3 gives a discussion on the parameters of the PEH design and modeling. The energy demand of the sensors

Chapter 4 gives a discussion on the design methodology. The new energy harvesters' shape and geometry are discussed. In addition, the Comsol Multiphysics model of the energy harvester is presented in this chapter. The material properties chosen for the experimental analysis and experimental setup and measurement system are presented in this chapter. The stress, stain, and fatigue analysis are presented in this chapter.

In Chapter 5 discussion of the results obtained from the new proposed PEH is given. First, the validation process of the Multiphysics model and mesh independency analysis is given. Then, the tire deflection as an input for the model is calculated. The output voltage, power, and energy obtained from the new PEHs are given and compared. It is experimentally observed that the generated power by the piezoelectric energy harvester is enough to run the sensors. The parametric study using the COMSOL Multiphysics model is done. The effect of vehicle speed, PEH depth, and piezoelectric material thickness on PEH output is investigated. The parametric experimental study is done to study the effect of tire inflation pressure and tire load on the output voltage of the PEH. The tire is used in different ambient temperatures; it is evident that as the tire roles, the tire temperature increases. Thus, here the effect of temperature on the proposed PEHs performances is considered.

Chapter 6 gives the summary and conclusion of the results of this dissertation.

CHAPTER II

BACKGROUND

The background of tire piezoelectric energy harvesting is discussed in this chapter. First, the intelligent tire is discussed. Second, the piezoelectric material behavior is discussed, and an introduction to the piezoelectric effect is given. The energy harvesting methods for tire application are introduced, and the drawbacks of these methods are studied.

2.1. Intelligent tires

The only interface between the vehicle and pavement is the tire; therefore, the tire plays a vital role in vehicle safety. in 2000, Bridgestone recalled the tires, and as a result of this recall, the United States Transportation Recall Enhancement, Accountability, and Documentation (TREAD) force via its regulations that the tire pressure monitoring system (TPMS) should be installed on all the new vehicles that were the first step to develop the intelligent tires [7]. To satisfy the tire safety requirements, especially for autonomous vehicles, the auto industry is seeking a comprehensive and cost-efficient monitoring system to better track the conditions of tires. At the first step of using sensors on the tire, the TPMS was the indirect measurement system to measure the tire pressure based on the wheel radius calculation [8] or using wheel speed sensors [9]. In 2005, Yokohama Rubber Company reported 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 [10]. Thus, it is important to mount some safety monitoring sensors inside the tire rather than other vehicle locations. Over the past few years, the installation of sensors inside tires for measuring and quantifying various parameters such as tire pressure, braking distance, contact path length, friction coefficient, slip angle, road condition, and tire wear has been given more attention by the auto industry. The direct and in-situ measurements of tire parameters lead to the development of 'intelligent tires,' mostly known as 'smart tires' to improve vehicle safety [11].

The tire monitoring system shown in Figure 1, includes wireless sensors mounted inside the tire to measure the tire parameters and a central receiver to receive the sensor signals and analyze data. Whenever the vehicle control system detects any fault in the tire, it warns the driver or may stop the autonomous vehicle to ensure passengers' safety.

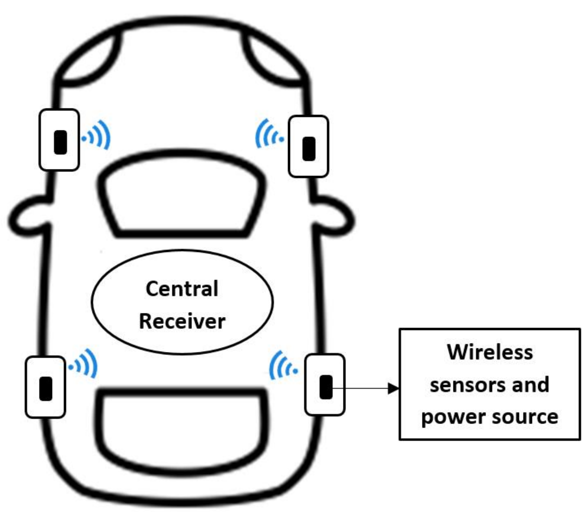

Figure 1. Schematic of the intelligent tire monitoring sensors and wireless communication with a central receiver of the vehicle.

2.1.1. Intelligent tires sensors

Passive and active wireless transmission can be used between tires and vehicles [7]. Passive wireless transmission requires a separately implemented data acquisition system that merely transmits the data whenever any fault is detected, such as temperature change or pressure drop. In contrast, the active wireless transmission requires a power source. It simultaneously transfers data which makes it a better choice for autonomous vehicles, where having them under control every second of running is required. In addition, it is critically important to provide self-sustaining energy for the tire embedded sensors. Batteries are one option for active wireless transmission; however, batteries embedded in intelligent tires cannot be used for a long time due to the necessity of replacement, recharging, and maintenance [12, 13]. This increases the maintenance intervals of tires. Therefore, batteries might not be an appropriate choice as an energy source for this application. Alternatively, an energy harvesting system is preferred to provide sufficient energy for wireless transmission in intelligent tire applications. Reviews on wireless sensor systems for tire monitoring of intelligent tires [7, 14] indicate that research for improving the output energy of energy harvesting systems is required to support a wide range of sensors embedded inside the tire.

2.2. Energy harvesting

An energy harvesting system provides methods to extract to-be-wasted energy from the surrounding environment [3-5]. Energy harvesting systems are used to extract a portion of different types of ambient or waste energy such as ocean wave[15-17], temperature gradient

[18], radio frequency [19], vibration[20], relative motion [21], strain [22], etc. Energy harvesting is a promising way to supply power from the vehicle wasted energy to small onboard electrical equipment [23-25]. In tires, several sources of waste energy are available such as temperature, vibration, and strain [26]. Therefore, it is possible to use the energy harvester system to extract a fraction of this waste energy [27].

2.2.1. Piezoelectric effect

A piezoelectric material generates an electrical charge as a result of the applied mechanical force or deformation. Also, it shows deflection as a result of the applied electric charge. Due to the nature of the piezoelectric material, which can convert the stress or deflection to the electric charge, lately harvesting energy from different types of waste energy with the use of piezoelectric material in various applications has grabbed researchers attention [28-34].

Around 1000 crystal materials are considered piezoelectric and can show a piezoelectricity effect. In some of these materials' piezoelectricity occurs naturally. Also, it is possible to induce piezoelectricity in some single crystal and polycrystalline materials piezoelectricity by applying high voltage or poling. The earliest piezoelectric material used in electronic devices is Quartz, but it has a low piezoelectric coefficient. Piezoelectric materials based on modified lead zirconate titanate (PZT) ceramics are one of the common materials used in sensors and energy harvesting applications. The polymer type of piezoelectric material is polyvinylidene fluoride (PVDF) and is usually used for high-frequency transducers.

2.3. Research Gap

2.3.1. Energy harvesting for tire application

For intelligent tire applications, various types of energy harvesters are studied in the literature, and generally, they can be classified into electromagnetic [35], electrostatic [36], and piezoelectric [37]. Compared to the piezoelectric, the electromagnetic and electrostatic systems have lower output voltage. In addition, electrostatic requires an external voltage source, and the integration of electromagnetic with electronics and microsystems is complicated [38]. Furthermore, piezoelectric energy harvesters have higher energy density than electromagnetic and electrostatic energy harvesters making them more efficient. Additionally, the piezoelectric energy harvesting structure is more simple [24].

Piezoelectric material generates electrical charge as a result of the applied mechanical force or deformation. The piezoelectric energy harvester (PEH) in tire application is divided into two categories depending on how the wasted energy is being used: 1- The vibration energy (flexure [39] and rectilinear [40]), and 2- The strain-based energy (tire bending [41], and shock loads [42]). The vibration-based technology that uses a piezoelectric cantilever beam and a tip mass as a mass-spring system is a well-known configuration. With this setup, the power output within a range of 2.5-349 μW is obtained [43]. In order to maximize the power output, this technology can take advantage of the resonant frequency of the beam, provided that the excitation frequency is known, which is not applicable for tires. Moreover, it cannot harvest the energy in multiple directions of motion; however, tires are exposed to multiple frequencies and multi-directional deflection during rolling at different speeds. Furthermore, the stabilization of the cantilever beam is hard, and the tip mass can only be anchored within a limited distance from the base of the beam and can only have a limited weight [44].

Strain-based energy harvesters create a favorable scenario for tire applications considering the given constraints stated above[45]. Drawbacks for using vibration-based piezoelectric energy harvesters in tire application and advantages of strain-based energy harvesters are discussed by the author in Ref. [45]. Starting from the Apollo project in 2005 [35], several strain-based PEH were studied for tire applications [41, 44, 46-50]. Bowen and Arafa reviewed the PEHs used for powering up the TPMS for tire applications and reported that the power output of the strain-based PEHs is between 40 μW to 4.5 mW [25]. The authors also introduced a strain-based rainbow piezoelectric energy harvester with a power output of 5.85 mW [22, 45]. The output power of the strain-based PEHs is significantly higher than the vibration-based technology used for tires.

2.3.2. Importance of temperature analysis on the PEH for tire application

The main component of the pneumatic tire is rubber which is a viscoelastic material. In viscoelastic materials, a phase difference between the stress and strain waves is somewhere between zero degrees which happens in a purely elastic material, and 90 degrees which happens in purely viscous material [51]. In the stress-strain curve of the viscoelastic materials during a full loading cycle, a hysteretic loop can be seen due to the phase difference. From the area of this hysteretic loop, the amount of heat generation and dissipation from the tire can be calculated [52, 53]. Due to the low thermal conductivity of rubbers, the generated heat leads to a temperature increase inside the rubber. For example, the thermal conductivity of the Styrene-Butadiene Rubber (SBR) is significantly lower than the steel (K_{SBR}=0.25 W/(mK) [54], K_{steel}=51.9 W/(mK) [55]).

Heat generation in the tire is affected by factors like under-inflation, overloading, speeding, and environmental factors. The temperature distribution of rolling tires has been studied by several researchers [56, 57]. It is proved that the increase in ambient temperature and vehicle velocity leads to the tire temperature rise [58-61]. In addition, temperature variations will result in a significant nonlinear behavior in the piezoelectric material coefficients in PZT ceramics [62], affecting the overall performance of strain-based piezoelectric energy harvesters.

Although there are several studies on tire temperature distribution, there is a big gap in research on the effect of tire temperature on the PEH. Here the performance of the developed PEH is studied to have a comprehensive understanding of the PEH performance in any condition in tire application.

2.4. Copyright notice

A significant part of this chapter was adapted with permission from the following publications:

1- Aliniagerdroudbari, H., Esmaeeli, R. & Farhad, S. (2021). Experimental study of a piezoelectric strain-based energy harvester for intelligent tires of autonomous vehicles. ASME 2021 International Mechanical Engineering Congress IMECE2021

2- Aliniagerdroudbari, H., Esmaeeli, R., Hashemi, S. R., Alhadri, M., Zakri, W., Batur, C., & Farhad, S. (2019). Design, modeling, and analysis of a high-performance piezoelectric energy harvester for intelligent tires. International Journal of Energy Research, 43(10), 5199-5212.

3- Aliniagerdroudbari, H., Esmaeeli, R., Hashemi, S. R., Nazari, A., Alhadri, M., Zakri, W., ... & Farhad, S. (2019). A rainbow piezoelectric energy harvesting system for intelligent tire monitoring applications. Journal of Energy Resources Technology, 141(6).

4- Aliniagerdroudbari, H., Esmaeeli, R., Hashemi, S. R., Alhadri, M., Zakri, W., & Farhad, S. (2019). A piezoelectric sandwich structure for harvesting energy from tire strain to power up intelligent tire sensors. In 2019 IEEE Power and Energy Conference at Illinois (PECI) (pp. 1-7). IEEE.

5- Aliniagerdroudbari, H., Esmaeeli, R., H., Nazari, A., Hashemi, S. R., Alhadri, M., Zakri, W., ... & Farhad, S. (2018, June). Optimization of a rainbow piezoelectric energy harvesting system for tire monitoring applications. In Energy Sustainability (Vol. 51418, p. V001T02A004). American Society of Mechanical Engineers.

CHAPTER III

PEH MODELING

3.1. Outline

In this chapter, the parameters for the design and modeling process of the PEH are given in detail. The PEH is supposed to provide power to the sensors embedded on the inner surface of the tire; thus, as the first step of the design process, the energy demand is calculated. The PHE here is working based on harvesting the tire bending waste energy; therefore, it is necessary to calculate the tire bending. In addition, an adhesive layer is used to attach the PEH to the inner layer of the tire, and the effect of this adhesive layer is studied.

The piezoelectric material is brittle, and thus any piezoelectric material cannot be used in strain energy harvesting. Therefore, here the piezoelectric material selection is explained in detail. Finally, the effect of temperature on the output of the PEHs is discussed.

3.2. Energy demand

Any energy harvester aims to harvest part of the ambient waste energy and provide power for a specific application. Thus, a fundamental part of energy harvester modeling is to calculate the required amount of power. The energy harvester must be designed so that the energy harvester's output power amount is enough to afford the energy demand. Here the PEH for intelligent tires is supposed to harvest a portion of energy waste due to the tire rolling resistance to supply the energy demand for sensors to measure and transmit data to the vehicle control system.

The amount of energy that wireless sensors for the active wireless transmission need in each revolution of the tire can be calculated from Eq. 1 [38]:

$$E_{rev} = n_{samples} \times n_{axes} \times 50\,pJ + (n_{bits} + 10) \times 10\,nJ \tag{1}$$

where, $n_{samples}$ is the number of samples per revolution, n_{axes} is the number of axes from which the data is acquired, and n_{bits} is the number of transmitted bits. Therefore, the required energy for a sensor to measure 1,000 samples per revolution in each axis and transmit 840 bits in each revolution (35 bytes per axis) would be 8.7 µJ/rev.

In a typical commercial tire monitoring system (TPMS), the average energy needed is assumed to be about 10 µJ/rev [63]. To reduce the amount of energy that a TPMS system uses, specific programming is required to transmit signals only once the system detects a faulty pressure or temperature. Meanwhile, in order to use the TPMS in autonomous vehicles monitoring the tire situation in every second of rolling will be necessary. If there is a need for 2 sensors to monitor different tire parameters and assume that each sensor needs 10 µJ/rev, then the PEH needs to harvest 20 µJ/rev.

3.3. Tire bending

As discussed before, the PEH here is a strain-based PEH which means that tire bending provides strain in the PEH, and due to the piezoelectric effect in the piezoelectric material layer, the voltage is generated. Therefore, tire bending is the input parameter in the modeling of the strain-based PEH in tire application. The second step for PEH modeling after calculating the energy demand of the tire sensors is to calculate the tire deflection.

Lateral and radial deformations around the contact point of the tire and pavement are present on the outer surface of the tire while the tire rotates around its axis. Several studies are focusing on measuring tire deformation [63, 64]. The total amount of strain increases with an increase in the applied load to the tire or the vehicle speed, while the effect of the vehicle speed may be marginal [63]. Another factor that influences the tire strain is the internal tire pressure. If the tire pressure remains constant, the lateral tire strain does not significantly influence the deflection of the PEH; therefore, only longitudinal tire strain is investigated.

The change in the tire curvature radius causes tire longitudinal strain as presented in Eq. 2 [65]:

$$\varepsilon = -\frac{Z_C - Z}{R} \qquad (2)$$

where, Zc is the no-load tire radius specified by the tire manufacturer, Z is the inner surface radius, and R is the radius of tire curvature as stated in Eq. 3 [66]:

$$a = R \sin\left(L/2R\right) \qquad (3)$$

where, L is the arc length (R×θ) and θ is the angle of the arc. In Eq. 3-2, a is the distance between the two points on the curvature (r_{i-1}, r_{i+1}) that can be calculated from Eq. 4 [66].

$$a = 0.5\sqrt{\left(r_{i-1}\sin\frac{\theta}{2} - r_{i+1}\sin\frac{\theta}{2}\right)^2 + \left(r_{i-1}\cos\frac{\theta}{2} - r_{i+1}\cos\frac{\theta}{2}\right)^2} \quad (4)$$

The data of radius change on 700 kg of the load presented by Lee et al. [66] is used to calculate the tire strain. The effect of the load on the tire is represented in the change of parameter a, which consequently commits to a change in radius based on Eqs. 3 and 4. The effect of the vehicle speed and tire inflation pressure may also be considered on the tire strain. It is reported that by increasing the tire rolling speed from 8 to 26 rpm, the longitudinal strain increases slightly by about 9%, and the vehicle speed does not affect the tire strain significantly [63]; thus, the effect of velocity is assumed to be negligible in this study. Although by decreasing the tire inflation pressure, the strain is increased, the rate of strain change by the effect of load and speed is almost independent of the inflation pressure [63]; therefore, it is assumed that the tire is used on the manufacturer recommended pressure. For applying the calculated strain to the PEH in COMSOL Multiphysics software, the input tire strain data (from Eq.2) concerning the vehicle speed is converted to the time domain function for one rotation of the 235/60R18 tire traveling at 40 km/h and used as a piecewise function input to prescribe displacement in COMSOL Multiphysics model.

