Design of Piezoelectric Energy Harvesting System for Intelligent Vehicle Wheels

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DEDICATION

I would like to dedicate my thesis to my parents and my siblings, who have always been supporting me and motivating me to study. I would like to express my gratitude to my parents who have always believed in me and encouraged me to work hard in the completion of this thesis. All the hard work, time, and understanding I have received from them have been very inspiring and I am grateful for it.

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Finally, I want to thank my family, friends, and colleagues for their continued support and understanding throughout this arduous and rewarding journey.

Abstract:

Due to the current mandates for TPMS in vehicles around the world especially in US since 2007 and EU 2022 regulations; challenges of battery disposal on the environment have emerged more sharply. In response, the study provides the novel solution known as Piezoelectric Energy Harvesters (PEH), which can potentially generate energy from a tire's mechanical deformation. Two different designs of PEH to power Tire Pressure Monitoring Systems (TPMS) in automobiles as a sustainable option for battery-powered devices. One PEH is designed to be mounted on the inner surface of the tire Aluminium substrate is used as a structural support, and PZT-5H is used as a piezoelectric material. This design collects energy from tire pressure and road contact directly thereby providing stable and higher energy yield. Results indicate that output voltage increases as the car's speed increases, reaching peak output at 90 km/h. The power output also increases gradually with speed, demonstrating that in addition to power TPMS, excess power can be stored. Second design consists of a cantilever beam substrate with a PZT-5H disk attached at the other end of the beam. The PEH is mounted perpendicular to the rim spoke to harvest energy during the tire revolution as a result of centripetal force. However, though this design is practical or can produce power the comparison proves that the in tire placement of the harvester produces more power as compared to rim-spoke mounted one. The higher deformations within the tire make for a more efficient way of tapping the energy which coupled with the advantage of efficiency given by this tire mounted design go to prove the superiority of the design in terms of energy generation and efficiency. Through presenting two sustainable designs and proving the effectiveness of the inner-tire-mounted PEH, this research indicates how the environmental impact of TPMS could be decreased along with the energy demand of the system.

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CHAPTER 1: Introduction

The most significant technological issue of our time is the increasing need for energy. Every year, the amount of energy used by humans rises by 1% to 2% [1], with the majority of this energy coming from environmentally damaging fossil fuels. The increasing prevalence of alternate green energy sources is a result of digitalization across varied applications. Energy harvesting, which gathers ambient energy and transforms it into electrical energy to operate low-power sensor systems, is one potential technique. [2]. Because of this zero-energy device approach, tiny gadgets become energy independent and may be installed in challenging-to-reach places. This helps lessen the impact on the environment in addition to saving money and time on system installation and maintenance. It contributes to a more sustainable future by using less raw materials in the production of cables and fewer batteries that are discarded [3].

Autonomous or self-driving vehicles, also referred to as intelligent cars, represent the mobility of the future. These vehicles can drive and interact with their environment by utilizing a wide range of sensors, processors, and communication devices installed in them. However, these systems' power needs pose serious problems for both the sustainability and availability of energy. Tires are a vehicle's only point of contact with the road, they are essential to vehicle safety. In particular, the auto sector is searching for inexpensive tire condition monitoring systems for self driving vehicles. Yokohama Rubber Company discovered in 2005 that sensors within tires and installed on wheels may detect motions in a vehicle 0.15–0.2 seconds faster than sensors installed on the vehicle body[4]. This emphasizes how crucial it is to install safety monitoring systems within tires. Generating energy from the rotation of a tire is an innovative concept. Car tire when are in contact with the road face mechanical deformation which can be utilized by piezoelectric components if they are incorporated inside the tire.

As per the US regulations, use of TPMS is mandated in tires of new vehicles from 2007 [5] followed by EU regulations from 2022 [6]. TPMS are usually powered by batteries that are discarded after 5-10 years of time depending upon the usage, which isn’t environment friendly. Energy harvesting may be the environment friendly substitute for it, as it can harvest energy from the deformation, compression and vibrations of the tire [7]. With the advancement in the field of wireless electronic devices, energy harvesting is becoming more common. With the rise of electric cars and the self driving cars, that rely on the sensors feedback require a power source. Instead of powering them from car battery or independent batteries in case of wireless sensors such as sensors used inside the tires. Automotive industry may need to shift to energy harvesting and most significant option for this is Piezoelectric Energy Harvesting.

1.1. Energy Harvesting

Energy harvesting is a new concept that is rapidly evolving and is also referred to as power harvesting or energy scavenging. In basic terms, it is recovering and capturing some minimal energies that would rather have been wasted in form of heat, light, sound, or even kinetic movement and altering them to electricity mainly. This process is not only creative but also the solution to the problems of energy and energy requirements which are getting out of hand. However, it is not the first time that the term of energy harvesting has been used. For centuries people have been using wind, water and suns energy to produce power. However, the development of microelectronics and the Internet of Things (IoT) made this energy harvesting even more interesting. These days, it's about enabling the low-power electronics of our current devices with this energy harvesting technology. From the growing number of wearable devices and wireless sensors to remote monitoring and implanted medicines or medical devices.

Energy harvesting is important since it ensures that these devices can operate independently. The drawback of reliance on conventional power sources, such as batteries, is the fact that they will eventually run out and will need to be replaced or recharged often. This is quite not only tedious but also creates environmental issues. Energy harvesting on the contrary, supplies uninterrupted power to the devices increasing their lifetime, decreasing maintenance, making the devices used friendlier to the environment. Energy harvesting allows these devices to tap into new areas that may not have been explored before there. For instance, devices can be operated at the outlying regions or other inaccessible places where you cannot change ooze batteries. In a similar manner, internally powered medical devices that will be embedded in people will not require long wires that pass through the skin thus less prone to infections. There are a number of ways in which energy can be harvested, and each of them mechanizes one form of ambient energy. These include solar energy, biofuel energy, thermal energy, kinetic energy, wind energy, and radio waves. Every method has its own strengths and weaknesses and in deciding which method to adopt a number of considerations are made such as the device in consideration, the energy needs and the place to be used.

1.2. Scopes of Energy Harvesting

In categorizing this aspect of energy harvesting, three levels are identified: macro, micro, and intermediate. Each level is designed for a specific aim and application, and each has its utility case depending on energy needed.

1.2.1. Macro level Energy Harvesting:

There are activities such as energy generation energy harvesting which fall under large scale energy harvesting. Some of these systems include wind farms, solar power plants and hydroelectric power stations among others. These systems are built to harness and transform large quantity of energy from the environment. For Example, solar power plant consists of hundreds and thousands of photovoltaic solar cells and once sufficient amount of sunlight is captured; houses, companies and factories can be powered with the electricity produced. Large scale energy harvesting systems is very useful in the energy system across the world. It contributes positively in fighting climate change as it reduces dependence on fossil fuels. But such systems are often capital and space intensive. Moreover, for efficiency, they may also depend on weather and geographical conditions.

1.2.2. Micro Energy Harvesting:

In contrast, smaller size energy harvesting is permeable on the basic energy to be used for small low power consuming devices. This could include devices such as wearable devices, wireless sensor networks, remote monitoring systems and other small electronic apparatus. Energy sources for small-scale harvesting is comprised of varied elements, which include solar and thermal energy, vibrations, as well as radio frequency waves. Small scale energy harvesting works particularly well for inaccessible or hard to maintain devices, such as sensors deployed in the Earth’s surface in remote locations, or internally implanted devices. These applications will provide benefits such as prolonged device life, less maintenance, and new capabilities due to the presence of continuous power through energy harvesting.

1.2.3. Infrastructure Energy Harvesting

Micro-scale energy harvesting is the lowest possible level of energy harvesting and more commonly found in micro-electromechanical systems MEMS. These systems are capable of harvesting energy from light, vibrations, or thermal fluctuations to operate micro-devices. Micro-scale energy harvesting is an emerging technology that has experienced a steady growth and development of nanotechnology, coupled with the need for smaller and efficient devices.

Energy harvesting on micro scale has some potential applications, from supplying power for micro-sensors and actuators in IoT devices to more advanced applications such as biomedical implants. Undoubtedly, there are challenges with micro-scale energy harvesting, such as the very low energy that can be harvested and the limitations in converting and storing this energy. Nevertheless its future for the electronic devices looks great.

1.3. Energy Harvesting Methods

Energy harvesting is categorized into different types according to the sources of ambient energy used for harvesting. The selection of method depends on various aspects like the type of the device, the power demands of the device, and the setting where the device will be used. Below are some of the types of energy harvesting based on the sources of the energy from the environment.

1.3.1. Mechanical Energy Harvesting

It involve the conversion of the vibrations, stress, deformation, or kinetic energy of a body in motion into electrical energy. Basically, piezoelectric and electromagnets are the systems that are commonly used in this type. This can be useful in powering wireless sensors, which do not have the need of battery or it can be used to enhance the battery life when used together with a battery.

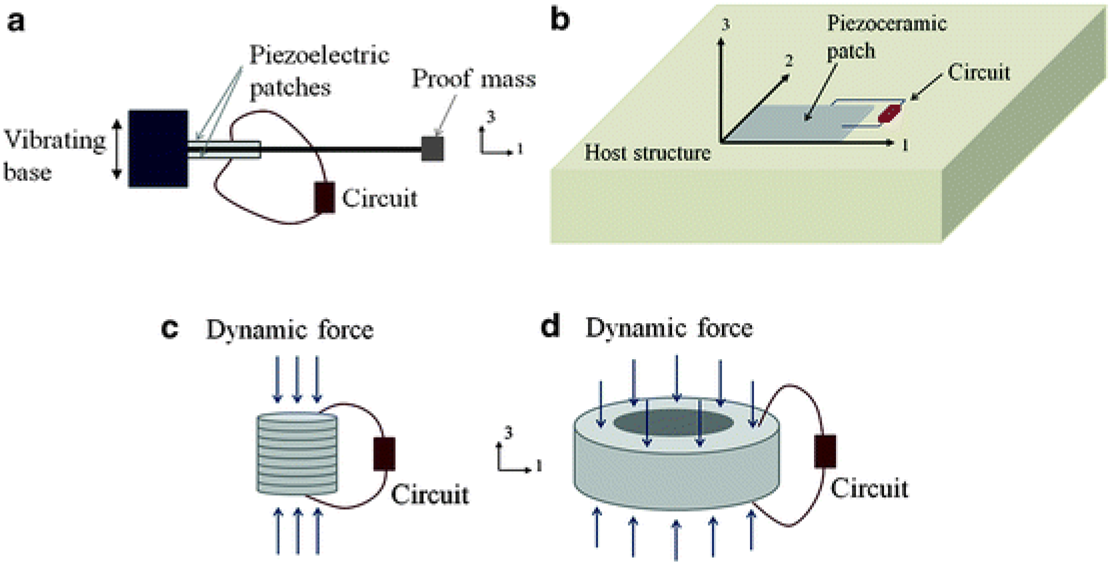


Figure 1: Mechanical Energy Harvesting [8]

1.3.2. Thermal Energy Harvesting

Thermal energy harvesting deals with the collection of heat energy and its transformation into electrical energy. This heat can come from various waste processes, the human body, or the surrounding temperature. The above conversion is most often performed by thermoelectric generators, which use a temperature differential across the device to produce electricity. Thermal energy harvesting can be very advantageous in making use of excess heat, but the process efficiency is heavily dependent on the delta temperature that must be present for it to work[9].

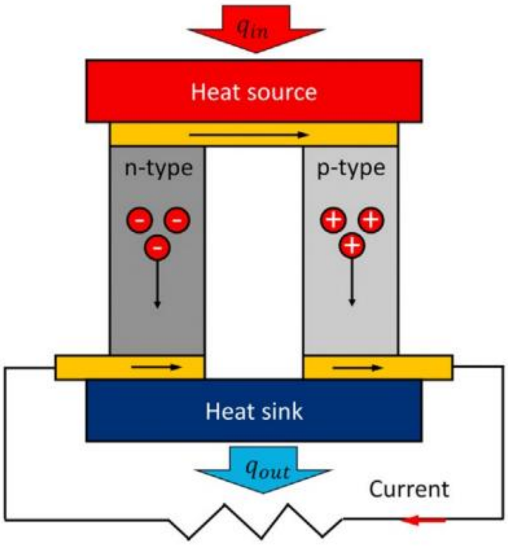


Figure 2: Thermal Energy Harvesting [9]

1.3.3. Solar Energy Harvesting

Solar energy harvesting perhaps is the most known among the various forms of energy harvesting. People have employed the use of sunlight, which is quite abundant and operating high fundamental frequencies to capture more energy and convert it to electricity using solar batteries[10]. This technique is applied on both macro scale as in power generating solar plants and micro scale in gadgets like watches and calculators powered by nano solar cells. When there is enough solar energy available, the main limitation of this type of energy harvesters is the availability of the solar energy resources. However, its effectiveness can be reduced due to other circumstances like the climate and the place where the system is installed.