3.4. Adhesive layer

In order to design the PEH system that can successfully work and provide energy to the tire sensors, all the system parts should be studied. One of the system parts is the Adhesive layer. The adhesive layer is used in order to attach the PEH structure to the inner surface of the tire. Along with the PEH structure, this adhesive layer also undergoes cyclic strain caused by tire deflection. Thus the proper adhesive material should be selected.

To choose a proper adhesive that can provide a satisfactory connection between the tire inner surface and the metal host, it is essential to know the amount of stress applied to the adhesive layer. For a vehicle weight range of 1500-3000 kg, the initial load on the tire is 3678.7 - 7357.5 N, which is approximately one-fourth of the vehicle's weight for 4-wheel vehicles. The tire resistance to the vertical load is called tire stiffness (δ) and is reported to be in the range of 150-250 kN/m [67]. The relation between the contact patch length (the length that the tire gets in touch with the pavement) and tire stiffness for a static tire is presented in Eq. 5 [68]:

$$L_{Patch} = 0.7 Z_c \left(\frac{\delta}{Z_c} + 2.25 \sqrt{\frac{\delta}{Z_c}} \right) \tag{5}$$

From Eq. 5, the contact patch length would be around 165-178 mm. It is noted that the load on the contact patch and contact patch length during the tire roiling at various velocities and with different inflation pressures may change. The normal load on a tire at a speed of 56 km/h with an initial load of 707 kg is reported to be in the range of 690 to 753 kg [68]. Therefore, for a tire with 235 mm width, the stress applied to the contact patch is the normal load divided by the contact patch area, and it is around 0.174MPa - 0. 176MPa. In addition, the tire temperature increases during the rolling, and the tire may be used in a range of relative humidity; thus, the adhesive must be durable in different conditions. Cyanoacrylate is an effective commercial adhesive for bonding metal and rubber. The Cyanoacrylate has a tensile bond strength of 12 – 3 MPa in a temperature range of 25 to 150°C and 13 – 11 MPa in the range of 40% to 100% relative humidity on mild steel substrates [69]. By comparing the stress applied to the contact patch and the bond strength of the Cyanoacrylate, it was evident that Cyanoacrylate is a reliable choice for connecting the PEH to the inner surface of the tire for various temperatures and humidity. According to the beam bending theory [70] the strain of the beam layers bonded together is different due to the difference in their elastic modulus. The strain of the Cyanoacrylate layer is reported to be about 25% of the strain of the tire inner surface [66]. This fact is used in the modeling, and only 25% of the tire inner surface strain is applied to the energy harvester.

3.5. Piezoelectric material selection

Typically the piezoelectric materials are brittle, and their strain and stress tolerances are limited. Here the piezoelectric material is going to be used in the strain-based energy harvesting system, and the marital undergoes several cycles of tire deflection. Thus, it was vital to study the piezoelectric material capability in handling the input tire deflection to choose the best material for the PEH system.

3.5.1. Stress and strain analysis

The piezoelectric polymer Polyvinylidene fluoride (PVDF) has a lower piezoelectric strain coefficient (d33) in comparison with piezoelectric lead zirconate titanate (PZT) ceramic. However, it has been used in several strain-based PEHs, because it can tolerate a large amount of strain (about 1%). Temperature change affects the PVDF piezoelectricity effect, and the output charge of PVDF decreases after cooling down [50]. As tire temperature increases during rolling due to friction and cools down once the vehicle stops, the piezoelectric energy harvesters made of PVDF will lose their effect after several cycles. In contrast, PZT has desirable resistance and tolerance to high temperatures but a lower strain limit.

Among PZT ceramics, the soft PZT (PZT-5H) can tolerate the maximum strain of 0.175%; however, the ordinary PZT has a lower strain level of 0.11%, and the hard PZT (PZT-8) has the lowest strain level of 0.105% [71]. The maximum longitudinal strain in the tire inner surface is about 0.3% [72]; therefore, the maximum strain of the adhesive layer would be about 0.075% (25% of the tire strain). In this study, the PZT and soft PZT-5H is chosen as the piezoelectric material for strain energy harvesting in tire since its strain level is in the range of strain transferred from the tire to the piezoelectric material through adhesive layer.

Another vital issue to consider is the yield strength. The yield strength is the point where the elastic behavior switches to plastic response to stress, as seen on a stress-strain curve. Below this point, a material will respond elastically to stress, which means it will return to its original geometry after removing the stress, and no microstructure change is seen. Moreover, beyond the yield point, there might be some microstructure change, and thus some portion of deformation is irreversible and permanent. That is why it is called plastic deformation. The amount of stress applied to the PEH host and the piezoelectric material layer should be less than the yield point. The yield straight of the PZT-5H and the metal host (Non-alloy structural steels structural steel) is 689 MPa [73] and 275 MPa [74], respectively. The stress applied to the contact path is calculated in section 3.4. the stress during the contact patch is about 0.174 MPa - 0. 176 MPa. Both yield strength of the materials is remarkably higher than the applied stress. Thus, the PEH is safe and never reaches the yield point.

3.6. Fatigue analysis

Fatigue is defined as system degradation upon exposure that causes a critical impact on the performance of the component over the lifespan. The degradation in piezoelectric materials depends on the variation of the dielectric properties and material properties of the piezoelectric patch that might change when exposed to cyclic loading, for example. When dealing with fatigue analysis, every component and parameter must be considered beginning with crystal growth, patch fabrication, PEH architecture, and the environmental and loading conditions that the energy harvester is subject to. Defects in the material during fabrication can be a source of weakness that can act as an initiator, which would affect piezoelectric PEHs lifespan. Understanding how piezoelectric patches will endure and ultimately fail upon exposure to these initiators will give useful information for their development. The commonly stated types of fatigue in piezoelectric materials are Crack [75-80], Leakage [81-84], Delamination [85,86], Depolarization [87,88]. Leakage happens when the cracking of the electrode happens. This impacts the ability of the patches to transport the charge flux from the generated electric field with each cycle. When a crack propagates longitudinally to the sharp interfaces within the patch or patch to substrate bond, delamination occurs. When domains shift into an alternative position, a lower net flux in the desired direction of the electrodes is observed as a result [89].

As mentioned earlier, the brittleness of piezoelectric ceramics should be studied further for these PEHs [90]. Certain imperfections in piezoelectric materials generated during crystal growth, such as crystal inhomogeneity, porosities and voids, dislocations, and crystal size, will act as high-intensity factors affecting properties and lead to cracking failure ultimately. In addition, piezoelectric materials are typically attached to the metal host in the PEH. This can be a source of imperfections in this interfacial bond that can induce fatigue phenomena depending on the defects. It is essential to consider these risks when a PEH is planned to be used.

The alternating electric field and polarization caused after each switching cycle lead to gradual degradation of these materials [89]. During the fabrication, the random orientation of grains and crystal lattice make the material need to be poled, which causes the generation of domains in the material [89]. The movement of crystal lattice and domains is induced by extremely high electric fields similar to the initial polarization electric field [89]. Fatigue failure will happen 10^3 cycles sooner in the piezoelectric material subject to a high electric field of more than 200 kV/cm and stress more than 30 MPa [85, 89]. This is not the case for the PEH in this study.

Several studies have focused on the fatigue of the piezoelectric materials and how it affects the lifetime and efficiency of the piezoelectric materials. In these studies, different types of stress are applied to the piezoelectric materials, and the number of cycles before failure is studied. In this study, some of the published data on PZT-5H fatigue is used to estimate the lifetime of the PEH. The experimental fatigue studies for the PZT material show that the lifespan of PZT is around 10^{10} cycles [95-96]. Based on the experimental study reported in Ref [80], the relation of the cycle life of the PZT and the strain is as Eq.6 [84]:

$$c = 2e^{13}(\%\varepsilon)^3 - e^{13}(\%\varepsilon)^2 + 2e^{12}(\%\varepsilon) - 9e^{10} \qquad (6)$$

where ε, is the strain and c, is the cycle life. Based on this equation, the strain increases over time due to the formation of the cracks in the PZT material.

As discussed earlier, the strain limit for the PZT-5H is 0.175%. Based on Eq.6 the PZT-5H material reaches its strain limit around 10^{10} cycles. A tire with a 30 in diameter and speed of 60mph will move with the speed of 560 rpm. If we put the limit life of 10^{10} cycles on the PEH lifespan, the PEH can work inside the tire for 178571 minutes without any fatigue issue. If we assume 3 hours of driving each day. This PEH can work for 992 days (2.7 years).

3.7. Reliability analysis

To consider the PEH design for the autonomous vehicle, it is crucial that the design be reliable for the tire's lifespan. The PEH will provide the power to the tire sensors, and it should be able to do so in the lifespan of the tire. To consider the reliability of the PEH, besides the fatigue analysis, it is important to consider the degradation effect of the piezoelectric material in cyclic stress and temperature.

It is known that if the 30 MPa cyclic load is applied to the PZT-5H the d33 will degrease around 5%, and it means 5% decrease in the ability of the material to produce charge [92]. The temperature affects the lifespan of these PEHs, and temperature cycles caused degradation in the piezoelectric material. Gall and Thielicke [91] had a study that showed that thin-film PZT thin film exhibited a decrease in film capabilities at higher temperatures for a cyclic tensile test. The effects of temperature on fatigue for a PEH were demonstrated by Henslee et al. [93] and Pandey and Arockiarajan [94]. These researchers demonstrated that if the temperature that the cyclic stress and strain are applied to the piezoelectric material increase from 20 C to 50C, the output power of the PEH is decreased around 5% at 1.6 million cycles.

It is very important that at the PEH design stage, based on the power demand in the autonomous vehicle tire sensors, it is recommended to consider this amount (around 10%) in the output power decrease due to the temperature change and degradation due to the cyclic loading in the PEH lifespan.

3.8. Energy harvesting efficiency

Another important parameter for the energy harvesting system is the energy harvesting efficiency, which depends on the amount of accessible energy. Generally, the tire deflection has a significant influence, about 90%, on the rolling resistance of the tire, which is a representative of the total amount of wasted energy [63]. The total rolling resistance force can be obtained from Eq.7 [97].

$$R = f_r N \tag{7}$$

where, R is the rolling resistance force, N is the 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. [97]. Tire vertical forces have approximately 73% effect on the rolling resistance [98]; thus, the final tire deflection energy can be assumed as 65% of the rolling resistance that is the waste of energy of the tire and is obtained by Eq. 8.

$$E_d = {}^{65}\!/_{100}\, R V t_r \tag{8}$$

where, V is the vehicle speed, and t_r is the time needed for one full rotation of the tire. The energy harvesting efficiency of the piezoelectric system is the valuable output energy obtained divided by the total input energy to the system as defined in Eq. 9.

$$\eta = E_{out}/E_{in} = E_{out}/E_d \tag{9}$$

The input energy of the system, E_{in}, is the sum of the tire deflection energy, E_d, and the output energy of the piezoelectric system, E_{out}.

3.9. Effect of temperatures on the PEH performance

Several variables such as vehicle speed, load, type of pavement, and ambient temperature can affect the tire temperature; therefore, the influence of temperature rise on the PEH should be considered. The PEH is connected to the inner surface of the tire; thus, its temperature is estimated by the air temperature inside the tire. Yokota et al. [99] tested the inflated air temperature of a tire traveling at 80 km/h at different ambient temperatures. They reported that the tire inflated air temperature rises from 33°C to 50°C when the ambient temperature rises from 15°C to 35°C. In addition, the d33, d31, and ε33 coefficients of soft PZTs change with the temperature increase [62]. To consider the effect of temperature, the model should take into account the dependency of PZT-5H properties on temperature change. For this aim, a curve is fitted based on the d33, d31, and ε33 data presented in Ref. [62] in the temperature range of 0 to 50, and equations 10-12 are used in the model.

$$\Delta d_{33} = -0.014\mathrm{T}^2 + 1.9\mathrm{T} \tag{10}$$

$$\Delta d_{31} = 0.002\mathrm{T}^2 - 0.75\mathrm{T} \quad (11)$$

$$\Delta \varepsilon_{33} = 0.043\mathrm{T}^2 + 7.76\mathrm{T} \quad (12)$$

In these equations, Δd_{33}, Δd_{31}, and $\Delta \varepsilon_{33}$ are the change in the d_{33}, d_{31}, and ε_{33} with the temperature change, respectively. T is desired temperature. Since the stress and deflection of the steel host affect the deflection of the PZT-5H layer, the effect of temperature on the steel host stress analysis should also be considered. In 2012, Wang et al. [100] proposed Eq. 13, which is used in the model to describe the effect of temperature on the elastic modulus of the steel host

$$E_t = E_{t_0}\left(1.02 - 0.035e^{T/280}\right) \quad (13)$$

In this equation, E_t is the elastic modulus at the desired temperature, and E_{t0} is the elastic modulus at room temperature.

3.10. Modeling process

The analytical process and coupling of the equations are shown in Figure 2. The tire deformation module, geometry model, and the energy demand are calculated at the same time, and then by choosing the proper host and piezoelectric material, the PEH model is developed, and the output power of the PEH is calculated. The steps of the modeling and equations are defined in this section.

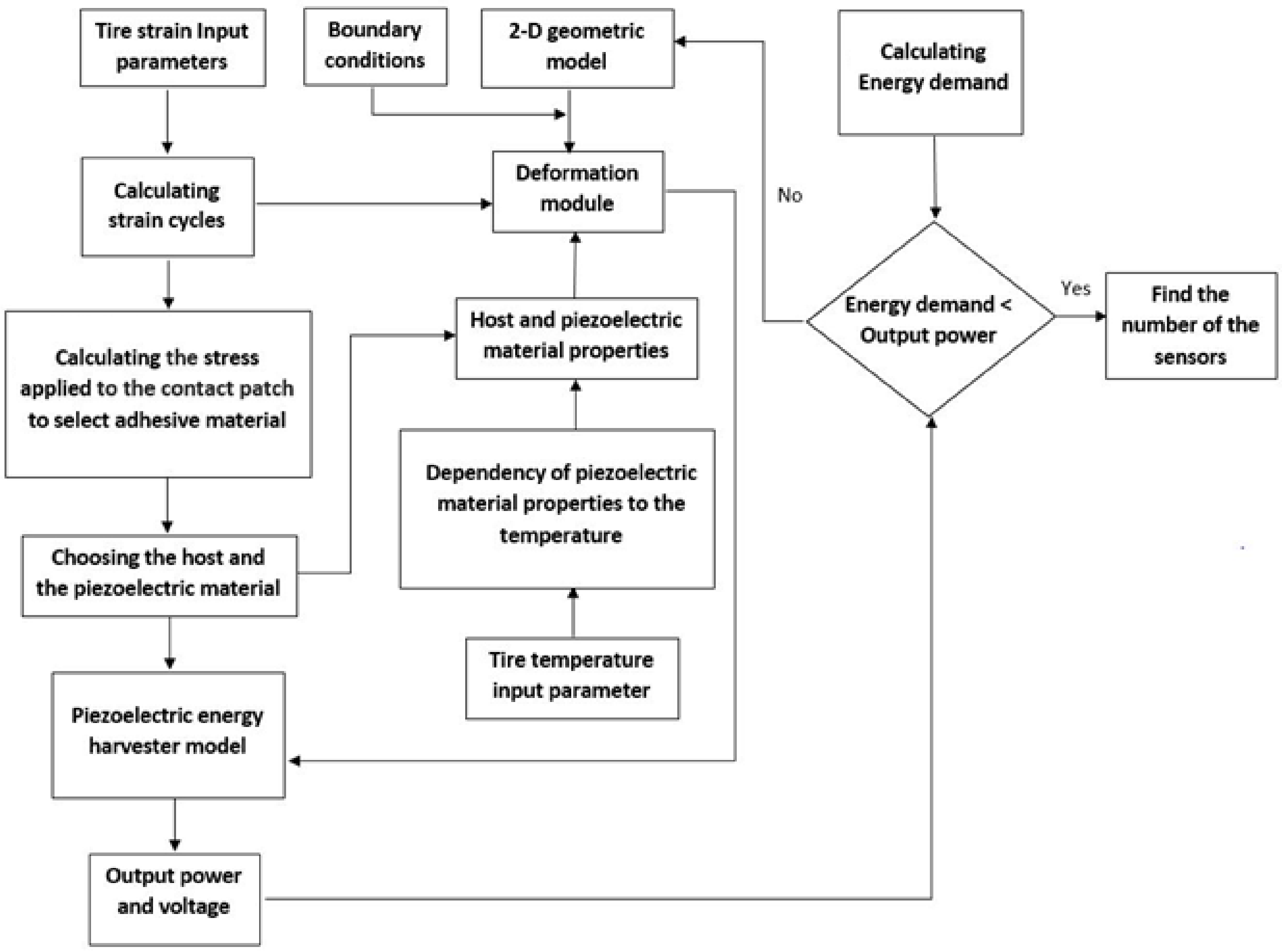

Figure 2. Analytical modeling process and coupling of the equations

3.11. Copyright notice

A significant part of this chapter was adapted with permission from the following publications:

1- Aliniagerdroudbari, H., Esmaeeli, R., & Farhad, S. (2021). Experimental study of a piezoelectric strain-based energy harvester for intelligent tires of autonomous vehicles. ASME 2021 International Mechanical Engineering Congress IMECE2021

2- Aliniagerdroudbari, H., Esmaeeli, R., Hashemi, S. R., Alhadri, M., Zakri, W., Batur, C., & Farhad, S. (2019). Design, modeling, and analysis of a high performance piezoelectric energy harvester for intelligent tires. International Journal of Energy Research, 43(10), 5199-5212.