Figure 3: Solar Energy Harvesting [11][12]

1.3.4. RF Energy Harvesting:

This technology is concerned with reduction of energy requirements for RF signal transmission. Energy is taken from ambient RF signals coming from mobile devices, Wi-Fi signals, broadcast antennas. The RF energy harvesting is achieved by antennas and rectifiers which change over the RF signals to a direct current. Focusing on wireless devices, some power sources sometimes may serve as relatively useful voltage sources, however do require a concentrated and consistent RF source to be effective in the former context.

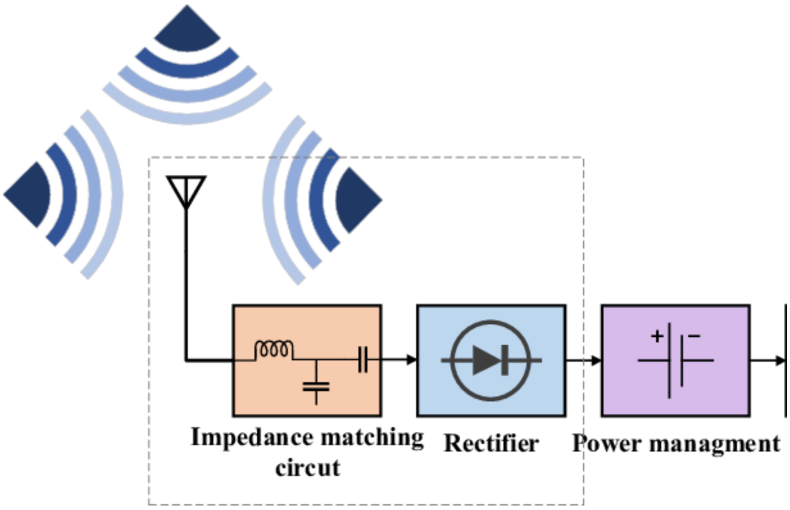


Figure 4: RF Energy Harvesting

1.3.5. Electromagnetic Energy Harvesting

Electromagnetic harvesters are a type of vibrational energy harvester that can capture kinetic energy in a low-frequency range. They can be classified by their structure, such as moving magnet or moving coil. In a moving magnet structure, the coil is placed near the moving magnet or the magnet moves inside the coil. Moving coil systems often have a high output voltage.

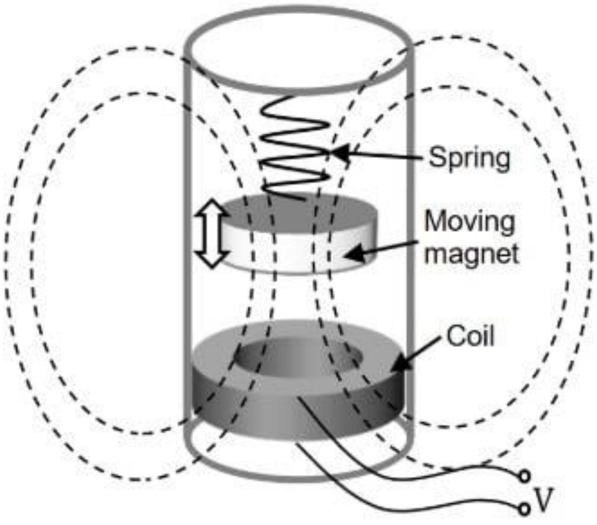


Figure 5: Electromagnetic Energy Harvesting[13]

1.3.6. Vibrational Energy Harvesting:

Vibration energy harvesting works by harvesting energy from motion associated with items such as machinery, vehicles, wind and so on and converting this energy to electricity. Piezoelectric materials and electromagnetic generators are commonly used to do this. Energy in the form of strain is imparted on piezoelectric materials which in turn induces an electric charge. Vibration energy harvesting is one of the methods of power harvesting that can be used for devices that are normally surrounded by mechanical vibration, but the amount of energy produced is more often than not limited[14].

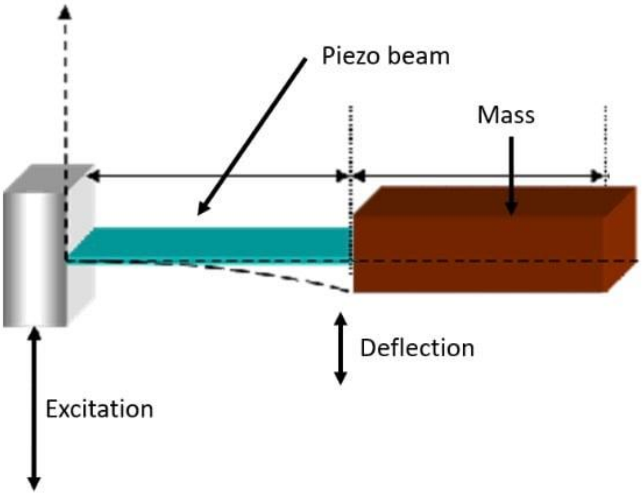


Figure 6: Vibrational Energy Harvesting[13]

1.4. Piezoelectric Energy Harvesting:

This unique method of energy harvesting makes use of energy released when a mechanical load or stress is applied on a material and the energy is released as electricity. Most of these types of materials when stress is applied on them, they produce electricity. This application is exploited in piezoelectric energy harvesting with the vibration of tires, foot traffic in busy places or just movements of the body bringing in energy from all areas. Piezoelectric energy harvesting is considered an attractive area of research with lots of possibilities but it also depends on particular material and structure design to deliver. Piezoelectric energy harvesting is one brilliant technique that makes the most out of energy created from the application of mechanical stress or strain and rest converting them into electrical energy. The very term of the piezoelectricity derives from the Greek words ‘piezein’, which means press, and ‘elektron’ meaning amber. The piezoelectric property describes the characteristics of materials whereby electric charge will form in the presence of some pressure.

1.4.1. Piezoelectric Effect

The emergence of this phenomenon, known as the piezoelectric effect, was documented in the 1800s by two brothers Pierre and Jacques Curie[15]. They proposed that compression of particular crystals stressed them further, something that quartz, troublesome, and Rochelle salt crystals startled out an electric charge. Indeed it was the beginning of piezo electricity which range of uses has rapidly expanded from the coupling or production and detection of sound to the more complex generation and storage of high voltages. This is due to the relative movement of positive and negative charge centers within the material producing an electric dipole. Application of a mechanical force causes movements within the material which affects the charge distribution of the internal dipole resulting into movement of charges which can be collected in an electric circuit and therefore put to use.

Piezoelectric materials can be basically divided into two major classes: those systems made of piezoelectric shapes as crystals and those composed of piezoelectric ceramic. The properties of the crystal, especially the quartz and Rochelle salt, were the first materials which had shown the piezoelectric property. However, these materials have relatively weak piezoelectric characteristics and are therefore impracticable for energy harvesting purposes While piezoelectric ceramics exhibit superior piezoelectric effects. The most extensively used is piezoelectric ceramic material is PZT. PZT has got great piezoelectric properties that are harnessed in energy harvesting systems.

1.5. Structures used in Piezoelectric Energy Harvesting

Below are the common types of structures used in Piezoelectric energy harvesting

1.5.1. Cantilever Beam Structure

The cantilever beam system is the most typical form of piezoelectric energy harvesting system because it has a simple structure and high effectiveness[16]. It is made up of a thin beam which is clamped at one end & remains free on the other. The beam will have a layer of piezo material on its surface, either one side (unimorph) or both sides (bimorph), that can translate mechanical strain into electrical energy. Vibrations or mechanical movements from the external environment result in bending of the beam causing deformation and generating a mechanical strain in the piezoelectric layer. This deformation gives rise to an electrical charge by direct piezoelectric effect that can be harnessed as useful energy. The cantilever beam structure remains a popular design and is especially sensitive to low-frequency vibrations, which makes it well-suited for applications where there are persistent or periodic mechanical movements such as in buildings, bridges or automotive systems. Being flexible it can efficiently capture vibrations even at low displacement. Moreover, the simplicity of cantilever design allows for easy fabrication and integration into many applications. Larger range of frequencies is captured by some designs where more than one cantilever beams are employed to provide higher efficiency in energy harvester. The cantilever beam structure offers a universal solution due to the flexibility and effectiveness of piezoelectric cantilever energy harvester models, especially in ubiquitous ambient vibration-based applications.

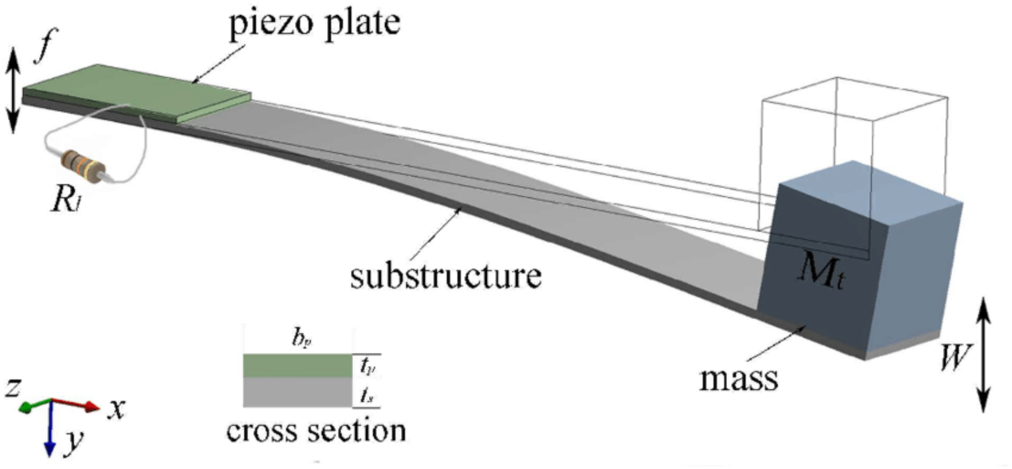


Figure 7: Cantilever Piezoelectric Energy Harvester[17]

1.5.2. Unimorph and Bimorph Structures

Bimorph and unimorph structures are fundamental piezoelectric energy harvesting configurations that cater to different design requirements. Unimorph StructureIn a unimorph structure, a single layer of piezoelectric material is bonded to a passive substrate with non-piezoelectric properties. When the structure is subjected to mechanical forces i.e. bending or vibration, the piezoelectric layer will be deformed leading to creating electric energy under the application of mechanical strain. Unimorph structures are rather simple and efficient, thus they can be utilized mainly for applications with a moderate power output need or when the structure is under bending loading. Meanwhile, the bimorph structure includes two layers of piezoelectric material, typically arranged on each side of a central substrate. This arrangement enables simultaneous piezoelectric contributions from both layers when the structure is bent (one layer compressive, the other tensile). Due to this dual-layer arrangement, the energy output performance is significantly improved compared to the unimorph design where only one side of the stack can be utilized for power production.

The bimorph structure makes it particularly well-suited to harsher field conditions or applications where energy output needs to be maximized. This mechanical deformation causes the material to have increased sensitivity, which is beneficial for monitoring applications such as vibration energy harvesting applied to industrial machines, automotive systems and wearable devices. This can help bimorphs absorb more vibrational frequencies than simply a single mode of vibration, also enabling bimorphs to function in different environments. Unimorph and bimorph configurations have been extensively used for energy harvesting applications due to their flexibility, ease of fabrication, and they are the most common structures which can scavenge mechanical sources such as bending, vibration, and pressure.

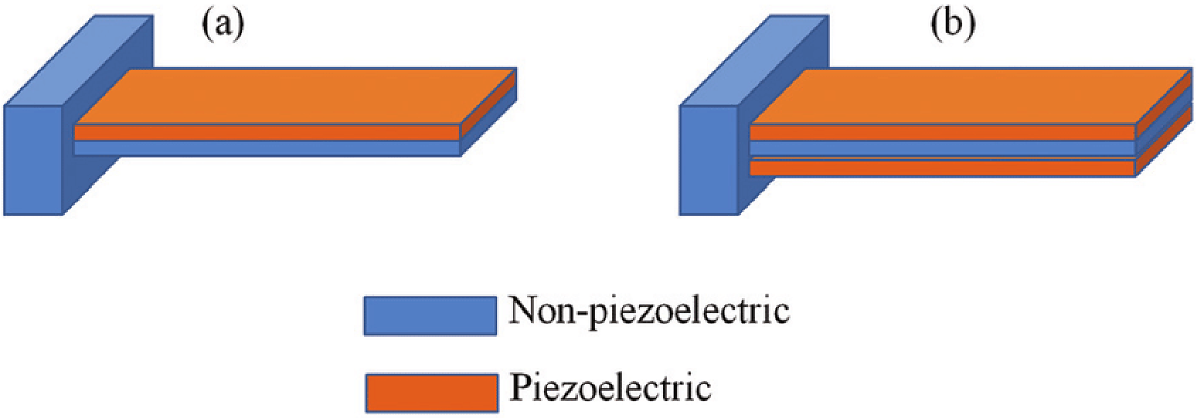


Figure 8: Unimorph and Bimorph Piezoelectric Structures[18]

1.5.3. Cymbal Structure

The cymbal design is a unique architecture in piezoelectric energy harvesters and has been previously proven to enhance mechanical strain and improve power output. So named for its similar appearance to a cymbal commonly used in music, this structure generally comprises a thin piezoelectric disk situated between two similarly curved metal caps. The purpose behind these caps is to increase mechanical deformation experienced by the piezoelectric disk under external load. If the structure is subjected to pressure or mechanical stress, the dome-shaped caps gather the applied load on the piezoelectric material, achieving much higher level force that goes through to the piezoelectric disk. The result is an increase in the electrical output compared to flat piezoelectric structures, which have no amplification.