3- Aliniagerdroudbari, H., Esmaeeli, R., Hashemi, S. R., Nazari, A., Alhadri, M., Zakri, W., ... & Farhad, S. (2019). A rainbow piezoelectric energy harvesting system for intelligent tire monitoring applications. Journal of Energy Resources Technology, 141(6).

4- Aliniagerdroudbari, H., Esmaeeli, R., Hashemi, S. R., Alhadri, M., Zakri, W., & Farhad, S. (2019). A piezoelectric sandwich structure for harvesting energy from tire strain to power up intelligent tire sensors. In 2019 IEEE Power and Energy Conference at Illinois (PECI) (pp. 1-7). IEEE.

5- Aliniagerdroudbari, H., Esmaeeli, R., H., Nazari, A., Hashemi, S. R., Alhadri, M., Zakri, W., ... & Farhad, S. (2018, June). Optimization of a rainbow piezoelectric energy harvesting system for tire monitoring applications. In Energy Sustainability (Vol. 51418, p. V001T02A004). American Society of Mechanical Engineers.

CHAPTER IV

DESIGN AND MODELING DIFFERENT SHAPES OF THE PIEZOELECTRIC ENERGY HARVESTER AND EXPERIMENTAL SETUP

4.1. Outline

In this chapter, different designs of the PEH is presented. Two different designs inspired by the Cymbal energy harvester are studied. Cymbal energy harvester is proven to be useful in energy harvesting with the use of piezoelectric materials [101, 102].

Here for the first time, the modified shape of the Cymbal energy harvester is used for tire application. For this purpose, the shapes for these energy harvesters are modified so that it can be embedded on the inner layer of the tire. In addition, for each proposed design, the detailed shape and structure are discussed, and finally, the modeling equations are presented for each design.

4.2. PEH design based on the Cymbal energy harvester

Mechanical stability should be considered for designing PEH for the tire application. The mechanical stability of the PEH structure in the tire, which undergoes high cyclic stresses in such a small dimension, favors the Cymbal structure. Due to the high curvature of the tire at the contact patch, it is necessary for the part of the energy harvester connected to the tire to be smaller than the contact patch dimensions [38]. The stability and durability of Cymbal transducer are proven under high cyclic stress environments such as roadway pavements [103, 104]. The original Cymbal shape is shown in Figure 3. The external force is applied on the top end cap, and the PEH is attached to the base from the bottom end cap.

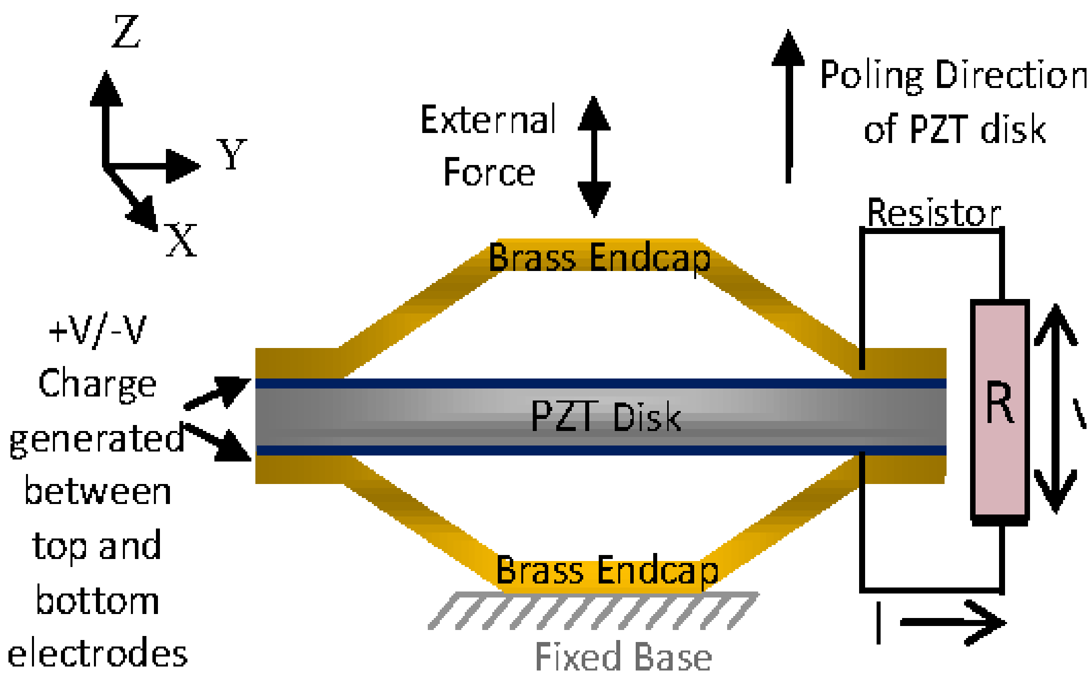

Figure 3. Original Cymbal PEH shape [105]

As it is obvious for tire application, there is no possibility of using the whole Cymbal design. Cause the external force and deflection are coming from the contact patch, which is where the PEH is connected to the inner surface of the tire as a fixed part. Therefore, here the PEH geometry is inspired by Cymbal shape, and some modifications are applied for embedding a design similar to the Cymbal shape on the inner surface of the tire. Here two different designs are studied.

In tire application, only the bottom part of the energy harvester, the metal layer, is connected to the tire's inner surface. The steel cap length, cavity length, and thickness of the steel host are the indicator parameters for the Cymbal PEH design. Mo et al. [106] determined that the smaller ratio of the steel cap length to the cavity length and the smaller thickness of the steel host lead to a higher energy-generating performance of a Cymbal energy harvester under high cyclic loads. They reported that the steel cap length to the cavity length ratio of 0.6 and the steel thickness of 2 mm is the reliable design parameters for which the stress present in the endcaps are within the steel and piezoelectric material endurance limits [106]. Considering the studies done by Mo et al. [106] relations of the Cymbal geometry, the structure and dimensions for two new PEH are designed.

Different materials are chosen for the metal base and the piezoelectric material for two designs based on the Cymbal energy harvester. Steel and aluminum are chosen as the metal base for the first and second designs based on the Cymbal energy harvester, respectively. As discussed in the piezoelectric material selection section, the PZT-5H and PZT both can tolerate the tire inner surface. The PZT and PZT-5H are selected as the piezoelectric materials for the first and second designs based on the Cymbal energy harvester, respectively.

In addition, the yield tensile stress strength limit of the streel caps (250 MPa), the PZT-5H (35 MPa), and PZT (81 MPa) are the constraints of the design. Referring to the adhesive selection calculations, the stress on the contact patch area is within 0.174 MPa - 0.176 MPa, which is much lower than the yield stress limit of the selected materials.

The external load resistance is modeled in COMSOL Multiphysics software to indicate the electrical power output in both designs. The output energy taken from the harvester can be determined by considering the stress distribution of the metal substrate, the electrical circuit of the load resistance, and the constitutive equation of piezoelectric material. The circuit model is out of the scope of this study, and readers may refer to Ref. [107] to find more information on the circuit model.

4.2.1. First design based on the Cymbal energy harvester

The first design of the PEH, as shown in Figure 2, is embedded on the inner surface of the tire for harvesting energy from tire bending. As it is obvious from Figure 4 the new geometry of PEH is inspired by the original shape of the Cymbal harvesters shape [6].

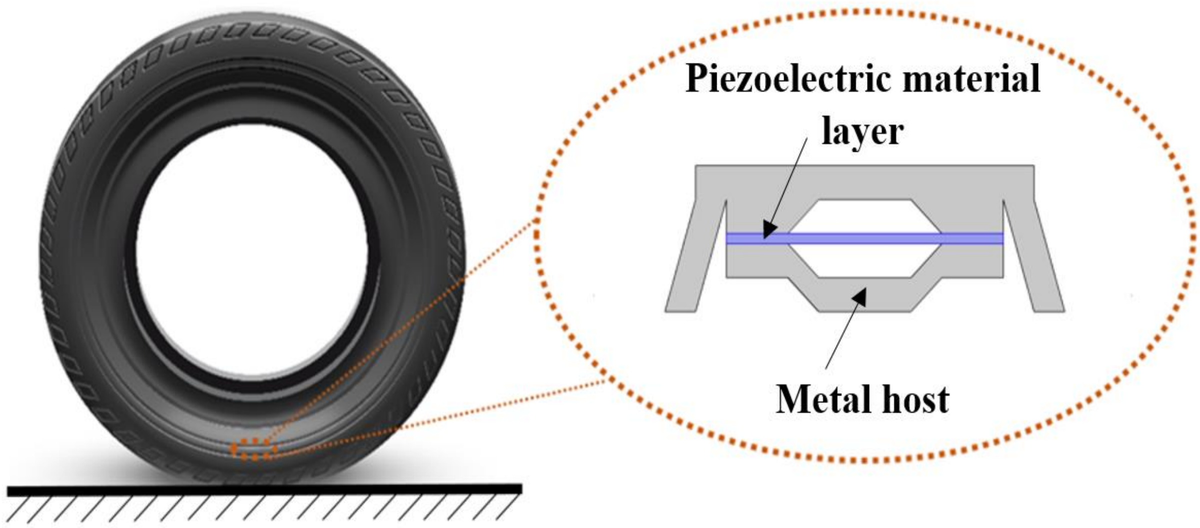

Figure 4. The first PEH design based on Cymbal PEH shape embedded on the inner layer of the tire

The first design based on the Cymbal energy harvester contains a flexible metal substrate and piezoelectric material layer, shown in Figure 5. Two supporting legs are designed to make it possible for the PEH to be used in the tire. The top and bottom metal layers are connected to the piezoelectric material layer at the end caps. At the same time, there is a gap separating each metal layer from the piezoelectric material layer, as shown in Figure 4. Using such gaps in the design lets the end caps convert a part of the radial displacements into longitudinal displacement in the PEH and amplify the resulting displacement. Thus, the piezoelectric material can benefit from both radial and longitudinal displacements. This will make both d_{33} (piezoelectric charge constant parallel to the poling direction), and d_{31} (piezoelectric charge constant perpendicular to the poling direction) coefficients contribute to the performance of the energy harvester [108]. Electrode caps on top and bottom of the piezoelectric material are connected to a load resistance to measure the electrical power output, modeled as an electric circuit.

The dimensions of the first design are given in Figure 5 as calculated in the adhesive section from Eq. 5; the contact patch length is around 165-178 mm. The total length of the PEH for the first design is just 11 mm that is much smaller than the contact patch length; thus, as mentioned in Ref. [38], it is acceptable.

Table 1 lists the input parameters for the PEH modeling for the first design based on the Cymbal shape. The depth of the energy harvester is set as 5 mm. The material properties are chosen from the material library of COMSOL Multiphysics software.

In the COMSOL Multiphysics model of the PEH the relative humidity is considered constant at 35%. The relative humidity was measured in the experimental study, and it was always around 35% to 50%. The effect of relative humidity on the performance of the PEH is not considered in this study and can be a possibility for future work.

Table 1. The material and model input parameters for the first design of the PEH based on Cymbal energy harvester

Item	Structural Steel	Soft ceramic Lead Zirconate Titanate (PZT- 5H)
Young's modulus (GPa)	205	64
Density (kg m^{-3})	7850	7500
Piezoelectric coefficient, d_{33} (pC/N)	–	585
Piezoelectric coefficient, d_{31} (pC/N)	–	-265
External load resistance (kΩ)	–	1
Dimensions	Refer to Figure 5	Refer to Figure 5
Depth	5mm	5mm
Temperature	23°C	23°C

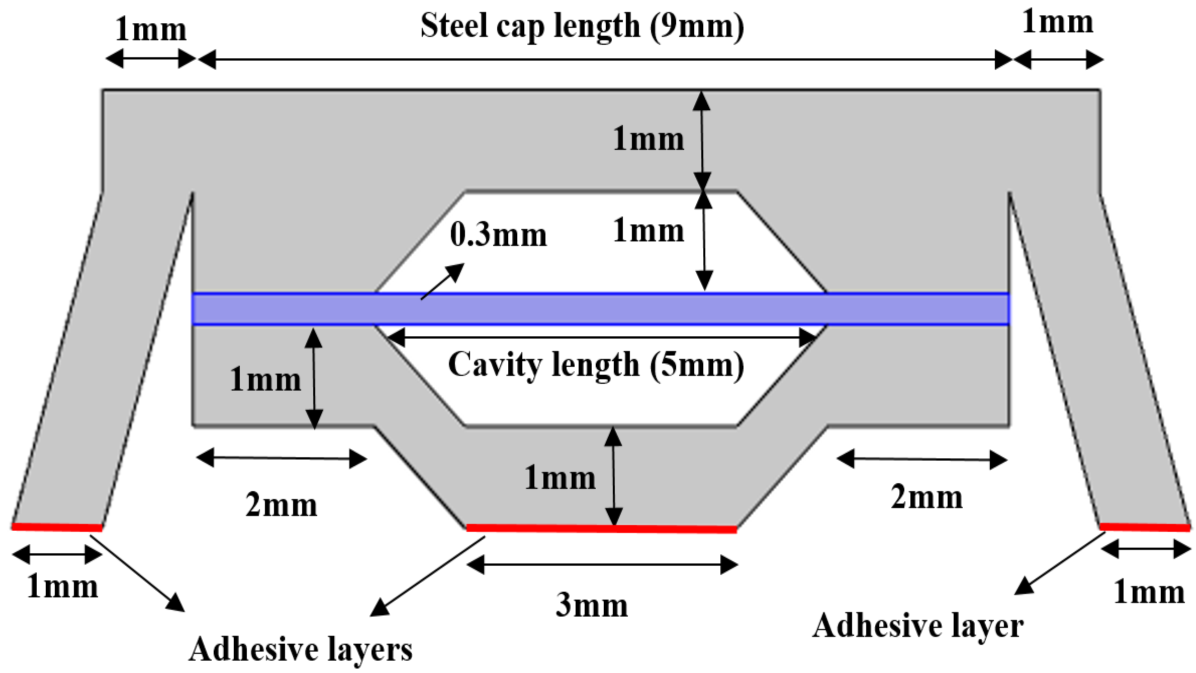

Figure 5. First PEH design based on Cymbal PEH shape

4.2.2. Second design based on the Cymbal energy harvester

As shown in Figure 6, the Second design based on the Cymbal energy harvester is embedded on the inner layer of the tire, and while the tire reaches the contact patch, the tire strain makes the energy harvester deflect. Because of the piezoelectric material nature, the energy harvester deflection is turned to electrical energy.