The cymbal architecture is particularly well-suited for applications in which low-frequency vibrations and/or pressure oscillations are present, such as: health monitoring structures, biomedical devices or underwater sensing. Among the strengths of cymbal design, it works well in low deformation situations, using curved end caps provides higher mechanical leverage. So it could prove very effective in energy harvesting measures of low-power systems etc., where you want to convert minute forms of motion into electrical power.

Furthermore, the cymbal physical compactness as well as its mechanical robustness oblige for multiple use in space constrained and wear prone applications. As cymbal design is the simplest among all zero-bending moment geometries for enhancing piezoelectric harvester energy output, it has been demonstrated to be a versatile solution for capturing vibrational energy of low-magnitude and small-scale mechanical inputs for which piezoelectric harvesters are designed. This peculiar geometry allows the design a high efficiency mechanical amplification and piezoelectric conversion system that is often necessary when it comes to maximizing the energy harvested from vibrations or pressure.

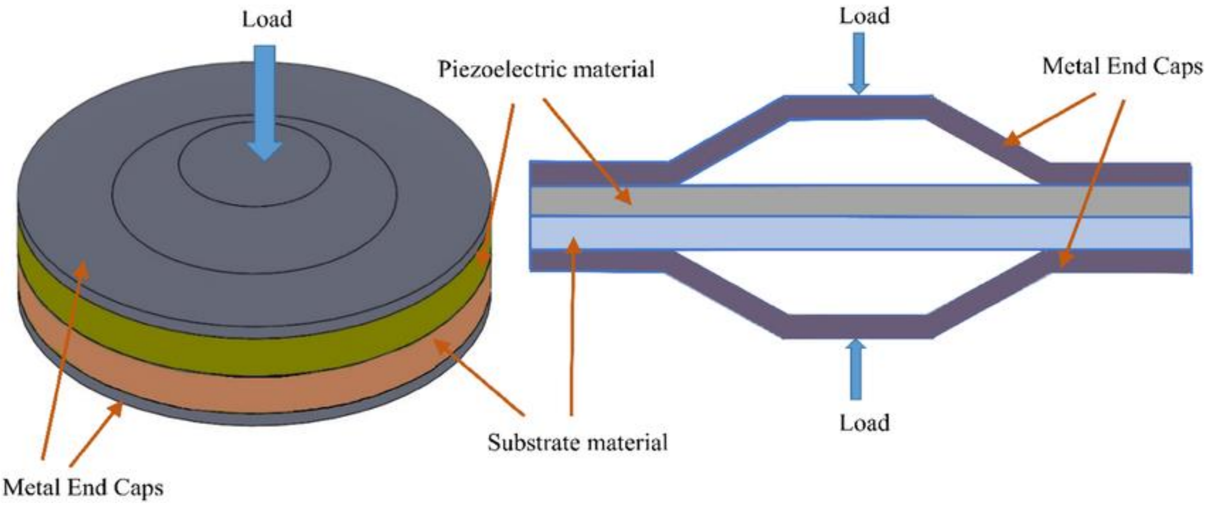


Figure 9: Cymbal Structure of energy harvester[19]

1.5.4. Stacked Structures

The stacked structure is an innovative design adopted in piezoelectric energy harvesters to maximize the amount of energy generated by implementing several layers of piezoelectric materials. In this arrangement, very thin layers of piezoelectric material are stacked (often in series format) Insulation or conductive layers are used to achieve electrical connectivity and mechanical compliance among different layers. When the device is subjected to mechanical stress like in vibrations due to airflow or compressive forces, piezoelectric layers generates electrical energy according to the strain it suffers.

This series-type architecture has the biggest benefit with respect to total electrical output by stacking the device compared to single-layer designs. The stacked configuration can generate higher voltage and power levels by adding up the outputs of multiple piezoelectric layers. This makes it especially attractive for power-intensive applications in space-constrained environments. Furthermore, the stacked configuration can be easily engineered to be sensitive for a variety of mechanical inputs, and thus is suitable for different energy harvesting conditions. Stacked structures uses available space efficiently by constructing it as multiple layers placed into small volume. It comes in handy when the size must be small to fit into a portable electronic device, or for some sensor, or even some sort of micro-mechanical system.

Moreover, the stacked configuration may be customized for specific frequency bands or mechanical loading conditions to enable an extensive broad range of operational conditions.

In terms of functionality, the stacked structure is appreciated for its high energy density and a small footprint which makes it ideal for applications where maximizing energy output is key. Vibration energy harvesting is directly related to the conversion and integration of mechanical vibration power into electricity for new-generation energy harvesting technologies, as they offer a unique advantage in being able to efficiently Tr tap into mechanical forces or vibrations and convert them into electrical power which cannot be produced by other solutions but this means displacing many non-commercial existing equipment with laminar aircraft flies on such locations where real estate is often at a premium.

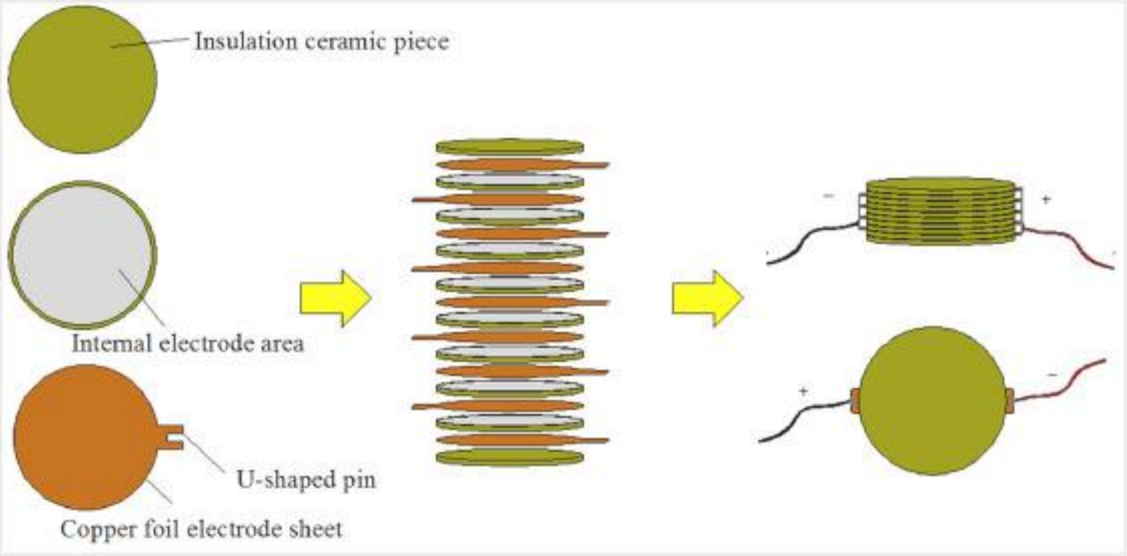


Figure 10: Stacked Structure of Energy Harvester[20]

1.5.5. Spiral or Helical Structures

Spiral or helical structure seems a wise design to select in the piezoelectric energy harvesting technique, and it is well known for its unique spiral geometry. It consists of a spiral or helical piezoelectric material around a central core/axis. This novel configuration benefits the energy conversion ability of a harvester by providing an effective solution to handle torsional or bending forces.

In the spiral, or helical structure, the piezo-materials are usually arranged so that their length has large strain distribution. If mechanical forces with rotational or twisting motions are applied to the spiral / helical component, then the deformation is felt along its entire length. The electrical charges are created by the piezoelectric effect, which is caused by deformation and converts mechanical energy into electrical energy. It makes it efficient to transfer the strain and harvest energy of forces which otherwise simpler geometries would capture less. Spiral or helical structures have clear advantages; they are able to harvest energy from the dynamics of the mechanical input, and from highly non-linear as well. The spiral or helical design is often preferred as these types of forces will be captured by the device and can easily capture, convert it into electrical power in a variety of applications with high rotational or oscillatory cases such as rotating machinery, wearable devices, etc., and also some biomedical applications. It is also possible for this design to be smaller and lighter weight than traditional linear designs, which can be a plus in many portable or space-constrained implementations. Importantly, the helical/spiral shape can be designed to resonate at different frequencies or even respond to certain types of mechanical excitation, which could increase its performance depending on targeted energy harvesting applications. That makes it an ideal solution for when you have the harvest energy from hybrid or irregular/inconstant mechanical sources.

At any rate, the spiral or helical form is interesting for enabling the capture and harvest of mechanical energy from a broad spectrum of dynamic inputs. The product includes an innovative design that increases energy harvesting efficiency, especially in the context of applications with torsional or rotational forces, leading to a new and compact solution for different needs of energy harvesting solutions.

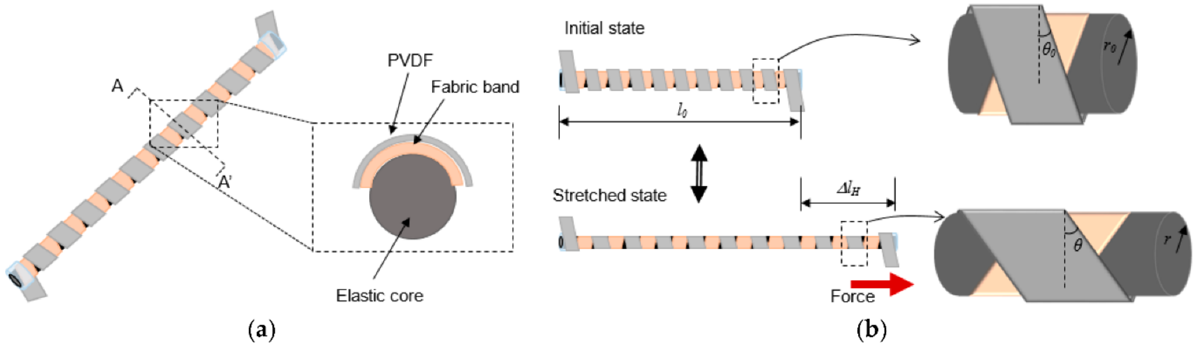


Figure 11: Helical Energy harvester[21]

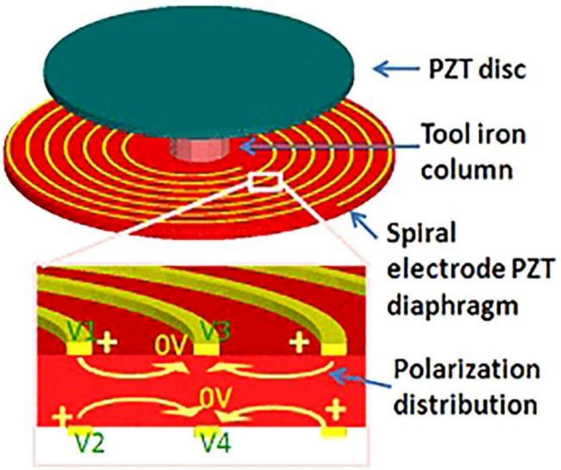


Figure 12: Spiral Energy Harvester[22]

1.5.6. Bridge or Truss Structures

Piezoelectric energy harvesting is one of the most versatile design, and bridge or truss structure based energy harvester is an acclaimed method. The main feature of these designs is that they are able to take the advantages of mechanical properties on system level as well-truss/conventional structures has been also attributed for improving other forms of energy converters. In this architecture, piezoelectric materials are combined into race-based beam or partular configuration framework like a girder or trained and interleaved together. A bridge or truss structure includes placement of the piezoelectric material into the structure, such as in the beams or nodes. These forces induce deformations or strains in the piezoelectric material when mechanical forces such as vibrations, oscillations, or structural loads act on the truss or bridge. When the piezoelectric material is deformed, electrical charges are generated by the piezoelectric effect that can be later harvested and converted into electricity.

One of the most valuable benefits of the bridge or truss structure is its ability to easily distribute mechanical stresses over a larger area. The truss (or bridge) environments can offer a robust and stable platform which evenly distributes mechanical loads, better suiting piezoelectric materials for optimized energy conversion efficiency. This type of design is attractive when mechanical loads are dispersed or variable, for example in civil infrastructure (bridges and buildings) as well as transportation systems (railways and highways), or even external applications. The bridge or truss structure is highly adaptable, and can be tailored for different loading conditions and mechanical requirements. As an example, truss types and materials can be selected to enhance the energy harvesting performance for particular mechanical stress types and frequency ranges. Furthermore, by embedding piezoelectric material within the truss or bridge framework, it becomes firmly attached to the applied forces due to the structural integrity of both the cantilever and beam, resulting in a reliable and consistent force specific energy harvester.