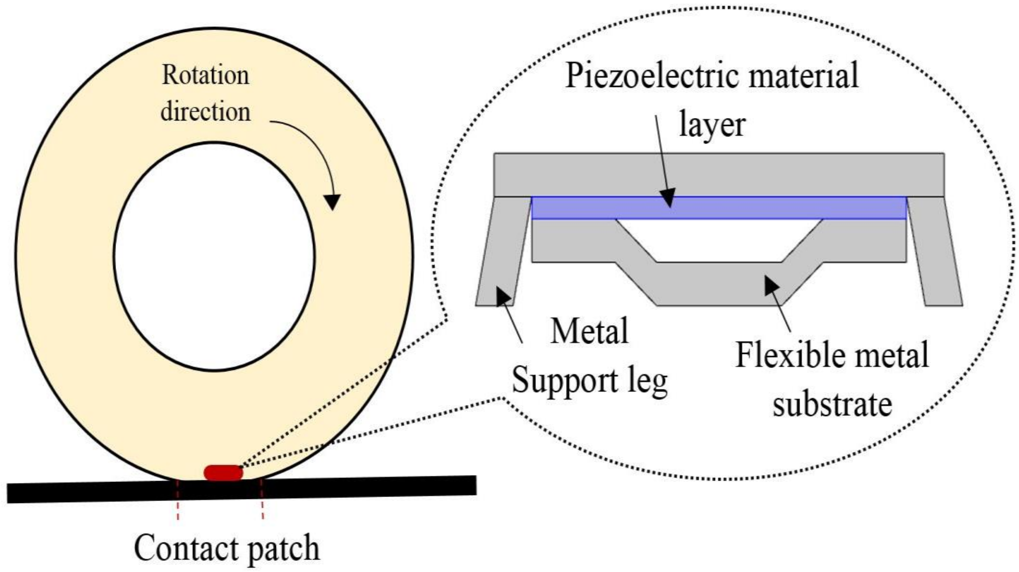

Figure 6. The second PEH design based on Cymbal PEH shape embedded on the inner layer of the tire

The second design of the energy harvester also consists of a flexible metal substrate and piezoelectric material layer, as shown in Figure 6. Aluminum is chosen for the metal substrate due to its lightweight. To maintain the tire balance, the energy harvester cannot be massive or too large in size. Ceramic Lead Zirconate Titanate (PZT) is chosen for the piezoelectric material. The material properties used in the model are taken from the material library of COMSOL Multiphysics software and are presented in Table 2. The dimensions of the piezoelectric energy harvester are given in Figure 7. The depth of the energy harvester is set as 5 mm.

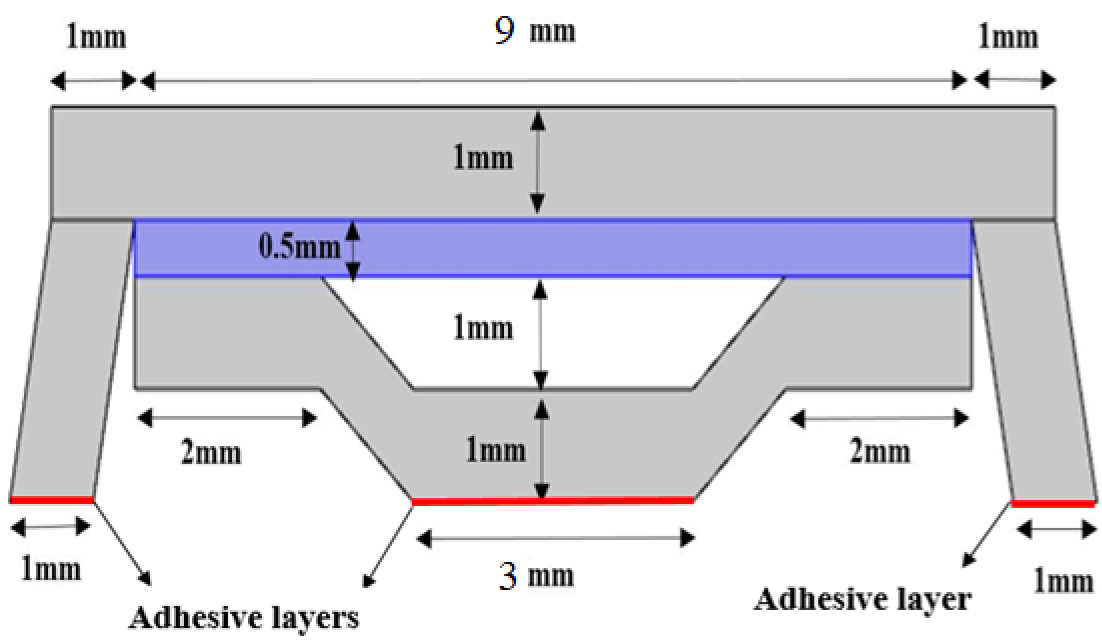

Figure 7. Second PEH design based on Cymbal PEH shape

Same as the first design, to make the second design of the energy harvester based on the Cymbal shape feasible for embedding on the inner layer of the tire, two support legs are designed, and just the bottommost of the metal layer and legs are attached to the inner tire layer. The top metal layer is attached to the piezoelectric material layer. The middle part of the bottom metal layer is separated from the piezoelectric material layer using a gap, and the end parts are attached to the piezoelectric material layer as shown in Figure 7. Because of the presence of the gap, the radial displacements are converted to the longitudinal displacement at the locations where the bottom layer of the metal is connected to the piezoelectric material. As a result, both piezoelectric charge constant parallel (d_{33}) and perpendicular (d_{31}) to the poling direction have a role in energy harvesting [108].

Table 2. The material and model input parameters for the second design of the PEH based on Cymbal energy harvester

Material	**Aluminum substrate**	**Ceramic Lead Zirconate Titanate (PZT)**
Young’s modulus (GPa)	69	66
Density (kg m^{-3})	2700	7800
Piezoelectric coefficient, d_{33} (pC/N)	N/A	311
Piezoelectric coefficient, d_{31} (pC/N)	N/A	-166
External load resistance (kΩ)	N/A	100
Dimensions	Refer to Figure 7	Refer to Figure 7
Depth	5mm	5mm
Temperature	23°C	23°C

4.2.3. Cymbal energy harvester modeling

In this Model, the modeling geometry is a modified shape of the Cymbal piezoelectric energy harvester discussed in previous sections, made of the flexible metal base and the piezoelectric material layer. The output energy of the PEH is determined from the stress distribution of the metal host and solving the constitutive equations of the piezoelectric material stated in Eqs. 14 and 15.

$$S_j = s^E_{ji}\sigma_i + d_{jm}E_m \tag{14}$$

$$D_m = d_{mj}\sigma_j + \varepsilon^T_{km}E_k \tag{15}$$

In these equations, S, T, E and D, are the strain, stress, electric field and electric charge displacement tensors, respectively. In addition, s^E is the compliance tensor measured at the constant electric field, d is the piezoelectric strain constant tensor, ε^T is the dielectric permittivity coefficient tensor measured at constant stress. Furthermore, i, j = 1, . . . , 6 and k, m = 1, 2 ,3 represent different directions in material coordinate system. Since the external electric field is zero under the tire deflection, Eqs. 16 and 17 are simplified to [104]:

$$P = \sum_{i=1}^{6} d_{3i}\sigma_i \tag{16}$$

where, P is the polarization of the piezoelectric material that generates an internal electric field (E_{in}):

$$E_{in} = \frac{P}{\varepsilon^T_{33}} = \sum_{i=1}^{6} g_{3i}\sigma_i \tag{17}$$

where, g_{3i} is the piezoelectric voltage constant and ε_{33} is the relative permittivity. The relation between the piezoelectric voltage constant (g) and piezoelectric strain constant (d) is:

$$g_{3i} = \frac{d_{3i}}{\varepsilon_{33}^{T}} \tag{18}$$

Finally, the voltage generated by polarization changing is:

$$V = \int E_{in} dh_P \tag{19}$$

where, hp is the piezoelectric material layer thickness. The output electric energy (U) of the PEH can be calculated from Eq. 20 [104].

$$U = \frac{1}{2} P E_{in} A_p h_p \tag{20}$$

where, Ap is the piezoelectric material layer surface area.

4.3. Experimental setup

The material properties chosen for the experimental analysis are presented in Table 3. The Waterjet cutting method is used to cut the top and bottom layers of the PEH from the low carbon steel bar. The size of the PEH is compared with a quarter coin in Figure 8 to show how small the proposed PEH is, and it will not affect the tire dynamics. The surface area of the PEH, which is attached to the inner layer of the tire, is about 0.2% of the whole tire inner surface.

The proposed design for the experimental analysis is shown in Fig 9. This design had a piezoelectric material thickness of 0.3mm, and this thickness was not commercially available and custom building of this thickness was expensive. Thus, the commercially available piezoelectric material sheet with a thickness of 0.5mm is chosen in this study. By choosing the 0.5mm as the PZT-5H thickness, the whole PEH is still in the 5mm limit for the PEH height.

Table 3. Material properties of the built PEH components.

Parameter	Low carbon Steel	PZT- 5H
Young's modulus (GPa)	210	64
Density (g cm−3)	7.85	7.500
d33 (pC/N)	–	585
d31 (pC/N)	–	-265
ε33	–	3400
Dimensions	Presented in Figure 2	9mm×0.5mm×5mm

Figure 8. Top and bottom layers of the PEH manufactured from low carbon steel by the use of the waterjet cutting method.

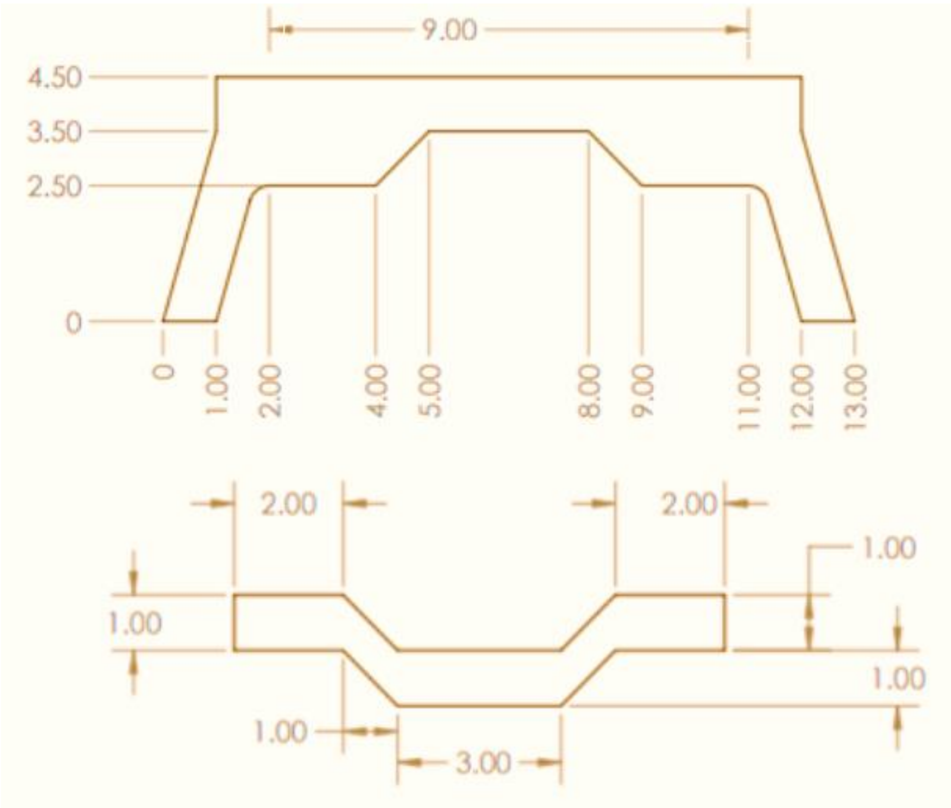

Figure 9. Design and dimensions of the PEH.

The aim is to experimentally measure the output voltage/power of the PEH, while it is attached to the inner layer of the tire. Most of the experimental setups in the literature lack realism. Usually, for this type of measurement resistance control box and the digital multimeter is used. However, this method needs a wired connection drilling into the rim or tire that is so complicated and may damage the tire or rim. Another option is to simulate the tire deflection on a laboratory scale for the tire section. This setup tends to mimic all conditions in an actual application; however, there is some complexity arising from deflections inside the tire, which affects the accuracy of measurement.

Furthermore, the effects of the forces resulting from tire rotation in a cymbal PEH are not discussed. Therefore, a test setup close to the real world should be prepared for testing PEH for tire application. Testing with the use of the mobile tire testing rig on the real pavement condition is the preferred and most realistic method, but this method needs infrastructure, and it is expensive. In this paper, the Hunter Engineering Road Force Elite machine [109], typically used to test tire performance, vibration, uniformity, and balance, is used to simulate the road conditions in the stationary testing setup. The use of the Road Force Elite machine for the experimental analysis of the PEH has several advantages. One advantage of this machine is its ability to simulate the tire-road conditions in a stationary situation. This method of testing is inexpensive and available in the laboratory scale. Finally, using this machine, the effect of PEH on the tire dynamic and balance can also be studied.

In order to solve the problem of wiring for conducting the measurement, the wireless measurement system based on Arduino hardware measuring system is used. The Arduino MKR1000 has a built-in Wi-Fi shield and two analog inputs for the voltage and current sensors. The experimental setup is shown in Figure 10. After dismounting the tire from the rim, the PEH and measurement system are attached to the inner layer of the tire using an ordinary commercial glue; and the data is transferred to the developed MATLAB code through the wireless connection. The PEH is electrically attached to the two analog inputs of the Arduino hardware measuring system. Then, the tire is remounted onto the rim and placed onto the Road Force Elite machine (Figure 11) [109]. The tire pressure is measured for each test using the Road Force Elite machine to control the tire situation.

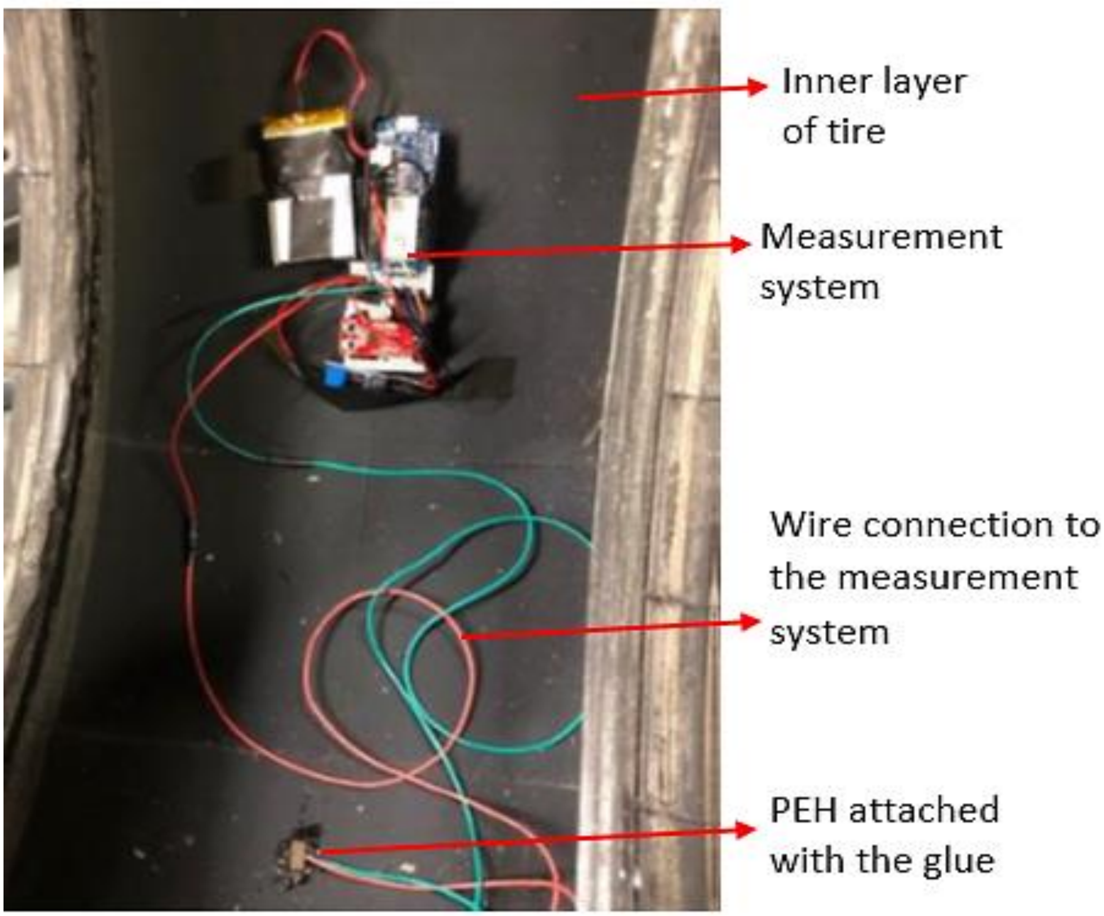

Figure 10. The experimental setup. The PEH and the measurement system are mounted on the inner layer of the tire.

Figure 11. The experimental setup. The tire setup on the Road Force Elite machine [109].

4.4. Copyright notice

A significant part of this chapter was adapted with permission from following publications:

1- Aliniagerdroudbari, H., Esmaeeli, R. & Farhad, S. (2021). Experimental study of a piezoelectric strain-based energy harvester for intelligent tires of autonomous vehicles. ASME 2021 International Mechanical Engineering Congress IMECE2021

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CHAPTER V

RESULTS AND DISCUSSION

5.1. Outline

In this work, two new shapes of the PEH were designed and modeled using COMSOL Multiphysics software. The purpose of the PEHs is to provide a sufficient amount of power to the sensors embedded on the inner surface of the tire in order to monitor the tire-road condition. In this chapter, first, the model validation is presented. During the validation, the developed COMSOL Multiphysics model is compared to the published research. After being confident that the developed model is validated, each design's output power, energy, and voltage are studied. Finally, the temperature effect on the performance of the PEH for tire application is discussed.

5.2. Model validation

One of the standard techniques for validating a finite element study is to compare it with an experimental study. In this study, the developed PEHs inspired by Cymbal geometry are all new and have never been used for tire strain energy harvesting. Thus, there is not any experimental study available for validation. Therefore, for the validation purpose of the PEH models based on the Cymbal energy harvester, an experimental study that applies cyclic force to the original shape of these PEH is chosen. The geometry of the chosen researches is developed, and the boundary conditions, same as the experimental studies, are applied. Then the results of the developed models are compared to the experimental results.

5.2.1. Model validation for the PEH based on Cymbal energy harvester

Daniels et al. [105] studied the effect of external load resistance and load frequency on the output voltage of a Cymbal PEH experimentally. The shape and dimensions of Cymbal PEH studied by Daniels et al. [105] is shown in Figure 12. They designed the Cymbal PEH to be placed in the heel of shoes and harvest the wasted energy of the human while walking. Their PEH, consisting of 0.3 mm Brass host and 1 mm PZT disk, is reproduced in our model. Their boundary conditions are also reproduced, and a 50 N constant excitation force at the frequency of 2 Hz is applied to the top brass cap of the PEH, while the bottom cap is kept fixed. As demonstrated in Figure 13, a good agreement between the output voltage obtained by Daniels et al. [105] and our model is observed. The comparison of our model with experimental data shows a maximum error of about 2%.

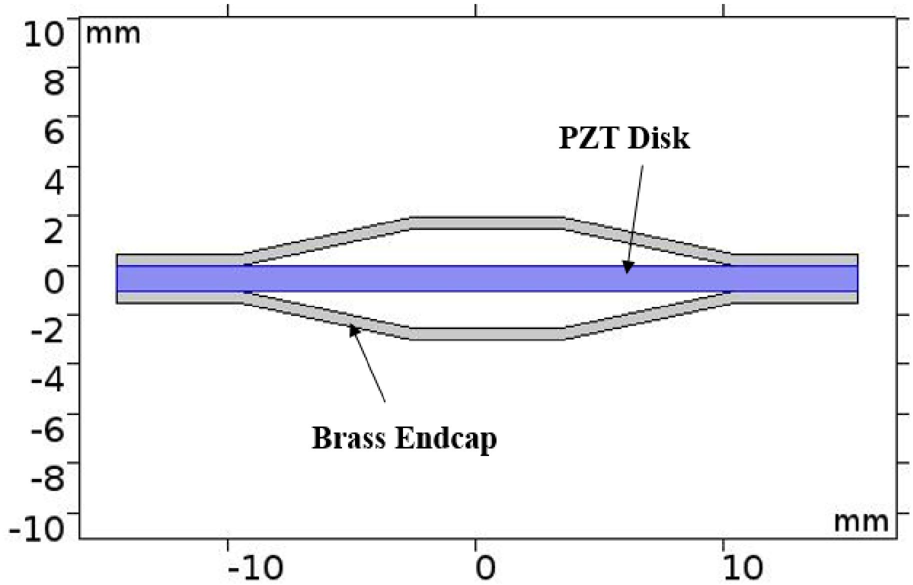

Figure 12. Cymbal energy harvester geometry used for validation with experimental results reported by Daniels et al. [105].

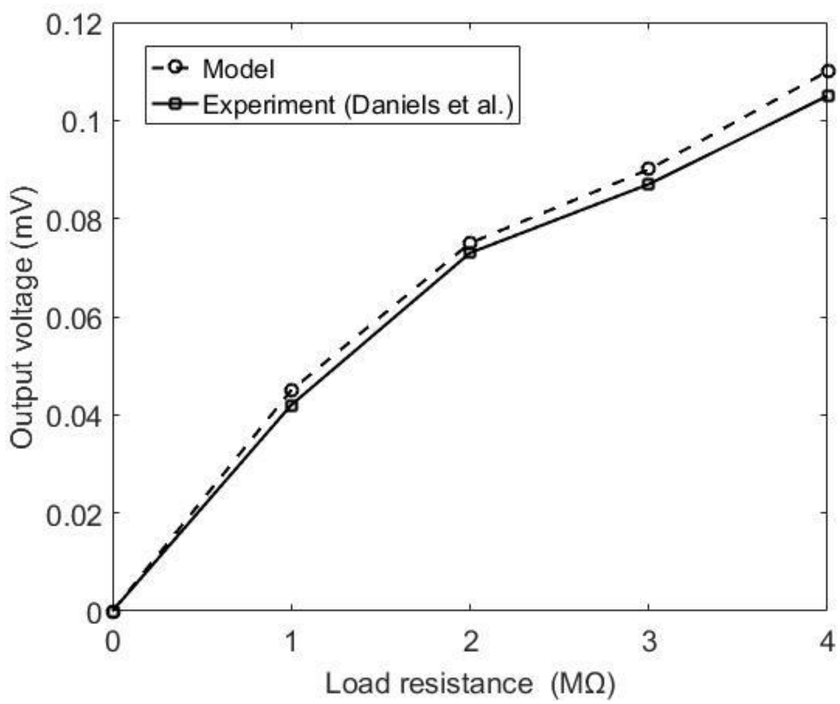

Figure 13. Comparison of the developed model with Daniels et al. [105] experimental results for 50N constant excitation force at 2 Hz.

5.3. Mesh independency analysis

The mesh independency analysis is necessary for the finite element analysis. In this study, the mesh independency analysis is done for one of the designs to ensure the total mesh element size, shape, and time step do not affect the results of the developed model.

The first PEH design based on the Cymbal energy harvester is modeled as it is connected to the inner layer of the tire. The finite element discretized model geometry is shown in Figure 14. The total mesh element size of 301, 1509, 5552, and 14096 are chosen, and the output power of the PEH is compared. It is noticed that the total mesh element size higher than 1509 does not have much impact on PEH output power, and by using the total mesh element size of 14096 the computational time and cost will be increased significantly. The PEH output power is compared with the two different mesh shapes while the total mesh element size is set as 5552 elements. The results have less than 0.02% difference by using triangular and quadrilateral mesh shapes.

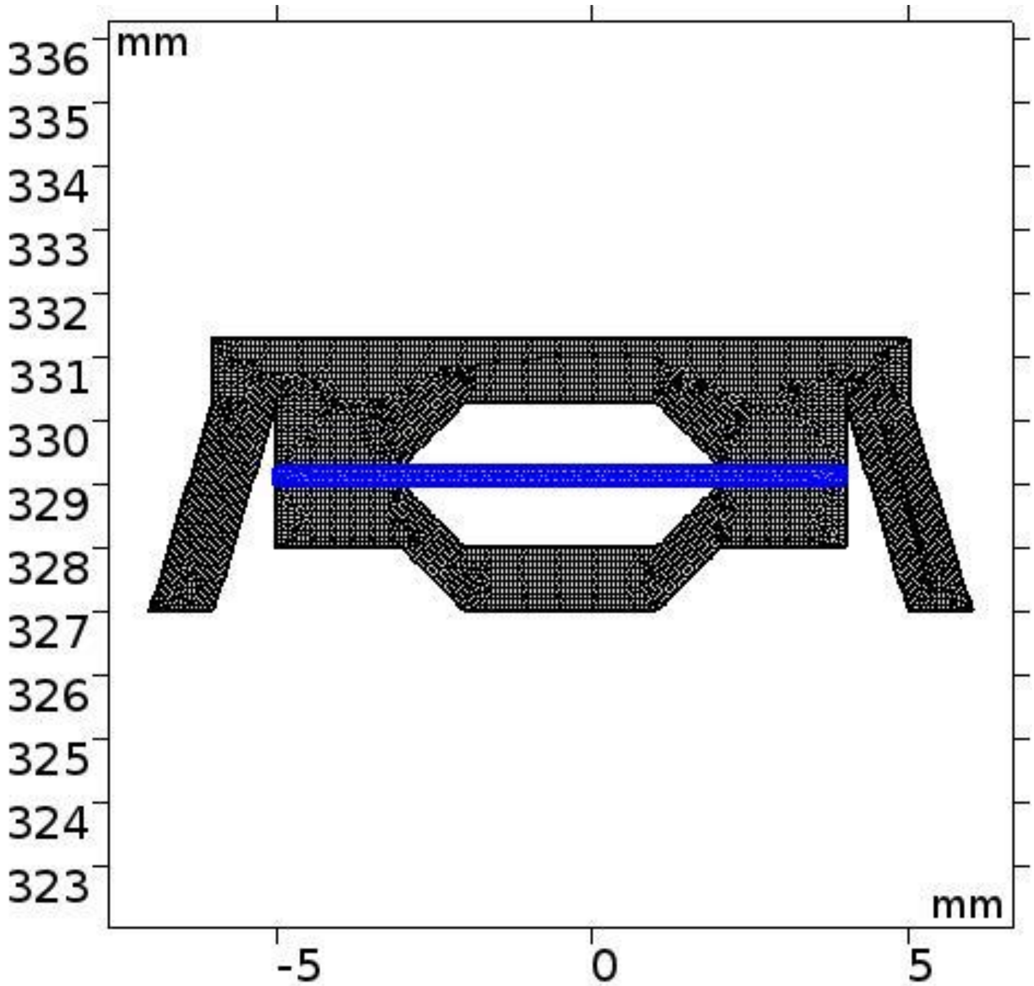

Figure 14. The finite element discretized model geometry of the first PEH design based on the Cymbal energy harvester

5.4. Tire deflection

The displacement of the 235/60R18 tire traveling at a speed of 40 km/h for one complete rotation (360°) is calculated from Eqs. 2-4 and presented in Figure 15. As it is obvious, the inner surface of the tire becomes under tension. In addition, just after and before the contact, the inner surface of the tire becomes under compression. The tension of the tire inner surface is higher than the compression before and after the contact patch. The maximum strain of the inner surface of tire is about 3150 με (microstrain). Although the effect of velocity on the tire strain is assumed to be negligible, it should be considered that by increasing the vehicle speed, the time duration that the PEH passes through the contact patch decreases. Thus, the voltage is generated in a smaller time period, and the time between two consecutive maximum voltages is decreased.

As discussed in previous chapters, almost 25% of the tire inner surface strain is transferred through the Cyanoacrylate adhesive layer [66], therefore in this study, only 25% of the tire strain is calculated and shown in Figure 8 is applied to the designed PEHs.

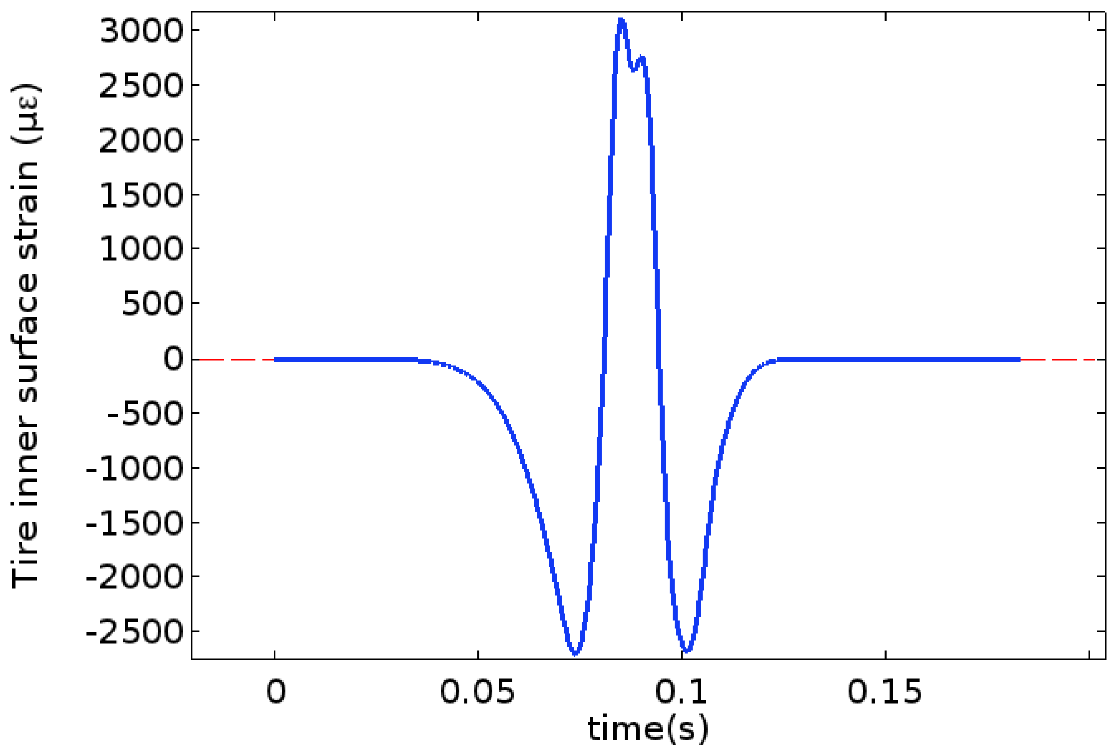

Figure 15. Strain of inner surface of a 235/60R18 tire traveling at 40 km/h for one complete rotation.

5.5. PEH output power, voltage and energy

5.5.1. First PEH design based on the Cymbal energy harvester output power, voltage, and energy

The output electric power and voltage in one full rotation of tire are shown in Figures 16 and 17, respectively. As seen, the maximum electric power and voltage are 2.86 mW and 3.5 V, respectively. The total accumulated energy harvested in one full rotation of tire is around 24 μJ/rev. In the modeling of the PEH the relative humidity is considered constant at 35%.

It should be noted that the generated output voltage signal is AC. A rectification device or an AC-DC converter will be required when the sensor operates with DC input power. In addition, vehicles travel at different speeds; thus, the output AC signal at different speeds is not uniform. Using the AC-DC convertor is recommended to have a consistent input power to the sensors. To power up the tire sensors in situations where energy harvesting is not applicable, such as situations where the vehicle is not moving, it is possible to save the produced energy using a charging capacitor.

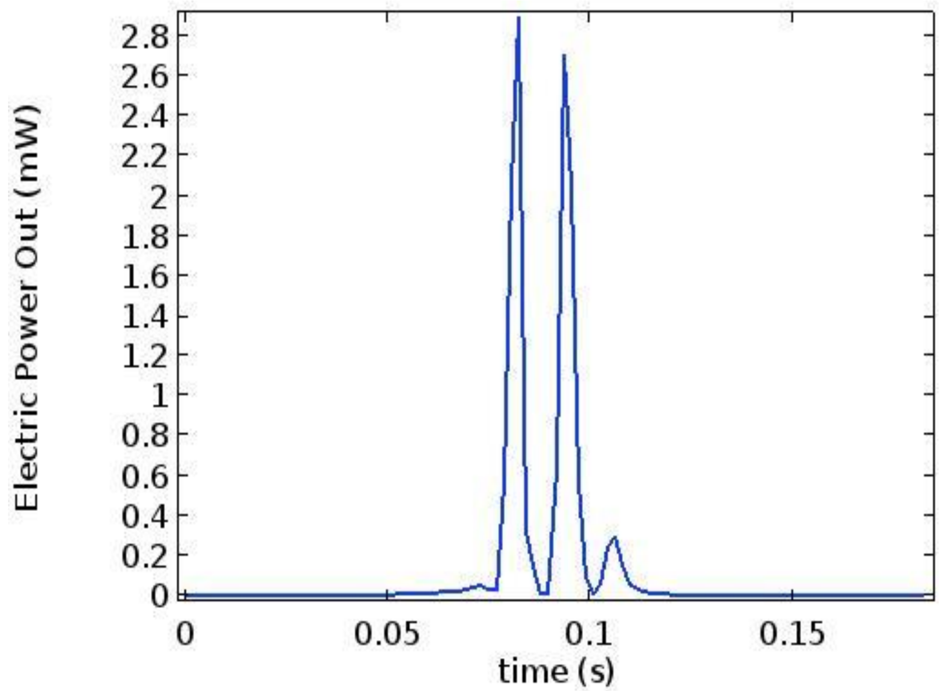

Figure 16. The first designed PEH output electric power for one full rotation of tire.