The bridge or truss structure makes a robust and high efficient solution to piezoelectric energy harvesting because of its consequent mechanical efficiency and effective vibration-energy conversion. They can manage distributed mechanical stresses and are tunable for a variety of applications, which aids their deployment in harsh or sporadically changing mechanical environments where energy harvesting is desired.

1.6. Benefits and Drawbacks of Piezoelectric Energy Harvesting

There are several advantages including efficiency with regard to the piezoelectric energy harvesting technique. It has a wide frequency range of operation making it suitable for multifarious uses. It can also function where other mediums of energy harvesting including solar or thermal are impractical. In addition, piezoelectric materials are tough enough to handle harsh environments and therefore do not require maintenance and are suitable in applications where they are used for a last long time. Nevertheless, piezoelectric energy harvesting is also confronted with some difficulties. The quantity of energy that can be harvested is generally small and hence efficient energy storage and energy management are key. How piezoelectric materials perform may also depend on the temperature and this may necessitate some insulation in hot working conditions. In addition, the availability of some materials such as PZT can create higher costs and ecological concerns for these systems. However, such particularities should not draw pessimism regarding the future of piezoelectric energy harvesting. With persistent efforts in researching and developing it, it can become a reliable and efficient energy solution for many devices. Depending on the desired application and the surrounding conditions, the energy harvesting source has to be chosen appropriately. Every source has its own advantages and disadvantages and thus some are more effective than others at a particular time [23]

1.7. Intelligent Tires

Intelligent tires also referred to as smart tires are the latest innovation in the automotive industry where conventional tire has been incorporated with sensor technology to enhance the communication between vehicles and the surrounding environment. Such tires are fitted with several sensors that help to measure different aspects of the tire functioning such as pressure, temperature and overall health of the tire. This information is very valuable in the enhancement of the safety, effectiveness and reliability of vehicles. Intelligent tire does not stop at the level of monitoring; it goes further to include the feeding of information to the vehicle control systems for real time adjustments for improved handling, safety and responsiveness. For instance, during stormy conditions, the intelligent tires are capable of identifying variations in road topography and temperature and pass on such information to the vehicle that may include changing the stability control or braking system.

This integration of sensor technology into tire design stems from the current need for better safety, improved efficiency and reduced automobile emissions. With the advancement of connected and autonomous vehicles the need for smart tires is only going to increase. They do not only act as inert components of the vehicle but as active members of the vehicle's environment, supplying important information that feeds ADAS and automation. Furthermore, it is pivotal to note that intelligent tires are very useful in solving some of the problems facing modern transportation like emission of carbon dioxide gases and poor fuel economy. They help to make sure that the tires of the car are always properly inflated and aligned, which helps in minimizing on the use of fuel as well as the rate at which the tires are worn out thus promoting a more efficient way of driving.

The advancement of intelligent tires can also be co-related with IoT and smart technology where even the normal use tire is transformed into an intelligent tire that can gather and share information. In this regard, tires transform from mechanical rubber products into intelligent systems that are capable of producing information about vehicle performance and the state of the road surface, which is a major growth in the development of vehicular intelligence. Thus, where the human control is limited or non-existent as in the case of 'autonomous vehicles,' the opportunities for monitoring driving conditions independently are critical. In this regard intelligent tires along with sensor technology deems remarkable position. These are located in the tires and wheels and their function is to provide information on different aspects such as temperature, pressure, and the surrounding terrain among others. It is necessary for the autonomous system to make decisions and it must know whether the environment is safe or not and how to maneuver safely.

There are several types of sensors, which are contained in Intelligent tires:

- **Tire Pressure Sensors:** These sensors continuously measure the air pressure inside the tire sending signals to the control of the vehicle in instances where the pressure deviates from the desirable range.
- **Temperature Sensors:** These measure the internal temperature of the tires which has an impact of the performance greatly weather it is in hot weather or cold.

- **Tread Depth Sensors:** These sensors quantify the state of wear of the tread of the tire thereby giving information on when a tire may be due for replacement.
- **Road Surface Sensors:** Such development sensors can identify the shifting of road surface features and that is very essential in changing the movement of the car in order to achieve better traction and safety.

1.7.1. Categories of Tire Sensors

The placement and specific functions of tire sensors vary, enhancing their ability to provide detailed and relevant data. The placement and specific functions of tire sensors vary, enhancing their ability to provide detailed and relevant data:

i. **Tire Mounted Sensors:** These sensors are fixed to the inner surface of the tire and offers pressure, temperature and identification number of the tire. Due to the closer contact with the tire, it is possible to monitor and report the conditions of the tire as they are, in real-time.

ii. **Valve Mounted Sensors:** These are threaded and mounted on the internal flange of the rim and provide many more other features excluding pressure and temperature indications. They can range from features like monitoring of spare tire, pre-set tire fill assistance, lock signals and for tire explosions and all sorts of security features.

iii. **Wheel Mounted Sensors:** Mainly used for measuring air pressure, such devices function as transducers and are in direct connection with a car's onboard control module. Some are fitted with powerful analytical systems that allow for the determination of pressure in each of the tires it is an indispensable factor in the stabilization of the motion of the car and achieving the correct distribution of the load on the site of the wheel-ground.

These sensors provide a guarantee of getting assimilated into smart tires that will greatly improve the performance of self-driving automobiles. These tires can transmit data to the self-driving system on the conditions of the tire and the surrounding environment to allow for adjustments in real-time thus improving safety, performance, and passengers' comfort. Thus, in the case of autonomous technologies, intelligent tires are expected to be already on the way to becoming even more integral to the overall ecosystem of vehicle intelligence and networking. Apart from serving the functional requirements of autonomous vehicles, it helps towards achieving other objectives of smart transportation systems which include safety, environmental issues, and vehicle efficiency.

1.8. Powering Intelligent Tires

Currently, the sensors that are built into intelligent tires have been using battery as source of energy. However, due to the drawbacks associated with batteries and in particular the issues of replacing batteries within the tires themselves, research has shifted its focus to find more sustainable and logistically viable source of power. Energy harvesting and in particular piezoelectric energy harvesting has been established as one of the most effective solutions. This revolutionary technology uses mechanical loads which tires typically subject to during normal operations and convert them into electricity.

Piezoelectric energy harvesting has some advantages, which are the following. First of all, it allows ‘tire sensors’ to work independently in terms of power supplies. ” It must be mentioned that these sensors are capable of generating the power needed for their functioning due to the kinetic energy generated during driving so there is no need for external power supply that makes the process of maintenance more effective and convenient. Second, integrated piezoelectric materials dramatically increases the endurance and dependability of the sensor systems. These are materials that are not only durable but can also sustain the entire lifetime of the tire without requiring replacement or any form of maintenance something that cannot be said of batteries. Moreover, the effect of the piezoelectric energy harvesting on the environment is not as bad as that of the conventional battery-operated systems. This green technology lessens the pressure placed on batteries so much so that the burden from manufacturing batteries, using them, and discarding them is less. This is especially important when it comes to combating the generation of hazardous wastes and in the promotion of sustainable living across the world. The use of piezoelectric energy harvesting in intelligent tires can thus be regarded to be consistent with general environmental imperatives as it supports the emergence of the green auto industry and fosters the utilization of sustainable energy solutions within the context of the auto industry.

As a result, the application of piezoelectric energy harvesting in intelligent tire design takes into account the practical challenges of using batteries as well as contributes to improving the environmental friendliness and operational efficiency of modern vehicles. This certainly is a major advancement in the advancement of intelligent transportation systems which will see more autonomous and environmentally friendly driving in the future.

Chapter 2: Literature Review

The primary problem associated with the use of the electronic devices is in the provision of power. They use electrochemical batteries which must be recharged or replaced frequently to be useful for operation again. Due to the need to increase periods between recharges, efforts have been made towards improvement of battery life. Due to the need to increase the battery power in portable technologies, the manufacturers have embraced innovations. One of such advancements is the lithium-ion battery which has now gained a lot of appreciation due to its long-life span. The automotive industry has focused increasingly on installing sensors within tires in recent years to monitor a variety of metrics, including pressure in tires, temperature, contact path and tire wear[24]. Direct measurement of these metrics improves the vehicle safety hence contributing to the development of the smart tires [25][26]. The tire monitoring system depicted in Figure 1 consists of a central receiver that receives sensor signals and processes data, as well as wireless sensors installed inside the tire to measure tire characteristics. To assure the safety of the people inside, the car's control system will either halt the self-driving car or notify the driver if it detects a tire malfunction.

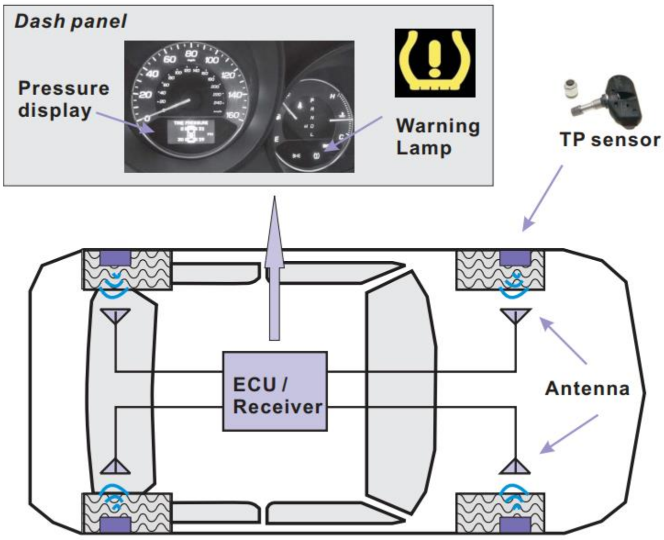


Figure 13: TPMS communication block diagram[27]

There are mainly two types of wireless transmission used to transmit data from tire to car. Active and passive transmission. In passive transmission data is only transmitted whenever fault is detected in tire such as pressure drop. Whereas in active data transmission data is being continuously transmitted to vehicle ECU, hence is a better option for self driving vehicle where continuous feedback is required. Active transmission is a power hungry task and therefore a self sustainable power source is required.

Currently batteries are being used but it isn't a long term solution as they require frequent maintenance like charging and replacement [28], [29] Piezoelectric energy harvesters can power the tire sensors by harvesting energy from the tire strain, providing eco friendly energy source [7]. Advancement in the field of piezoelectric materials and manufacturing process at micro and nano scales have increased the significance of piezoelectric technology. For new piezoelectric materials, there are currently numerous thin films and nanostructures available, including ceramics, composites and polymers. These materials are appropriate for emerging industries because of their high piezoelectric coefficients, flexibility, and durability. As a result, piezoelectric energy harvesting has gained enormous attention on a global scale. The most prevalent ambient energy source that is also the easiest to harvest and transform into usable electric power is mechanical energy[30]. Because piezoelectric materials generate electricity based on their own internal properties (intrinsic polarization), they are ideal for this application. This phenomenon works without the need for an external power source, in contrast to other harvesting techniques like electrostatic, electromagnetism or triboelectric.[31]. Compact and small-sized piezoelectric generators can easily be incorporated into microelectromechanical systems (MEMS). Additionally, they are resilient to environmental elements like humidity[32]. Piezoelectric transduction is a leading ambient energy harvesting technology because of these benefits. It has been used in many different domains, such as wearable and implantable biomedical devices, wireless electronic devices, MEMS and automotive industry [33].

Application of PVDF based piezoelectric patches to harvest energy from tire deformation, shows a considerable voltage generation which is inversely proportional with the tire inflation pressure and directly proportional to patch size, load and speed[34].

The car industry especially considers truly self-powered TPMS, which are playing a major for improving on fuel economy as well as safety[35], [36]. Piezoelectric energy harvesters (PEHs) have been seen to be the most suitable technology to use in TPMS because they can generate power from the dynamic mechanical vibrations that are experienced in tires[37]. Mangone et al. [38] integrated a PEH in a sandwich structure in which a piezoelectric polymer (β-PVDF) is intercalated with two conductive elastomer layers to achieve an output power of around 28 mW for a TPMS sensor. Compared with PZT type of piezoelectric ceramics, PVDF has better range of force bearing, so it can be widely used in dynamic application such as tire. The conceptual design is illustrated in Figure 14.