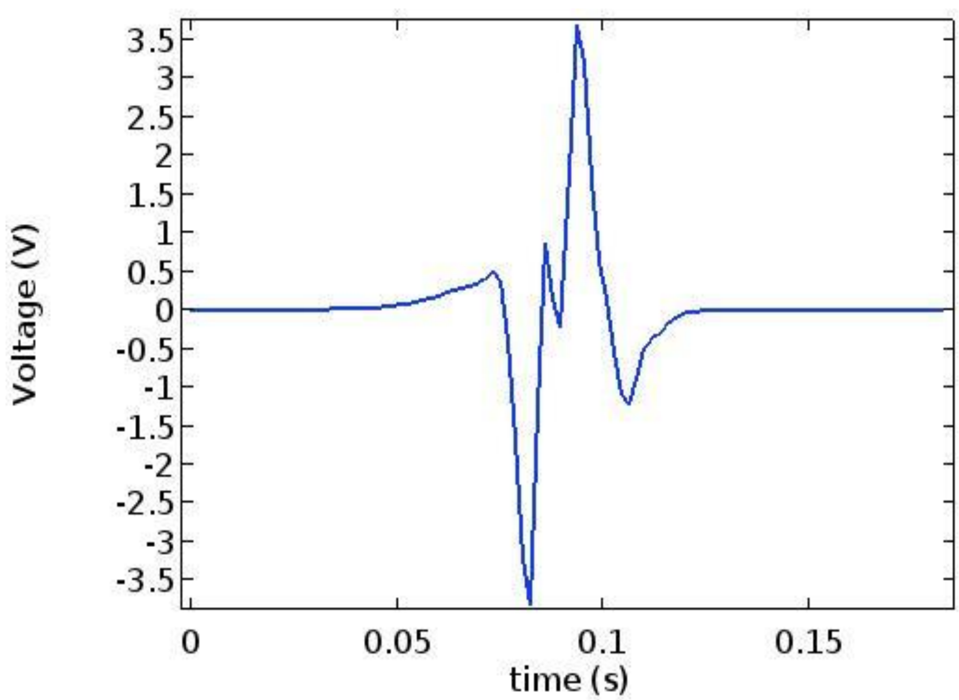

Figure 17. The first designed PEH output electric voltage for one full rotation of tire.

5.5.2. Second PEH design based on the Cymbal energy harvester output power, voltage, and energy

In Figures 18 and 19 the output electric voltage and power in one full rotation of tire are plotted. The maximum amount of electric power and voltage are 5.2 mW and 7 V, respectively. The total energy harvested in one full rotation of tire is 65 µJ/rev.

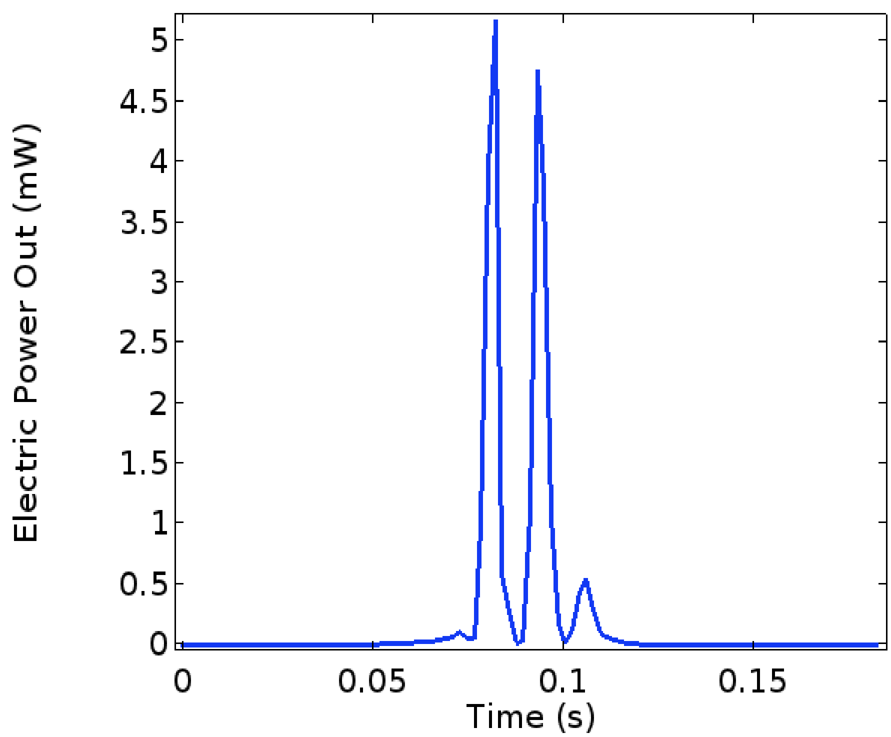

Figure 18. The second designed PEH output electric power for one full rotation of tire.

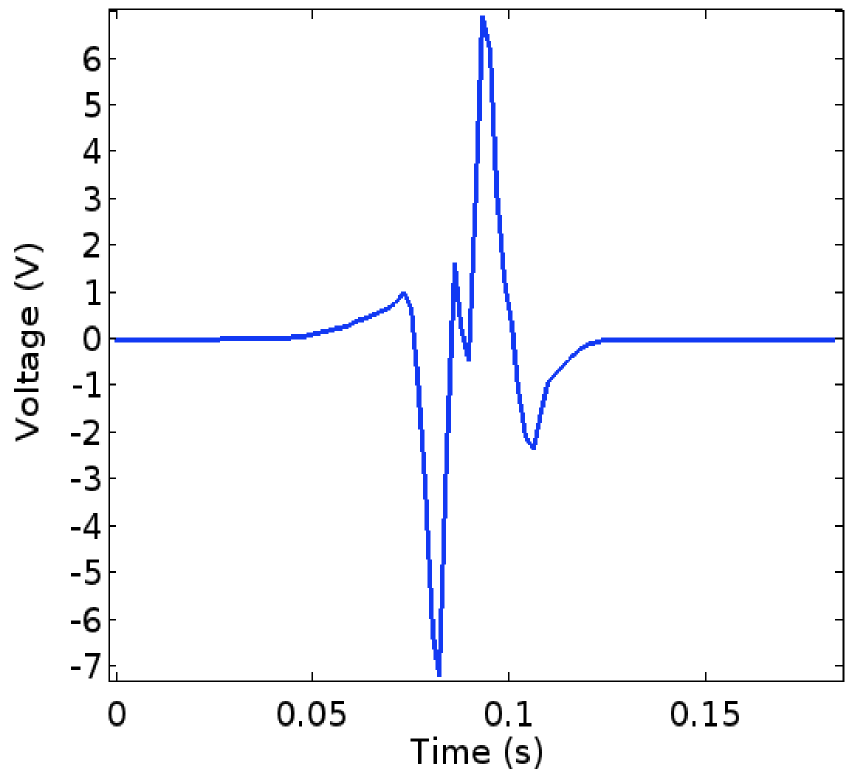

Figure 19. The second designed PEH output electric voltage for one full rotation of tire.

As shown before, the first and second designs of the PEH harvest 2.86 mW and 5.2 mW, respectively. In intelligent tire application, the goal is to provide sufficient energy for tire embedded sensors. It is known that in a TPMS with 10-60 sample/min transmission speed, an energy need of about 120 µW – 1 mW is required [47]. The harvested energy achieved in this study using the first design is sufficient for 1 to 2 sensors of this type. Also, the harvested energy using a second design is sufficient for 1 to 5 sensors of this type.

From Eq.1, 8.7 µJ/rev is required for one wireless tire sensor, and the amount that the energy harvester proposed in this study can provide is sufficient for two sensors of this kind.

In addition, it is reported that an average TPMS needs 10 μJ/rev for wireless communication with the vehicle control system [110]. The first and second designs of the PEH provide 24 μJ/rev and 65 μJ/rev as output energy. Therefore, the proposed first and second PEH design is sufficient for 2 and 5 sensors of this type.

Furthermore, from Eq.1, it is calculated that the required energy for an accelerometer embedded inside the tire to measure and wirelessly communicate with the vehicle control center is about 8.7 μJ in each tire rotation. Also, the proposed piezoelectric energy harvester's first and second design is capable of powering up about 2 and 9 sensors of this type.

In addition, it is reported that for a vehicle traveling at a speed range of 60-120 km/h with a TPMS with high transmission speed (60 sample/min), the required energy is about 30-60 μJ/rev [47]. Only The second PEH design can supply energy for this type of high transmission speed TPMS at 120 km/h. As it is reported in Ref. [45], by increasing the load resistance, the output power of the strain-based energy harvester is increased. Consequently, if a higher power output is needed, it is possible to increase the load resistance.

Although the flexible metal base material, piezoelectric material, and dimensions of the designs were different, both provide sufficient power output to provide power to the sensors embedded on the inner layer of the tire.

The designed PEH output electric power is higher than most of the reviewed PEHs. The highest power output in the literature (6.5 mW) is achieved using a high load resistance (42 kΩ) and a large PEH structure of brass with 40 mm diameter and 0.3 PZT as the piezoelectric material [25]. As discussed before, to maintain the tire balance, the PEHs embedded on the inner layer of the tire should be small [38]. In addition, the 42 kΩ is a considerable load resistance, and in reality, the TPMS may have a much lower equivalent load impedance. For the strain-based PEHs, the output power is decreased significantly by a decrease in the load resistance [45]. Thus, by using smaller load resistance, the 6.5 mW output power is not achievable. The rainbow PEH with 5.85 mW output electric power is introduced in Ref. [45], which needs the specific piezoelectric manufacturing process to have the curved piezoelectric structure; however, the advantage of the PEHs here is the absence of difficulty to manufacture just by using the piezoelectric material sheet and gluing it to the metal host.

5.6. Energy harvesting efficiency

The energy harvesting efficiency is calculated for all the PEH designs. For a tire with an inflation pressure of 34 psi and a vehicle weight of 2500 kg, the rolling resistance coefficient is 0.016 [97]. Using Eq. 1, the rolling resistance force would be 10 lbf. Hence, the tire wasted energy in each rotation of the tire would be 13.31 J/rev as calculated from Eq. 2. Based on Eq. 3 and the output energy of the PEHs, the energy harvesting efficiency of the designed PEHs can be calculated. The energy harvesting efficiency for the PEH first and second designs is 0.019% and 0.068%, respectively.

5.7. Stress Analysis

The displacement of the 235/60R18 tire traveling at a speed of 40 km/h for one complete rotation (360°) is calculated from Eqs. 2-4 and presented in Figure 20. As it is obvious, the inner surface of the tire becomes under tension. In addition, just after and before the contact, the inner surface of the tire becomes under compression. It is obvious that the tension of the tire inner surface is higher than the compression before and after the contact patch. The maximum strain of the inner surface of the tire is about 3150 με (microstrain). The stress and deformation are applied to the PEH due to the tire passing the contact patch. Figure 20 shows the times that the maximum deflection happens when the PEH passes through the contact patch. Time 0 is the time that PEH reaches to the contact patch.

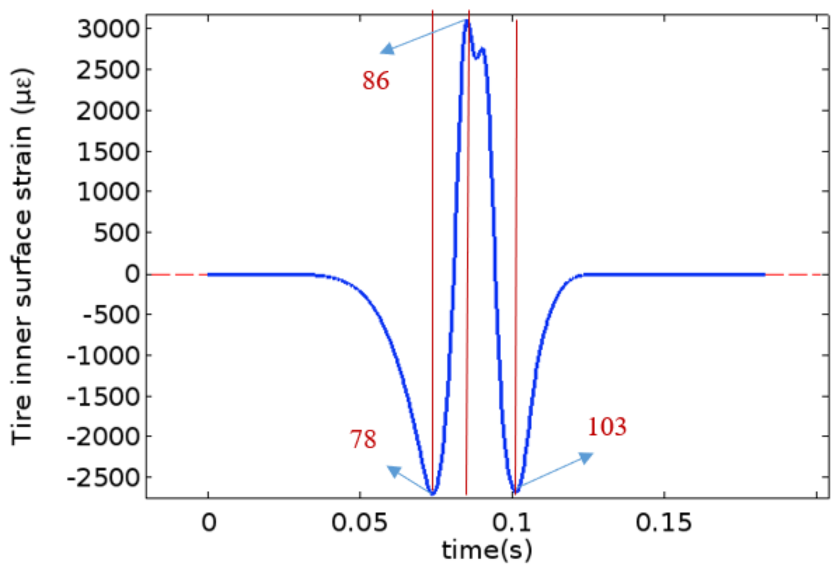

Figure 20. The effect of the PEH first design thickness on the output electric energy for one full rotation of tire

The Von-Misses stress is shown these three pick deflection paint is shown is Figures 21-23. The yield stress of the PZT-5H and the metal host (Non-alloy structural steels structural steel) is 6.89×10^8 Pa [73] and 275×10^8 Pa [74], respectively. From the figures 21-23 the maximum Von-Misses stress in the whole PEH is around 9.5×10^7 Pa.

The yield stress of both steel and PZT-5h is much higher than the maximum Von-Misses stress in the PEH; therefore, the design is safe.

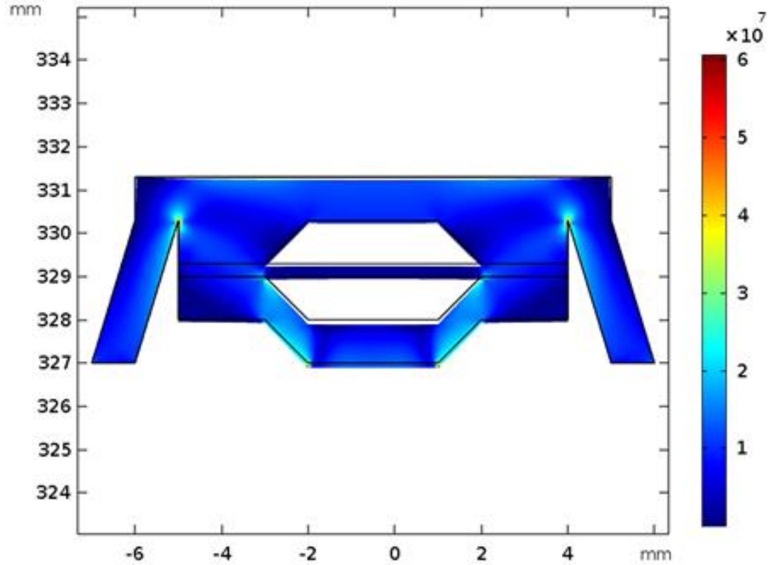

Figure 21. Von-Mises stress and deformation of the piezoelectric assembly based on the line applied strain and line fixed constraint, at t=78 ms

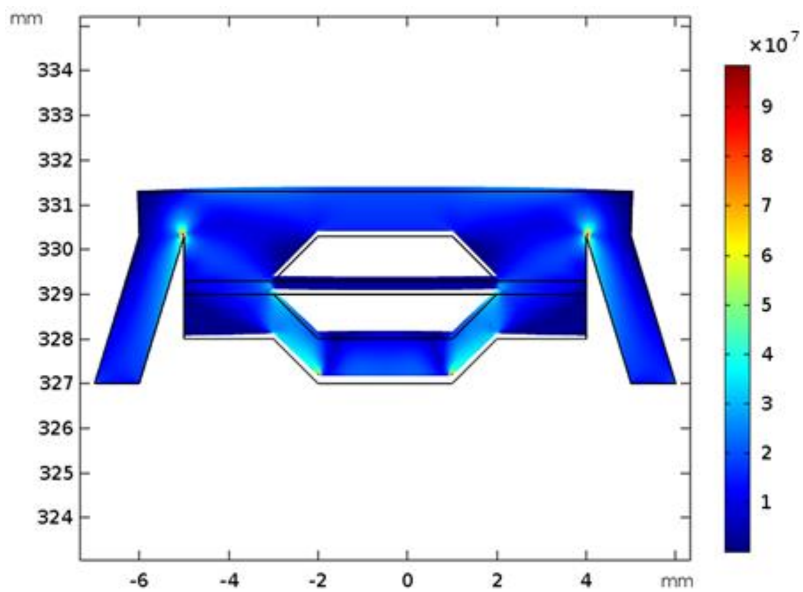

Figure 22. Von-Mises stress and deformation of the piezoelectric assembly based on the line applied strain and line fixed constraint, at t=86 ms

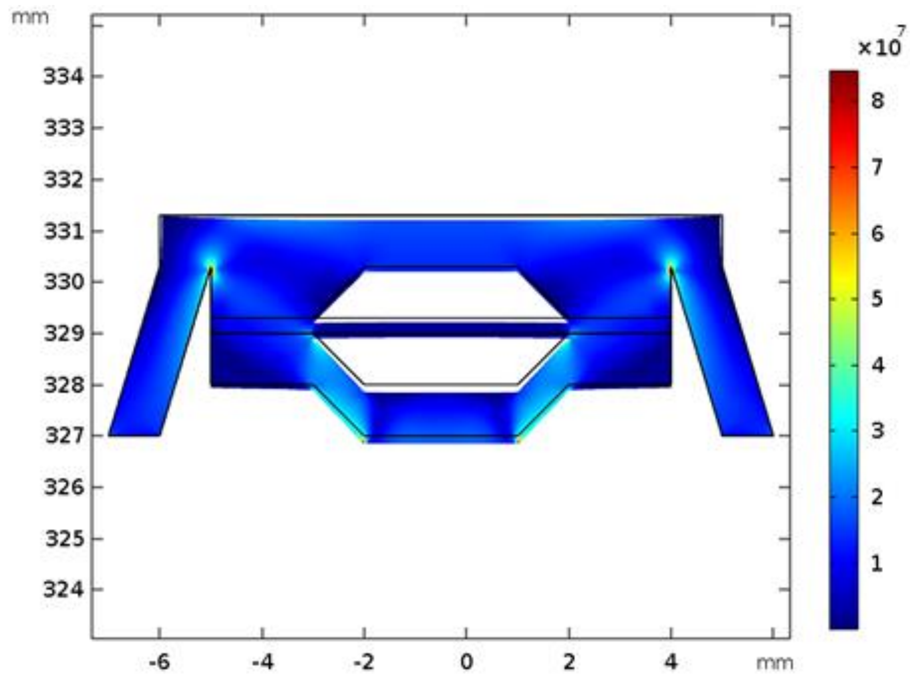

Figure 23. Von-Mises stress and deformation of the piezoelectric assembly based on the line applied strain and line fixed constraint, at t=103 ms

5.8. Parametric analysis

Different parameters such as vehicle speed, piezoelectric material thickness, PEH depth, and temperature may affect the harvested energy. Thus, a parametric study is done to study the effect of vehicle speed on the proposed PEHs. In addition, a parametric study is investigated on the first design of the PEH to find the effect of the dimensions on the PEH. Finally, a parametric study is investigated on the first design of the PEH to study the effect of the temperature on the harvested energy

5.8.1. Effect of vehicle speed

In literature, researchers have found that longitudinal strain slightly increases about 5% by increasing tire rolling speed from 8 to 26 rpm; therefore, vehicle speed has little influence on tire strain [50]. So, this study considers the effect of vehicle speed negligible. However, it should be noted that by an increase in vehicle speed, the time duration that the PEH passing through the contact patch area is reduced, and this leads to the generation of voltage in a smaller time span, thus a decrease in time difference between two consecutive maximum voltage is expected.

5.8.2. Effect of PEH dimensions

Another parameter that affects the output power is the PEH dimensions. The dimensions of the first design of the PEH based on the Cymbal energy harvester is chosen as shown before, and the PZT-5H thickness is 0.3 mm. For the parametric study here, the PZT-5H thickness is increased from 0.3 mm to 0.8mm. The effect of the PZT-5H thickness on the PEH accumulated output electric energy for one full rotation of tire is shown in Figure 24. As it is obvious, by increasing the PZT-5H thickness, the PEH output electric energy is increased. Therefore, the optimum thickness can be chosen for the PEH regarding the number of sensors and the required energy. If the 0.8 mm is chosen for the piezoelectric material thickness, the first design of the PEH can provide energy for about 5 sensors.

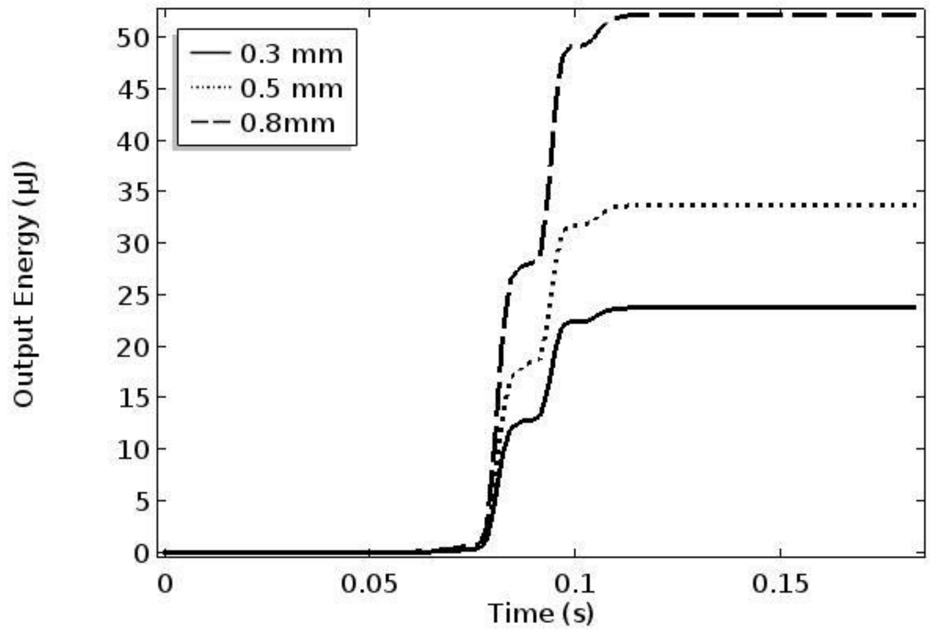

Figure 24. The effect of the PEH first design thickness on the output electric energy for one full rotation of tire

The PEH depth is another parameter that can be changed on the PEH design to match the energy supply with the energy demand of the tire sensors. In the initial PEH first design, 5 mm is chosen for the depth. Figure 25 the effect of reducing the PEH depth, from 5mm to 2 mm, on the total energy harvested in one full rotation of tire. The total energy harvested decreases from 24 μJ/rev to 4 μJ/rev once the PEH depth decreases from 5 mm to 2mm. Then, if just one sensor with 10 μJ/rev energy is needed, the PEH depth can be set to 4 mm.

In addition, this analysis shows that by increasing the PEH depth, the total energy harvested in one full tire rotation is increased. Thus, as far as the tire manufacturer limitations allowed to maintain the tire balance, it is possible to increase the PEH depth. Alternatively, if another PEH is connected to the tire inner surface, 180° ahead of the first

PEH, the energy demand for up to four or five sensors can be supplied. The parametric study on the PEH output energy in each tire rotation shows that the increase in piezoelectric material thickness has more effect than the PEH depth.

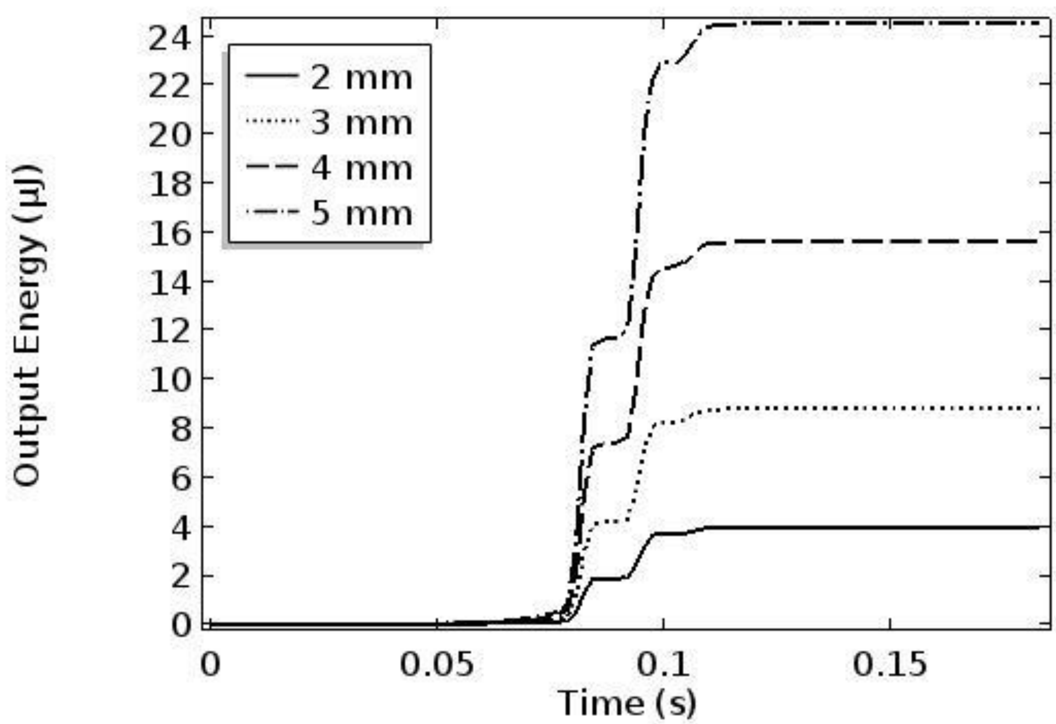

Figure 25.The effect of the depth of PEH first design on the accumulated harvested energy for one full rotation of tire.

5.9. Effect of temperature on the PEH performance

Another important parameter on the PEH performance is the air temperature inside the tire. The air temperature inside the tire may vary in different ambient conditions. In addition, the tire tread rubber temperature increases during the tire rolling; therefore, the air temperature inside the tire also changes during tire rolling. As a result, the PEH will be exposed to temperature change during different ambient temperatures and during tire rolling. Here the effect of the air temperature inside the tire on the PEH first design based on the Cymbal energy harvester is studied.

It is proven that by an increase in the ambient temperature from 15°C to 35°C the inflated air temperature rises from 33°C to 50°C [68]. Eqs. 10-12 and Eq.13 are applied to the PZT-5H and steel material properties of the model, and a parametric study is conducted to determine the dependency of the accumulated harvested energy to this temperature. As shown in Figure 26, the total energy harvested is increased from 24.4 µJ/rev to 26.5 µJ/rev, once the tire air temperature increases from 23°C to 50°C.

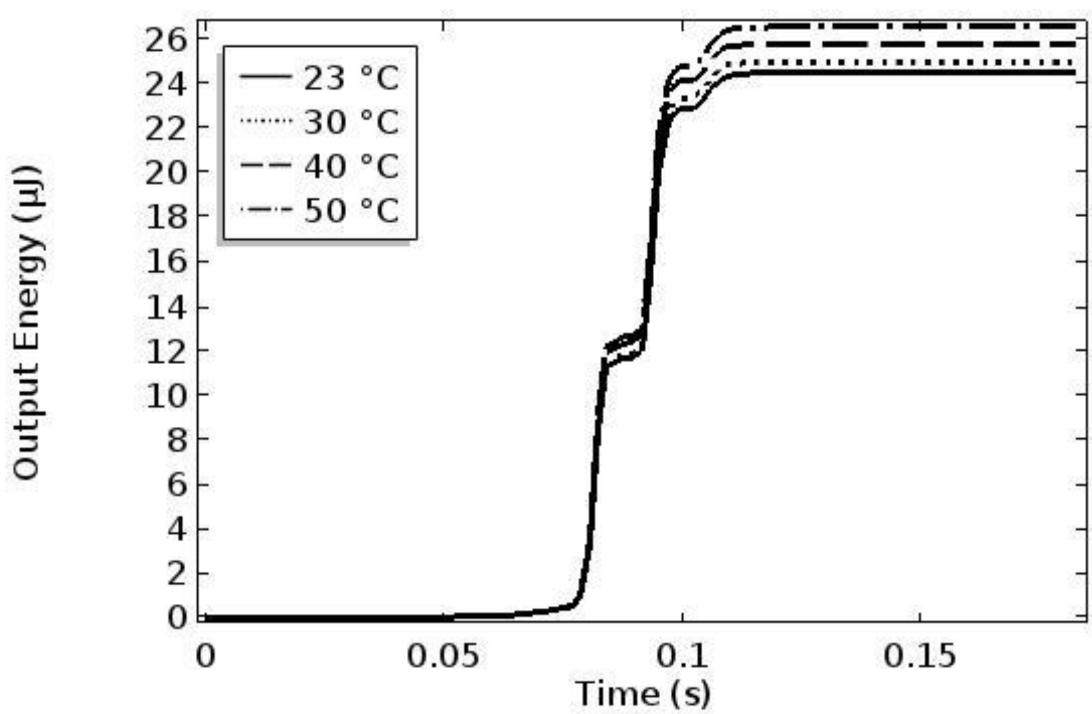

Figure 26.The effect of the tire air temperature on the accumulated harvested energy from the first designed PEH for one full rotation of tire.

5.10. Experimental Analysis

The effect of velocity on the tire strain is reported to be negligible [63]; hence, here, there is not any concern about the tire traveling speed. The main impact of the tire traveling speed on the results is that the frequency of the voltage/power pulse generation varies with tire speed (the time takes for the PEH to reach and pass to the contact patch varies). In addition, by the increase in the tire speed, the one rotation of the tire happens faster and the PEH produces power in a shorter time.

Our proposed design in the modeling section had a piezoelectric material thickness of 0.3mm. This thickness was not commercially available and custom building of this thickness was expensive. Thus, the commercially available piezoelectric material sheet with a thickness of 0.5mm is chosen in this study. Then with this new thickness of the piezoelectric material, another COMSOL Multiphysiscs model is generated to compare the experimental results with the experimental analysis. The results of the COMSOL Multiphysiscs model showed that the maximum output voltage and electric power of the PEH is about 2.4V and 1.7 mW, respectively. The PEH output power, predicted from the COMSOL Multiphysiscs model, is presented in previous sections. The experimental output power of the first PEH at the tire normal load of 368 kg and the tire inflation pressure of 35 psi is shown at Figure 27.

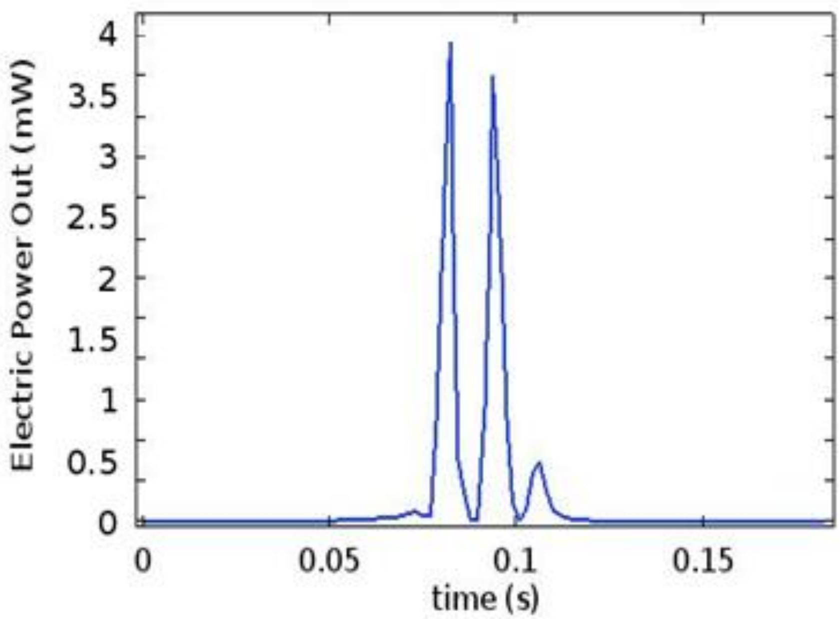

Figure 27. The output electric power of the first PEH with the 0.5mm PZT-5H thickness, predicted from the COMSOL Multiphysiscs model for one full rotation of tire.

Before and after reaching the contact patch the tire undergoes compression and during the contact patch the tire undergoes tension. Just some parts of the PEH are connected to the tire inner layer, therefore the stress distribution in the PEH structure is a little bit different from the exact compression - tension-compression that happens for the tire, and the voltage output of the PEH undergoes the pick during the contact patch.