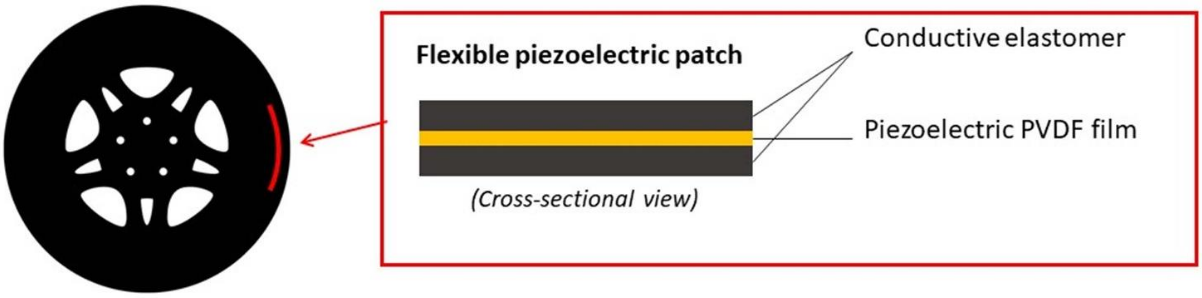


Figure 14: Sandwich type flexible piezoelectric energy harvester[38]

For better adhesion of the conductive elastomers, the PVDF film involves processes like; Oxygen plasma and silanization, which are significant in the performance of the energy harvester. Preliminary tests and evaluations are carried out on the design parameters followed by dynamic evaluations using the rolling tires of the harvester for adhesion performance. The synthesized piezoelectric patch of PVDF film and conductive elastomer reinforced with 6 wt% of carbon nanotubes produced an output power density of 28 μW cm^{-2} at certain frequencies 100 Hz, temperature (90°C) in a dynamic mechanical analysis (DMA) system. Frequency and temperature are the main factors that affect the output power since high frequency and higher temperatures produce more electricity.

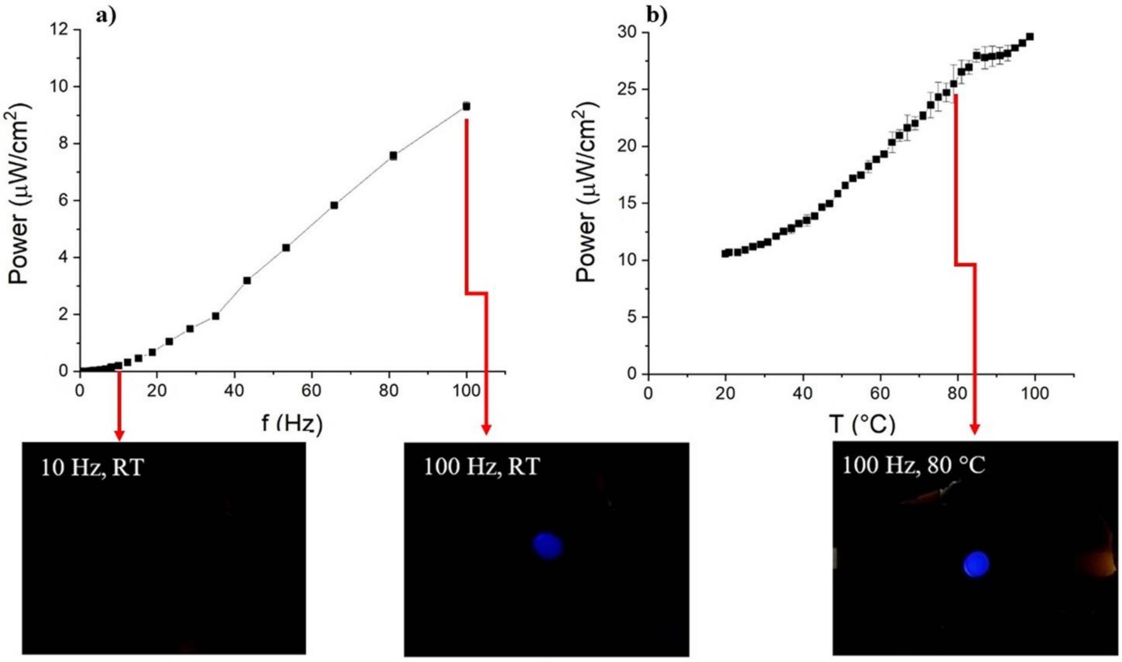


Figure 15: Output power generated under frequency ranging from 0 Hz to 100 Hz[38]

Experimental results showed correlation between the controlled environment of the laboratory and actual tire rolling situations. The piezoelectric patch was able to light an LED bulb as well with the brightest light intensity obtained at 100Hz, 80°C however, it could not power the LED at low frequencies and normal temperature. This study also focuses on the possibility of incorporating the patch into the inner liner of a tire, which can extract kinetic energy from stresses produced when driving and supply power to TPMS without any interruption.

Henrik et al. [2] proposed with a new modeling method called the "dynamic bending zone. " Unlike the previous modeling approach that models the whole tire including bending zones, this method only models the bending zone that the tire makes contact with the ground. The points above neglected improves the efficacy and realism of modeling tire deformation and the effects on the energy harvesters. All numerical simulations use COMSOL Multiphysics: it models the piezoelectric harvester functioning together with tire deformation. MATLAB/Simulink provides further modeling, especially to the positioning of the piezoelectric ceramics at the tire-rim guard.

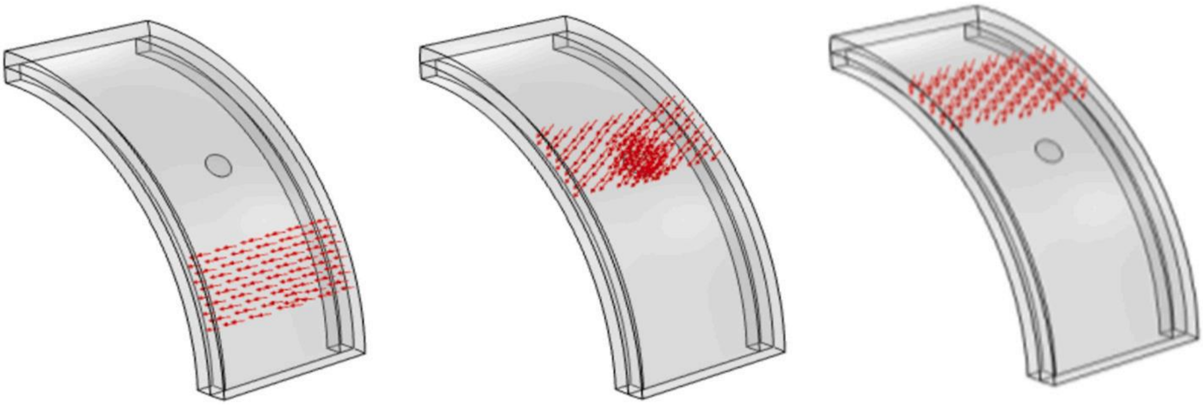


Figure 16: COMSOL analysis of dynamic bending zone[2]

The study examines different geometrical shapes that are used while designing the harvester such as circular, rectangular and square geometrical shapes. From the results it is clear that the circular harvester provides higher output voltages at each measurement than does the rectangular shape even when the overall surface area under test is the same at 4 cm^2. This result implies that the morphology of the harvester is a factor that has a bearing on energy harvesting effectiveness.

Energy output also depends with the layer configuration. For instance, a three-layered harvester in circular form reaches a cumulative energy density of roughly 22 µJ and a single layered circular harvester produces energy densities of 23 µJ at lower velocities of oscillation. This means that the higher is the number of layers, the higher is the energy harvester efficiency, however the complexity of the structure has to be taken into consideration.

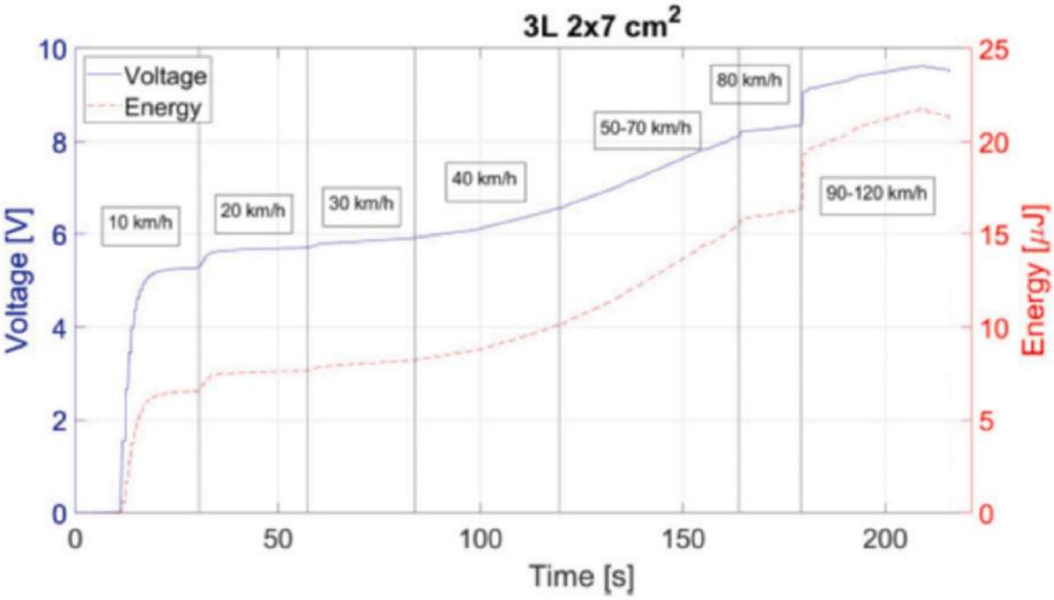


Figure 17: Measured voltage and energy generated by three layer harvester[2]

Material option is found to play another significant role, and PVDF is shown to be ideal for the tire applications because of its flexibility and the capacity to sustain large deformation. Conversely, while conventional PZT materials used in current applications are effective, they are comparatively brittle and complex in terms of strain and deflection that can negatively impact the aspects of life cycle and energy return. This new modeling technique can model the deformation of the tire and the performance of the harvester at the same time quickly, and to compare these simulations to experimental data more effectively. Of the two, the first is its convenience in extrapolating the data for low velocities to those of higher velocities, without having to perform system tests. Concerning the experimental outcome, it is identified that at Nokian Tyres PLC, a three-layer harvester (2 × 7 cm²) harvests about 22µJ of energy at speed range 10 km/h to 120 km/h. It was found that a one-layer circular harvester produces measurable energy of 23µJ for velocities ranging from 0 km/h to 40 km/h, proving the feasibility of both designs.

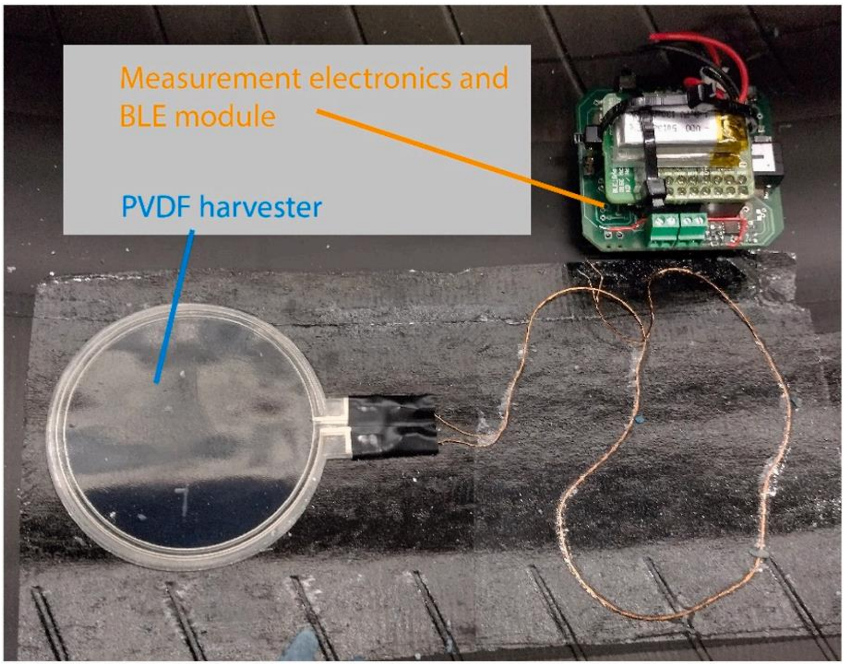
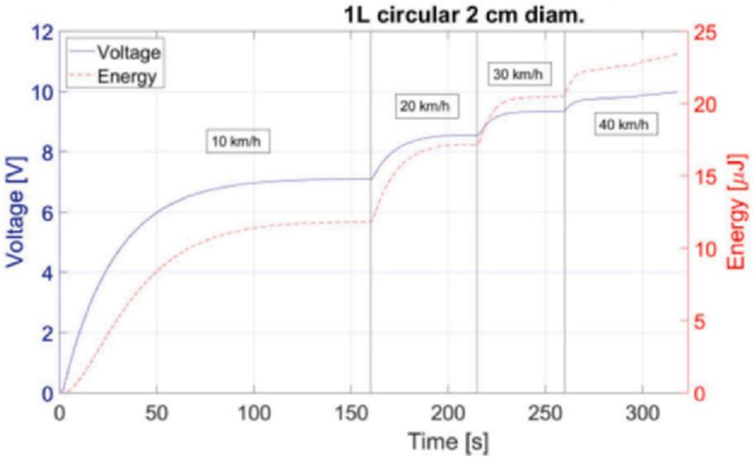


Figure 18: Circular disc harvester installed inside the tire[2]

Furthermore, one-layer circular harvester produces the saturated voltage of 7. 1 V, 8. 3 V, 9. 140 kPa, 76. 5 kPa and 50 kPa at various speeds; ranging from 0 Km/hr to 40 Km/hr at voltage of 1 V, and 10 V. The maximum of accumulated energy for this design is 23 µJ. This indicates that simpler designs are also able to produce acceptable levels of energy outputs. Slower rise velocities entail faster voltage build up and a less steep voltage characteristic, this because certain parameters such as self leakage in the capacitor affect the rise in voltage.



Hazeri et al.[39] simulated real conditions created in a model tire by installing piezoelectric elements at the outer surface of the tire circumference for capturing energy from tire deformations in the movement of vehicles. It also consists of a steel structure meant for transferring loads to the tire so that all the tests can be done at constant frequency and pressure as shown in the Figure 19

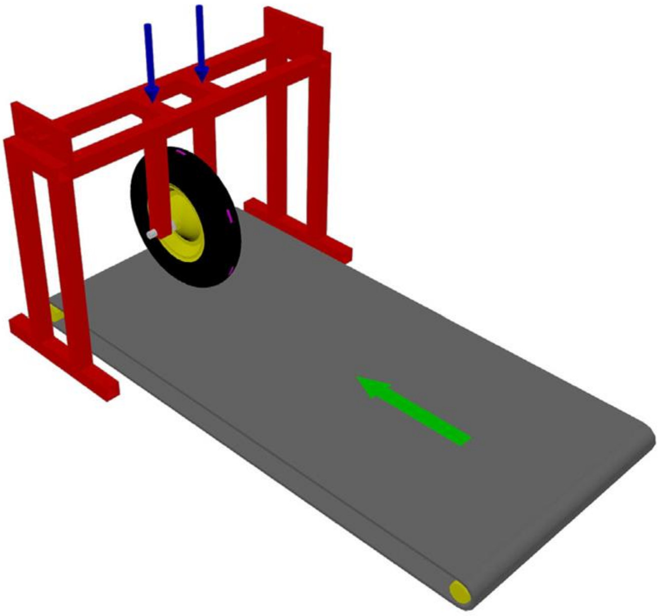


Figure 19: Experimental setup for PEH testing[39]

Tests are performed at different velocities with maximum velocity of 55 km/h simulating operational status of a reference car. As a result, new piezoelectric elements are employed before any test is conducted to reduce the risks of a fatigue effect on the results. The amount of energy harvested when tires are rotated rises with speed and the weight applied on them, based on sensitivity analysis, which examines the reliability of the results obtained, especially regarding the changes in the quantity of piezoelectric material. Figure shows the piezoelectric patches attached to the outer surface of the tire.

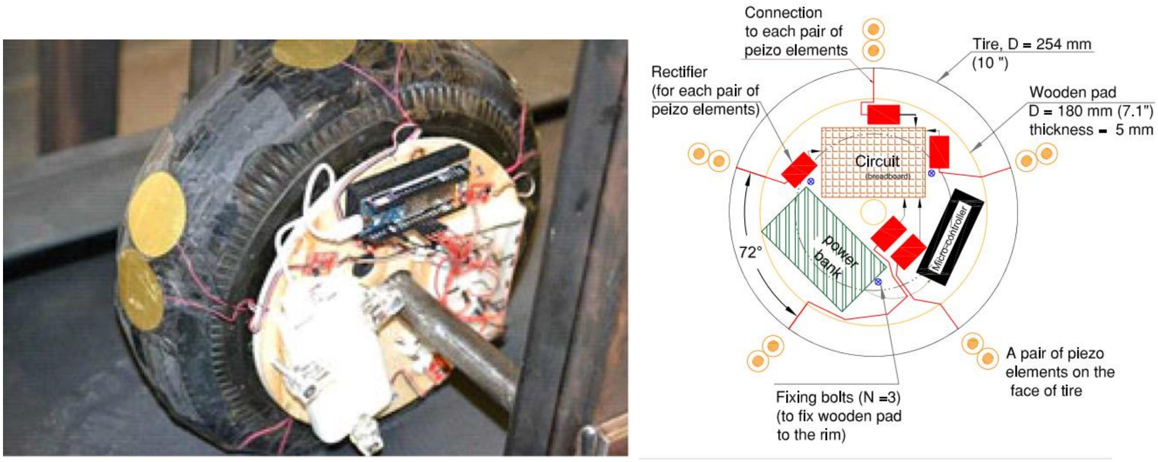


Figure 20: Piezoelectric energy harvester mounted on the outer surface of the tire[39]

A life cycle assessment, charting the environmental effects of piezo-tires against ordinary tires, shows that although piezo-tires capture some waste energy, they marginally provide a slightly higher environmental cost especially in terms of material extraction such as niobium which is utilized in manufacturing piezo-electricity. The LCA also identifies the impacts that may occur in the context of using and disposing piezoelectric material. This investigation also proves that mounting piezoelectric segments on tires enables conversion of mechanical energy into electrical energy with the harvested energy at its peak of 0. 035 µW s per tire rotation, scaling up to 10.11 µW s for a reference tire and 40.44 µW s for a reference car with four piezo-tires. The output voltage also rises with the increase in speed, and the load; it doubles when the velocity goes up to 4mph from 2 mph, though it goes a little high with any further increase in speed because of the limited charge discharge cycles.

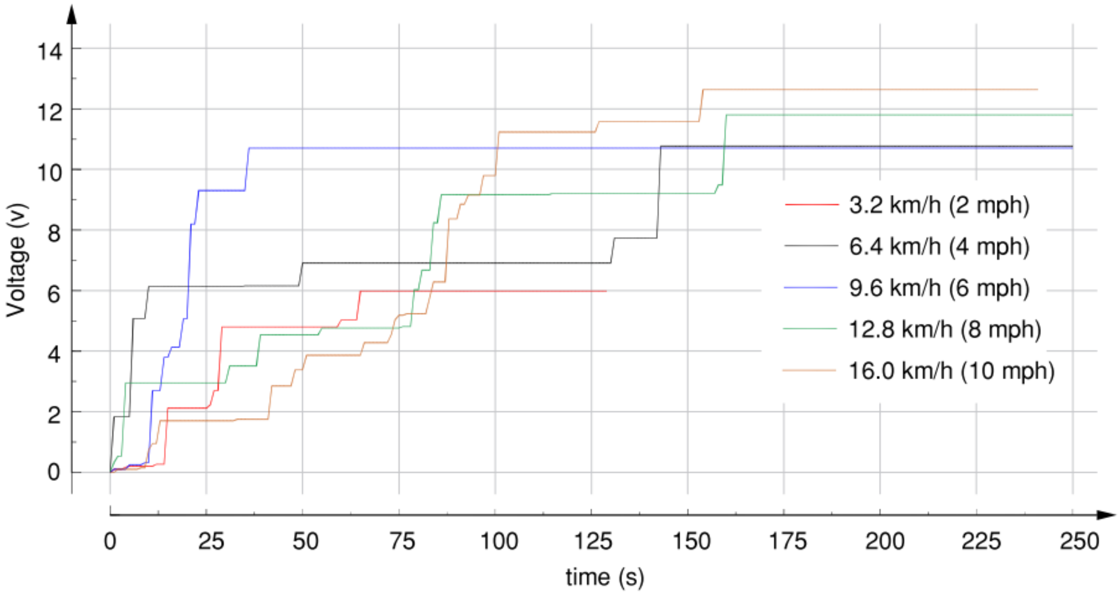


Figure 21: Voltage produced at different speeds[39]

Direct stretching of piezoelectric ceramics would not be particularly effective due to its high Young's modulus. In order to induce higher strain, many types of piezoelectric energy harvesters (PEHs) have been designed based on different bending mechanisms; including: cantilever, cymbal and stack structures. The number of papers in web of science database, which was published after using the keywords “cantilever piezoelectric energy harvesting,” “cymbal piezoelectric energy harvesting” and “stack piezoelectric energy harvesting” are shown in the Figure 22. Findings suggest that cantilever PEHs have been the most appealing for manufacturing because of their relative simplicity in fabrication and realizing much larger strains. The cantilever structure has an upper hand in generating large strain under base excitation in vibrational systems[40].

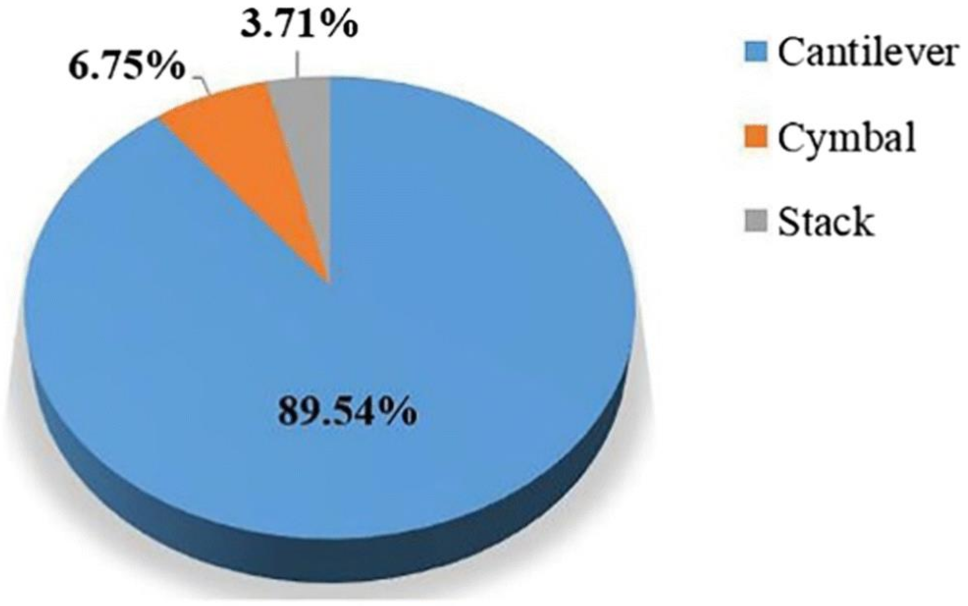


Figure 22: Structures of PEH from 2000 to 2016 [40]

Unimorph and bimorph are common configurations of cantilever-based PEHs as shown in the figure.

Rui et al. [41] developed the Integrated Wheel Spoke Piezoelectric Harvester (IWSPEH) utilizing piezoelectric mechanism for direct conversion of mechanical energy to electrical energy from the rotation of wheel spoke. This mechanism works with the help of centrifugal force which helps in the process of rotating to get a better energy conversion efficiency. Another distinguishable aspect of the IWSPEH is the its auto-tuning mechanism that tunes the resonance of the harvester in relation with the wheel rotating frequency in order to continuously achieve enhanced energy harvesting efficiency at varied wheel speeds. The design process entails calculating the influence of such a force in the beam stiffness, where the centrifugal force in relation to frequency exerts an influence on the systems resonant freq. Maintenance of the mechanical structures hence recommends the use of T6061 aluminum alloy due to its suitable elastic modulus while bearing in mind the efficiency impact of the piezoelectric material in the system. Block diagram of the designed harvester with the placement is shown in the Figure 23.

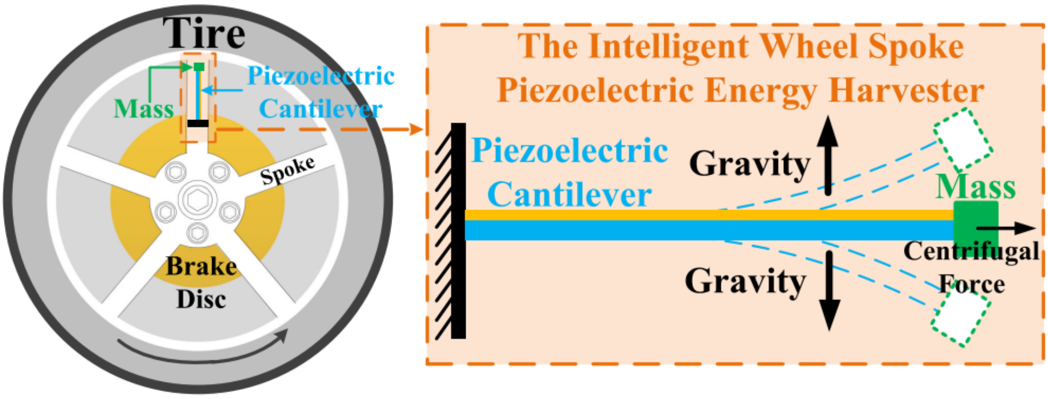


Figure 23: IWSPEH Placement and block diagram[41]

The Euler-Lagrange method is used for deriving dynamic model to predict design parameters like the design factor D for optimal design To verify the harvester design specifically for R16 wheel, experiments are conducted for real-world application, evaluating the voltage output and energy conversion efficiency at various design factors. The experimental platform for the IWSPEH is intended to verify the effectiveness of the system collecting energy in real-world conditions. The main part of the prototype is the piezoelectric cantilever beam of R16 wheel with additional elements such as the DC motor, motor driver, and the speed controller to produce the frequency range from 0Hz to 17Hz. The experimental prototype is shown in the Figure 24.