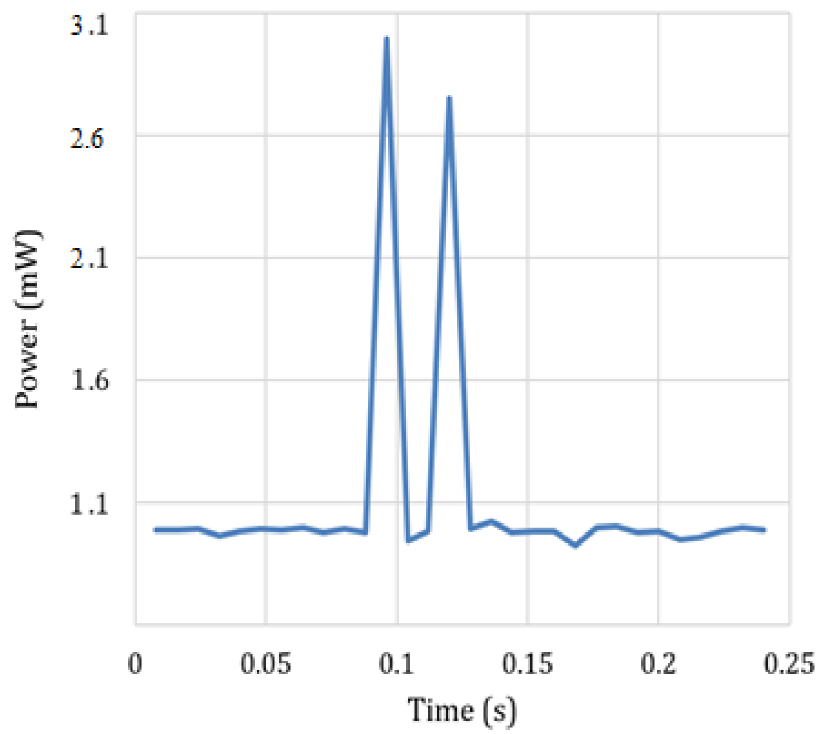

Figure 28. The experimental output power of the first PEH at the tire normal load of 368 kg and the tire inflation pressure of 35 psi.

In the last section, it was calculated that for measuring 1000 samples per each tire rotation and to transmit 35 bytes per axis in each tire rotation, the required energy for a typical tire sensor would be 8.7 μJ/rev. Here, the experimental output energy of the PEH is obtained about 28.8 μJ for one full rotation of the tire. Therefore, the proposed PEH can provide the energy required for three sensors of this type. Furthermore, the required energy for the commercial TPMS is reported to be 10 μJ/rev [63]; thus, the proposed PEH can harvest enough energy for two commercial TPMSs.

In the real-world application, only PEH is attached to the inner layer of the tire, and there may be no need to keep the measurement system inside the tire. Thus, to study the effect of the PEH on the tire balance and dynamic, the measurement system was detached and only PEH has remained on the inner surface of the tire. As discussed earlier, the PEH is only 0.2% of the tire inner surface area. The tire balance was investigated using the Road Force Elite machine and no unbalancing was observed. Therefore, it is expected that the proposed PEH will not affect the tire dynamics.

A study was done to evaluate the effect of the tire load on the output voltage of the PEH. The PEH output voltage was measured for the tire normal loads of 368 kg and 112 kg and the results are shown in Figure 29. The tire pressure was kept constant at 35 psi for both loads. It is evident that the PEH in both tire normal loads shows the same trend of voltage production. As seen in Figure 29, the increase in the load leads to an increase in the output voltage of the PEH. Since the Road Force Elite machine applies the load directly to the tire tread to simulate the tire-road contact, the increase of the load increases the tire strain. As a result, the applied strain to the PEH is increased and the output voltage is increased. As a remarkable result, notice that the load was increased about 3 times, while the output voltage was increased about 1.8 times.

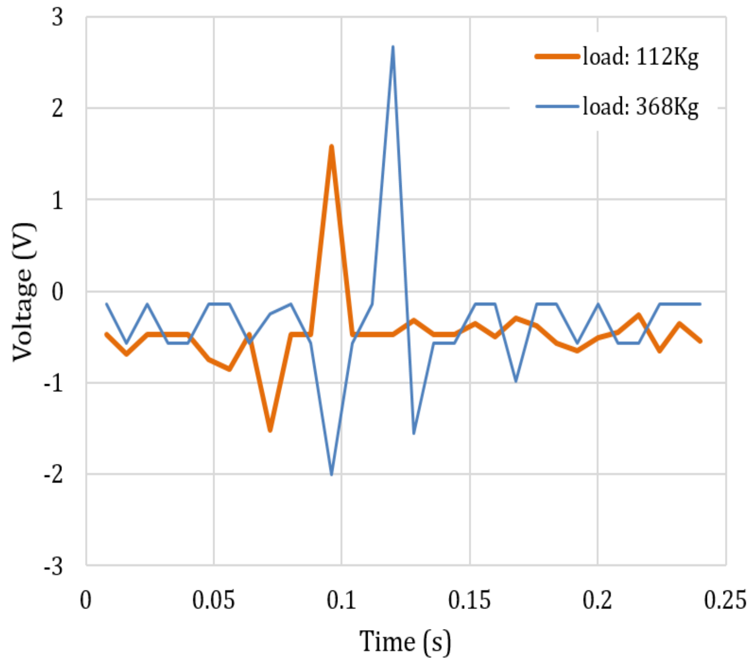

Figure 29. The experimental output voltage of the PEH at the tire normal load of 368 kg and 112 kg and the tire inflation pressure of 35 psi.

A study was also done to evaluate the effect of the tire inflation pressure on the output voltage of the PEH. The PEH output voltage was measured for the tire inflation pressures of 35psi to 20 psi at the constant normal tire load of 368 kg, and the results are shown in Figure 30. As seen, the decrease in the tire inflation pressure leads to an increase in the output voltage due to the increase in the tire strain. As a remarkable result, notice that the inflation pressure was decreased about 40%, while the output voltage was increased only about 20%. The change in the output voltage of the PEH is the result of the tire strain change. The effect of the load and tire pressure on the tire strain was addressed in the literature before. Finally, this effect of the load and pressure change to the PEH output is related to each other.

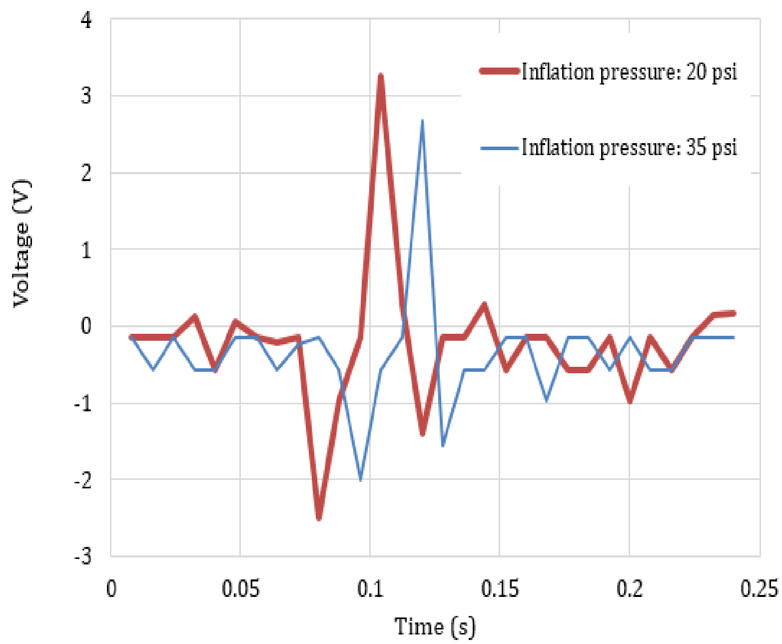

Figure 30. The experimental output voltage of the PEH at the tire inflation pressure of 35 psi and 20 psi at the tire normal load of 368 kg

5.11. Broader impact of the PEH

The proposed strain-based piezoelectric energy harvester can have applications in various fields such as transportation and railway systems, structures, aerial applications and biomedicals. A comprehensive review on the state-of-the-art of piezoelectric energy harvesting can be found in the Ref [111]. The strain and load from moving the vehicles on the road can be used in the strain-based PEH to provide power for the traffic signal lights, monitor the structural health of roads, self-powering vehicle weighing system [111]. The proposed PEH can have application in the bridges. The deflection and strain of the bridge due to the vehicles passing the bridge can be used as a source of strain for the PEH. For example, The PEH can be used to provide power to some sensors to monitor the structural health of the bridge. The PEH can be applied on the speed bumps of the road and cover the energy to be used in the sensors in the road. The PEH can be used to convert the mechanical energy from human body movements into electrical energy to power up some wearable sensors. The PEH can also be used on biomedical applications such as knee joints to monitor the health of the replaced knee joint [111]. For each of these potential applications, the design of the PEH should be studied to optimize the PEH design based on the input strain and output needed energy.

5.12. Copyright notice

A significant part of this chapter was adapted with permission from the following publications:

1- Aliniagerdroudbari, H., Esmaeeli, R. & Farhad, S. (2021). Experimental study of a piezoelectric strain-based energy harvester for intelligent tires of autonomous vehicles. ASME 2021 International Mechanical Engineering Congress IMECE2021

2- Aliniagerdroudbari, H., Esmaeeli, R., Hashemi, S. R., Alhadri, M., Zakri, W., Batur, C., & Farhad, S. (2019). Design, modeling, and analysis of a high-performance piezoelectric energy harvester for intelligent tires. International Journal of Energy Research, 43(10), 5199-5212.

3- Aliniagerdroudbari, H., Esmaeeli, R., Hashemi, S. R., Nazari, A., Alhadri, M., Zakri, W., ... & Farhad, S. (2019). A rainbow piezoelectric energy harvesting system for intelligent tire monitoring applications. Journal of Energy Resources Technology, 141(6).

4- Aliniagerdroudbari, H., Esmaeeli, R., Hashemi, S. R., Alhadri, M., Zakri, W., & Farhad, S. (2019). A piezoelectric sandwich structure for harvesting energy from tire strain to power up intelligent tire sensors. In 2019 IEEE Power and Energy Conference at Illinois (PECI) (pp. 1-7). IEEE.

5- Aliniagerdroudbari, H., Esmaeeli, R., H., Nazari, A., Hashemi, S. R., Alhadri, M., Zakri, W., ... & Farhad, S. (2018, June). Optimization of a rainbow piezoelectric energy harvesting system for tire monitoring applications. In Energy Sustainability (Vol. 51418, p. V001T02A004). American Society of Mechanical Engineers.

CHAPTER VI

SUMMARY AND CONCLUSION

With the increased attention to autonomous vehicles nowadays, vehicle safety is of immense importance. One of the critical parameters in vehicle and passenger safety is tire safety. Intelligent tires use sensors embedded on the tire to monitor tire and tire-road conditions. Intelligent tires are an essential part of autonomous vehicles. Some tire condition parameters such as tire temperature and pressure and some tire-road parameters such as contact patch dimensions and friction are measured through intelligent tire sensors.

The sensors embedded in the intelligent tire need power to measure the parameters. Previously batteries were used to power up intelligent tire sensors, but batteries need maintenance, and they are not a sustainable energy source. Energy harvesting is a way to reuse part of the ambient waste energy. Energy harvesting is a sustainable source of energy and can provide energy for the intelligent tire sensors precisely at the place that the energy is needed. With the use of an energy harvesting system for the intelligent tire, the waste energy of the tire is converted to valuable energy.

Due to the nature of the piezoelectric material, they are helpful in energy harvesting. The piezoelectric material can convert the input force or deflection to the charge.

Nowadays, the piezoelectric material is an integral part of energy harvesting systems. In tires, there are different sources of waste energy available such as vibration, excess temperature, and tire strain or deflection. And with the use of any of these waste energy sources, there are several ways developed for energy harvesting from tires, such as vibration, temperature, and strain energy harvesting.

Here in this study, two new designs of the strain-based piezoelectric energy harvesters are proposed and studied with the use of COMSOL Multiphysics software. The shape of the proposed PEHs is inspired by Cymbal energy harvester geometry. The Cymbal energy harvester is proven to be useful for piezoelectric energy harvesting. Here for the first time, these PEH shapes are used for strain-based energy harvesting for tire application.

The modeling of the PEH system consists of several studies. First, the tire deflection is calculated as the input parameter of the energy harvesting system. Then, the required energy of the tire sensors is calculated. The PEH needs an adhesive layer to be attached to the inner layer of the tire and after studying the contact patch stress and the stress applied to the PEH, Cyanoacrylate is chosen as the adhesive layer. Considering the strain and stress limit of the piezoelectric materials and the tire strain applied, the PEH, PZT and PZT-5H are chosen as the piezoelectric material for this study. The PEH will be undergoing cyclic loading in the tire application. Therefore, the fatigue failure of the piezoelectric material is also considered in the design stage.

The Multiphysics model is developed for the piezoelectric energy harvesting based on the Cymbal energy harvester. The models are validated with the published experimental studies. As part of the finite element study, the mesh independency analysis is done, and the best mesh size and the time step is chosen for the study. The output power of the first and second designs are 2.86 mW and 5.2 mW, respectively. The output voltage of first and second designs are 3.5 V and 7 V, respectively. The output energy of the first and second designs are 24.4 µJ/rev and 65 µJ/rev, respectively.

Finally, one of the developed PEHs is tested experimentally. For this purpose, the commercially available PZT-5H sheet was used as the piezoelectric material. The soft PZT-5H was used due to its high strain limit that can withstand the high tire cyclic strain. A wireless measurement system was developed for online measurement of the voltage and power output of the PEH. The PEH and the measurement system were attached to the inner layer of a passenger car tire and tested using the Road Force Elite machine that can simulate the tire-road contact. The PEH output voltage and power of 2.5 V and 1.9 mW were obtained in the experimental test that can supply power to four TPMS sensors. The total output electrical energy of the PEH was calculated at about 28.8 µJ per full rotation of tire that can provide the energy required for three sensors of this type. The size of the proposed PEH is only 0.2% of the tire inner surface area, and the tire balance test showed no unbalancing; thus, it is expected that the proposed PEH will not affect the tire dynamics. Overall, this study showed that the performance of the proposed PEH is acceptable to power 2 to 5 sensors of intelligent tires.

The PEH is designed to be used in autonomous vehicles tire to provide power to the tire sensors. Due to this application, the PEH is subjected to temperature change, tire inflation changes, vehicle speed change, and tire load changes. Therefore, in this study, some parametric analysis is done to investigate the effect of these changes on the PEH performance. The parametric study with the use of COMSOL Multiphysics model is done, and the effect of vehicle speed, PEH depth, piezoelectric material thickness, and the temperature on the output on the PEH is investigated. The parametric experimental study is done to study the effect of tire inflation pressure and tire load on the output voltage of the PEH.

These newly proposed strain-based PEHs are proven to provide sufficient energy to power up intelligent tire sensors. There are different shapes and dimensions with different metal host materials and piezoelectric material, which a tire company can use in between them due to its availability to the material and the manufacturing process. These PEHs can be utilized to power up intelligent tire sensors. This device may have been used for the tire companies to predict the tire pressure, temperature, contact patch dimensions, friction, wear, and other important tire-road conditions to improve vehicle safety.

APPENDIX A: LIST OF SYMBOLS

Symbol	Description
A_p	Piezoelectric material surface area
a	Distance between the two points on the tire curvature
D	Electric charge displacement tensor
d	Piezoelectric strain constant tensor
d_{33}	Piezoelectric strain coefficient in 33 direction (pC/N)
d_{31}	Piezoelectric strain coefficient in 31 direction (pC/N)
E	Electric field tensor
E_{in}	Internal electric field
E_{rev}	Amount of energy that wireless sensors need in each revolution of tire (J/rev)
E_{t0}	Elastic modulus (MPa)
E_t	Elastic modulus at elevated temperate (MPa)
g_{33}	Piezoelectric voltage constant in 33 direction (10^{-3} voltmeter/N)
g_{31}	Piezoelectric voltage constant in 31 direction (10^{-3} voltmeter/N)

Symbol	Description
h_p	Piezoelectric material thickness (m)
L	Arc length (m)
L_{patch}	Contact patch length (m)
$n_{samples}$	Number of samples
n_{axe}	Number of axes
n_{bits}	Number of transmitted bits
n*J*	Nano Joule (10^{-9}J)
P	Polarization
pJ	Pico Joule (10^{-12}J)
R	Radius of tire curvature (m)
r_{i-1}	Point on the tire curvature
r_{i+1}	Point on the tire curvature
S	Strain tensor
s^E	Compliance tensor measured at constant electric field
T	Temperature (°C)

Symbol	Description
U	Output electric energy
Z_c	Radios of unloaded tire (m)
Z	Tire inner surface radius (m)

Greek Letters

σ	Stress tensor
θ	Angle of arc (deg)
δ	Tire stiffness
ε	Tire longitudinal strain
ε^T	Dielectric permittivity coefficient tensor measured at constant stress
ε_{33}	Dielectric permittivity coefficients
Δ	Change in parameter

Abbreviations

TPMS	Tire pressure monitoring system
PEH	piezoelectric energy harvester
PVDF	Piezoelectric polymer Polyvinylidene fluoride
PZT	Piezoelectric lead zirconate titanate
SBR	Styrene-Butadiene rubber

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