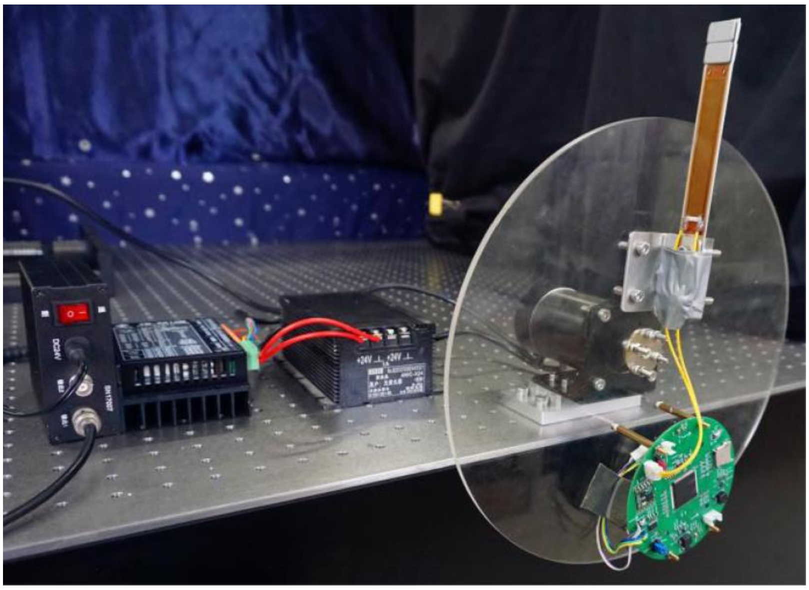


Figure 24: Experimental prototype of IWSPEH[41]

Smart Material Corp 's Macro Fiber Composite (MFC-M8514-P2) was bonded to the cantilever beam by epoxy adhesive to promote efficient energy conversion. The setup is placed on an optical vibration isolation platform to minimize environmental vibrations in a bid to enhance measurand stability. The prototype has a measuring module that stores the output voltage and the rotational acceleration with a MEMS sensor, and the data is processed with the help of an STM32 microcontroller; all the received information is saved on an SD card. Furthermore, a real-life assessment of the prototype was conducted by integrating it on a Volkswagen Sagitar car and measuring its effectiveness while the car was on the road. The experimental platform used a Macro Fiber Composite to produce an output power of 0.61-6.28 mW at wheel speeds ranging from 40 to 120 kph and is shown in Figure 25

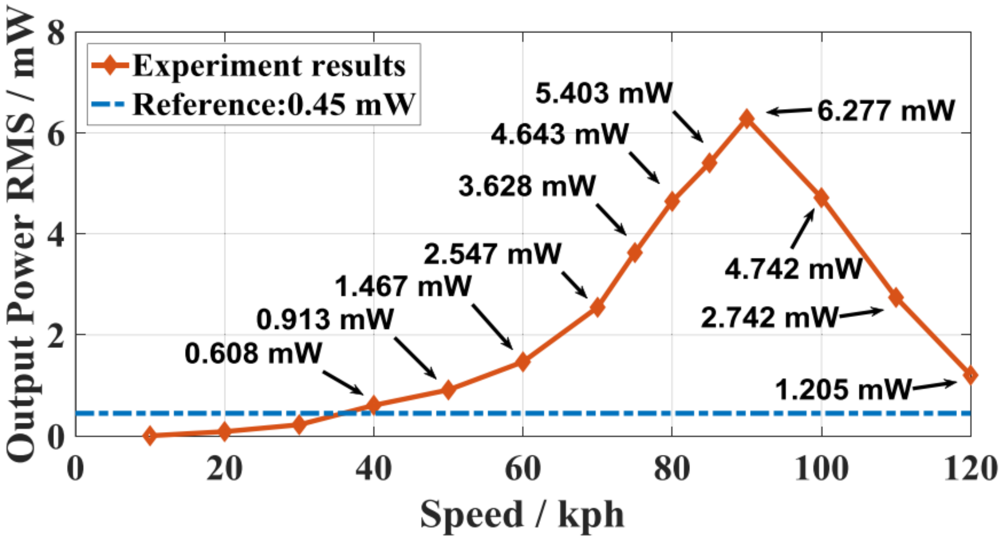


Figure 25: Generated Output Power of IWSPEH at different speeds[41]

The findings demonstrate the harvester's ability to support a wireless, independent intelligent vehicle wheel system. A primary disadvantage of the cantilever beam harvester is observed in the frequency bandwidth where the maximum power is delivered. A low matching condition between the resonance frequency band and the excitation frequency leads to low efficiency in energy conversion. The nature of the varying speed of the vehicle will reduce the conversion efficiency to a very serious level hence the need to look for broadband mechanism that will have maximized the energy harvested.

A wheel spoke mounted PEH is proposed by Vaishak et al.[42] to power low consumption sensors within tires for autonomous driving (AD) and advanced driver assistance systems (ADAS). The results showed that sufficient power to charge battery is generated at the speed above 60 km/h. Zhao et al. [43] study a unique PEH that achieved high power outputs under various driving conditions by employing noncontact magnetic force in car suspension systems. The vibration model of a dual-mass suspension system with piezoelectric energy harvester as depicted in the fig is designed to harvest a maximum RMS power of 18.33 mW. On a pulse road drive the highest values of 102.24W and 88.09W are achieved at 30km/h, in unladen and laden conditions respectively.

In their study of mechanical energy harvesting methods in traffic environments, Ronghua Du et al. [44]emphasized the technologies' potential for self-powered infrastructure applications in green intelligent transportation systems. Kan et al. [45] developed a wheel-type cantilevered PEH that effectively harvested rotational energy, with experimental results confirming its feasibility for powering LEDs and other low-power devices.

Makki et. al. [46] did a comparative study between PZT and PVDF. Energy harvester is designed to be mounted inside the tire. The study concluded that PZT disk of 0.23mm generated more power output then that of PVD film with a thickness of 0.11mm, with the same dimensions of 40x40mm. Around 4.52mW of power is generated by PZT and 0.85mW from PVDF. A self-power source for the strain energy sensor can be generated through a simple beam bending, as demonstrated by Elvin et al.'s theoretical and experiment model[47], which used a beam element to harvest power from PZT material. Rather than use a cantilever beam vibrating at resonance, Adhikari et al.[48] proposed a stochastic technique using a stack structure. Stack-type piezoelectric transducer employs the d33 mode of piezoelectric materials and has multiple layers of piezoelectric material resulting in a large capacitance, it is capable of producing a significant amount of electrical energy. The cymbal structure may produce a significant in-plane strain when an external force is applied, which makes it an excellent choice for micro energy harvesting. Installing PEHs into tires is essential to maximizing the effectiveness of energy harvesting. A device featuring two ring-type piezoelectric stacks, two elastic plates designed resembling bows, and a shaft that pre-compresses them was presented by Li et al[49]. They discovered that in comparison to the conventional flextensional mode, this flex-compressive mode piezoelectric transducer generates higher electric voltage and power production.

Yei et al. [50] analyze the statistics of the road traffic accidents stating that tire-related problems are among the top causes of accidents, therefore, necessitating TPMS. A new approach to harvesting energy is introduced piezoelectric buckled bridge to harvest low frequency rotational kinetic energy of the tires with the idea of powering TPMS in real time. A gear system is employed which applies constant compressive forces to the piezoelectric units such that they vibrate and produce high densities of energy as shown in the Figure 26.

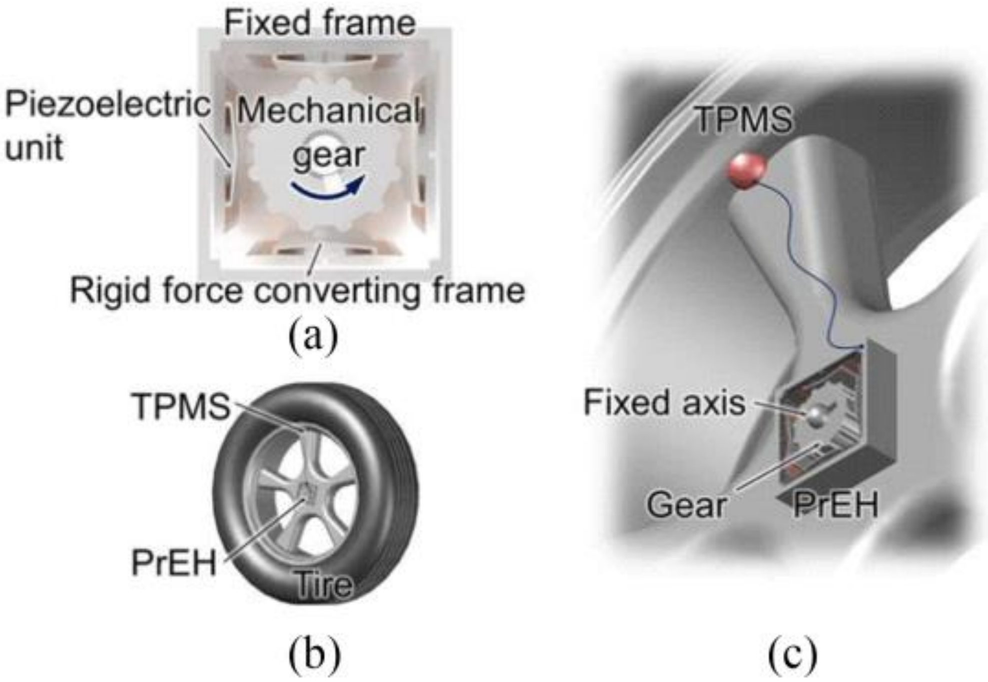


Figure 26: Rotaional Piezoelectric energy harvester for TPMS[50]

Both structures of piezoelectric units are made up two flexible bridges as shown in the Figure 27 the amount or lack of compression force put on these bridges during operations contributes to this variation in output performance. The engagement of the gear teeth and the piezoelectric units is considered to be the key to energy harvesting enhancement during tire rotation.

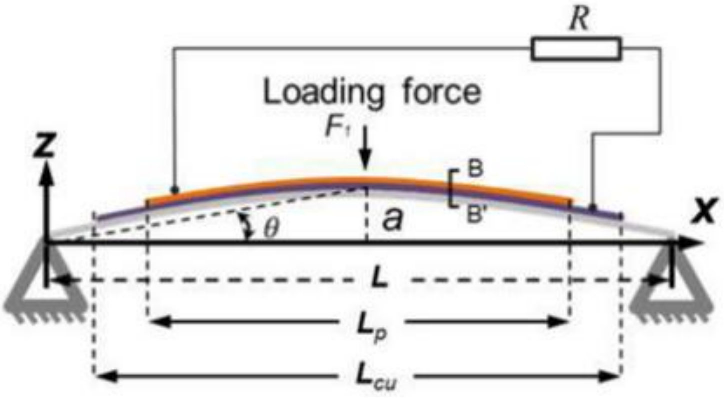


Figure 27: Illustration of piezoelectric buckled bridge

A simple electromechanical model is designed to simulate the response of the piezoelectric material under applied mechanical stress, comparing the mechanical displacement with the electrical generated output. This model employs constitutive equations and energy equations for piezoelectric material, extending special focus on the energy coupling in piezoelectrics. It is further demonstrated that the output power of the energy harvester is a function of the resonant frequency and fixed design parameters. The range of optimal frequency for energy harvesting is established, with lower frequencies yielding higher power values because of the gear mechanism effect frequency conversion. In order to achieve this, the design is optimized for a low harmonic distortion which minimizes frequency dependence of the output power possible while adapting to the low rotative frequencies characteristic of vehicle usage. The variation in the voltage output waveforms is caused by variations arising from fabrication and they indicate peak to peak voltages that range between 20V and 30V. A FFT analysis of the source and load current waveforms confirms that the output frequency is equal to the expected rotational speed of the harvester and therefore verifying its efficiency.

A maximum working voltage of 25 V capacitors is used to measure energy storage and evaluates charge control at varying capacitance levels. It can be seen from the results that about 0.6 mJ of electrical energy is stored per second which points the efficiency of the harvester for managing energy in TPMS applications. The developed energy harvester as shown in the Figure 28 is capable of harvesting low frequency rotational kinetic energy and has an output voltage at the open circuit of 19V and an output power of 8.9mW. The demarcation rotational frequency showing the best operation of TPMS is considered between 3-3.7 Hz while real time operating condition is attained at a frequency greater than 8 Hz. The potential of PZT-5H in automotive applications is demonstrated by its power output, which is sufficient to enable real-time tire pressure monitoring.

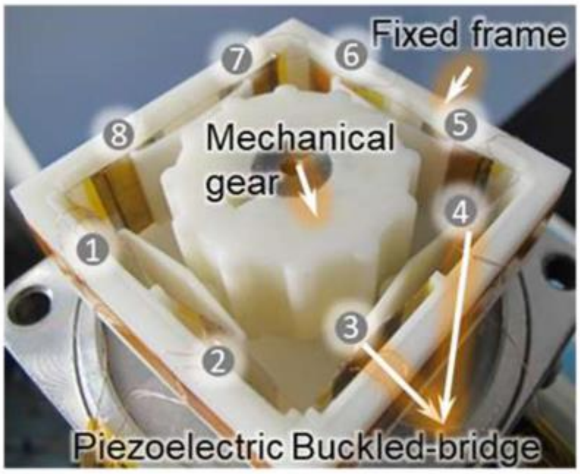


Figure 28: Developed Piezoelectric energy harvester

Energy harvesting systems can come in various forms where by they capture and utilize ambient energies such as vibrations from the tire dynamics to power intelligent tire monitoring systems crucial for self-driving cars[51]. Esmaeeli et al.[52] proposed energy harvester that is designed to be mounted at the inner lining of tire in a way that it can harness the energy from the generally exerted force during tire deformation when in use. This is a preferred location because tire constantly deforms and rebuilds whenever it is in contact with the road thus continuously providing mechanical energy that could be harnessed to produce electricity as shown in the Figure 29 . Due to the extremely curved surface of the tire especially the patch that comes in contact with the ground, the harvester should be small in size.

Because of the space constraint within the tire, the energy harvester has to be limited to less than 5 mm × 5 mm × 5 mm [53] which allows it to operate optimally in the specified context while at the same time exhibiting efficient functionality and structural integrity of the tire. The design of the PEH is based on Cymbal structure which is widely used for its mechanical strength and ability to sustain high cyclic loads. However a new design of Cymbals as been altered from the regular design for a tire and has to withstand conditions such as continuous flexing, high force impacts, as well as rotational momentum. An important modification is that the bottom part of the energy harvester is attached to the internal surface of the tire only. This way, the size of the device is contained and is within the permissible size limits while at the same time attaining a high efficiency in the energy harvesting process from the tire's motion.

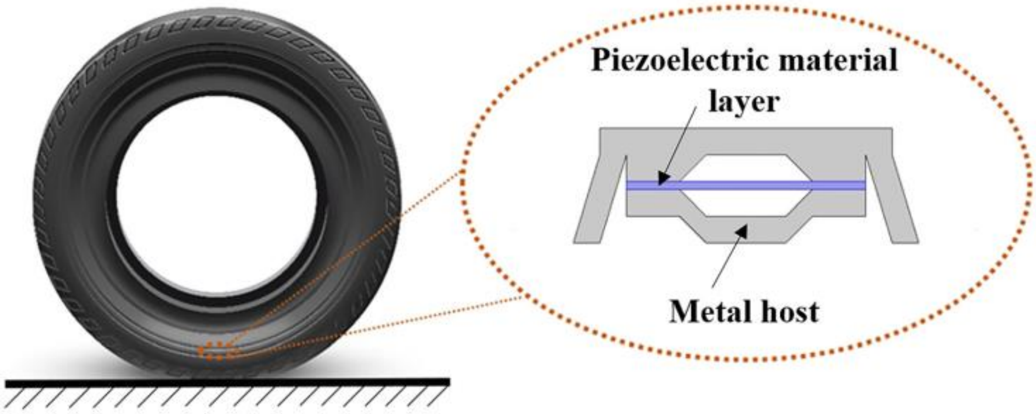


Figure 29: PEH harvester mounted on the inner surface of the tire[52]

The harvester is designed to harvest energy from radial and longitudinal displacements which appear due to the complex movement of the tire. To this end, gaps are provided between the metal layers and the piezoelectric material, whereby the end caps of the harvester transform radial movements which result from tire compression into longitudinal movements. This bi-directional movement improves the device's ability to capture energy in response to dynamics occurring in the tire. The harvester can combine both radial and longitudinal forces that are available in that sector and they note that the new harvester will significantly perform better than the poor and inconsistent energy source.

Thus, the adhesive used in the construction of energy harvester is chosen depending on the load and stress that occurs in the contact area with the tire. The adhesive used in the method must be able to sustain the wear and tear as well as stress that the rolling movement of the tire puts into it and still adhere firmly to the harvester and to the surface of the tire. It is important for the operation of the harvester, the secure attachment is never to be broken or moved any nearer to the wheel in case the efficiency of the harvester is lost or in the worst-case scenario the tire is damaged. These materials and design features are chosen to make the energy harvester perform well within a tire environment and augment its capability to provides power for TPMS as well other low power devices in real-time. Cyanoacrylate is used in study to bond the harvester with the substrate. It is used in industrial applications primarily as a adhesive for bonding of two surfaces particularly metals and rubber using. It possesses Tensile bond strength that varies between 12 & 3 MPa with 25°C – 150°C temperature and 13 & 11 MPa of 40% – 100% R. H on mild steel substrate[54].

The energy consumed by wireless sensors that are utilized in the tire monitoring systems has also been estimated providing a figure of about 10 µJ per tire revolution on an average[55]. The study computed the stress on the inside surface of the tire and estimated it to be about 3150 micro-strain as shown in the

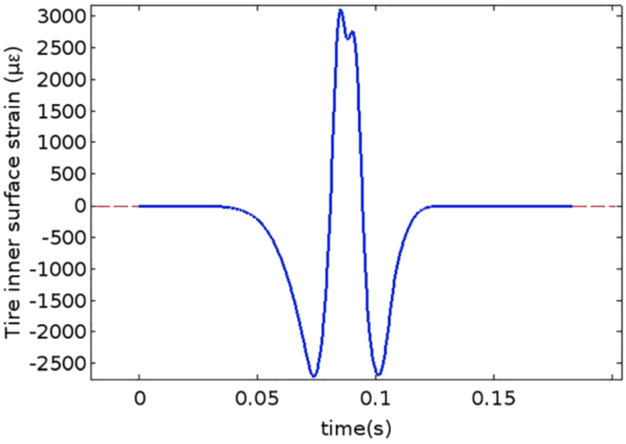


Figure 30: Tire strain vs time graph[52]

In one complete rotation of a tire the PEH generated a maximum output power of 2.86 mW, with the associated voltage of 3.5 V as shown in Figure 31 (a) and (b) respectively.

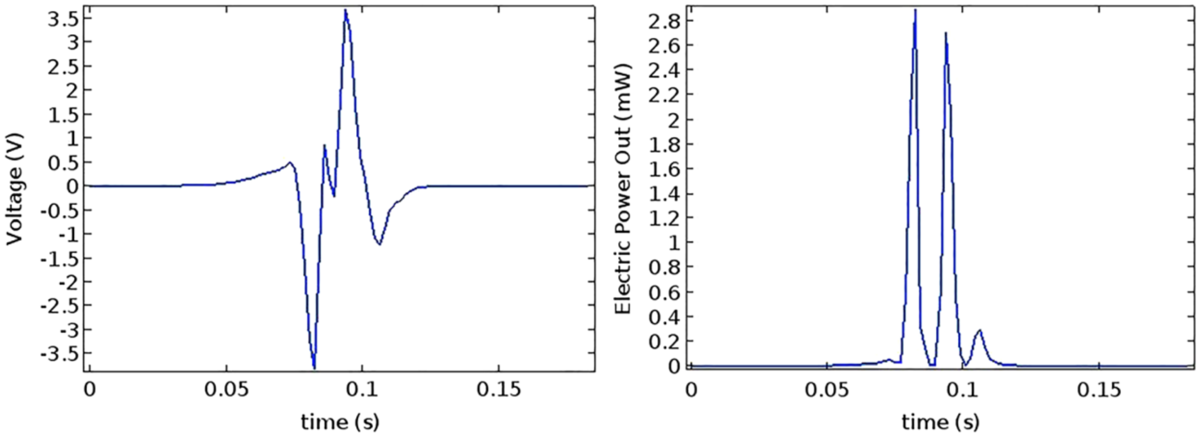


Figure 31: In one complete rotation of tire (a) Total Voltage produced (b) Total electric power produced[52]

At even lower speeds (8 km/h), the PEH generated sufficient energy for only one sensor. The study also identified thickness of the PZT-5H as another parameter that influences output energy; output energy increases with the thickness of the material to 0. 8 mm allowed the PEH to deliver energy to five sensors therefore it was clear that thickness played crucial role towards energy availability. In addition to being smaller and lighter, piezoelectric harvesters provide three times the energy density than electrostatic and electromagnetic harvesters[56]. Anil and Sreekanth[57] proved that the output voltage is directly proportional to the input force, thickness, and capacitance of piezoelectric device and inversely proportional to area of the piezoelectric disk.

Chapter 3: Methodology

There are two main placement of piezoelectric energy harvesters, on the inner surface of the tire and on the rim spoke. In this research two different energy harvesters are designed for the both placement respectively. For placement on the inner surface of tire the Piezoelectric Energy Harvester (PEH) experiences strain when a tire bends. Because of the piezoelectric effect, this strain in turn induces voltage to be generated in the layer of piezoelectric material. Thus, the tire's deflection must be determined while modelling a PEH. The tire experiences longitudinal strain as a result of variations in the curvature radius which is given[58] as Equation (1)

$$\varepsilon = -\frac{Zc - Z}{R} \tag{1}$$

Z refers to radius of inner tyre surface. Zc represent the radius of tyre with no load. Where as R is the radius of curvature.

$$a = Rsin\left(\frac{L}{2}R\right) \tag{2}$$

The product of radius R, and arc angle θ represents the arc length L. In Equation 3, variable 'a' denotes the distance between two points on the curvature, represented by (ri−1, ri+1). This distance can be determined by using [59] [52] equation (3.

$$a = 0.5\sqrt{\left((r_{i-1}\sin(\theta/2) - r_{i+1}\sin(\theta/2)\right)^2 + \left((r_{i-1}\cos(\theta/2) - r_{i+1}\cos(\theta/2)\right)^2} \tag{3}$$

The effectiveness of tire-integrated piezoelectric energy harvesters depends on a number of important factors, such as tire deformation and the pressure the harvester is subjected to. The contact area enables to determine the size constraint of PEH and also the placement to maximize pressure distribution and energy production. The contact area and the load acting on the tire surface is measured as [60]

$$Tire\ Width = P/0.8 \tag{4}$$

$$Tire\ length = 6.4\,\gamma\,(1 + IM/100) \tag{5}$$

Where

P= Design Wheel Load (kip)

IM = Dynamic load allowance percent

γ = Load Factor

3.1. Material Selection:

Choosing the right kind of piezoelectric materials for energy harvesting in car tires involves striking an optimal balance between high energy conversion efficiency, robustness, and suitability for the demanding conditions to be encountered inside a tire. PZT is the most widely used piezoelectric material because it has a high efficiency, great piezoelectric sensitivity, and produces an efficient electrical output for a certain mechanical stress level. PZT-5H's appropriateness for energy harvesting applications differs significantly from that of other piezoelectric materials, including PZT-5A, PZT-4, and PMN-PT. Because of its exceptional strain capabilities, PZT-5H which is renowned for its high piezoelectric constants and strong electromechanical coupling is frequently chosen for low-frequency applications and conditions with fluctuating mechanical loads. According to [61] variations in mechanical damping and elastic compliance might cause PZT-5H's electrical output to be lower than PZT-5A in some situations, even though the latter has a higher d31 constant. Shahab et al. [62] determined that PMN-PT performs better than PZT-5H in terms of power production for broadband random vibrations because of its higher piezoelectric coefficients, yet PZT-5H works well in low-frequency off-resonance conditions. Furthermore, Saxena et al. [63] discovered that PZT-5H's capacity to produce significant voltages and displacements makes it very useful in low-frequency piezoelectric energy harvesters, such those used for tire applications. These conclusions were corroborated by Zhou et al. [64], who showed that the PZT-5H's performance in a symmetrical ring-shaped harvester enhanced the output during temperature variations an important factor for tire mounted devices.

A comparison analysis of different piezoelectric materials is done in TABLE.

Material	Piezoelectric Constant D_{33} [pC/N]	Dielectric Constant	Young's Modulus [GPa]
PZT-5H	593	3400	63
PZT-4A	289	1300	90
PVDF	20-30	10-12	2-4
PMN-PT	1500-2500	5000-6000	10-20
BaTiO3	190	1500-1700	67

Given that PZT-5H has a high dielectric constant and d33, as well as being useful for low-frequency piezoelectric energy harvesting, it is selected for the proposed application based on the comparison study of several piezoelectric materials in Table 1. While BaTiO3 is safe and has a reasonable dielectric constant, PZT-5H has a higher piezoelectric constant. PVDF is highly flexible and works well for wearable technology, but has the lowest piezoelectric constant and dielectric constant. Although PMN-PT shows exceptionally high d33 and dielectric constant make it ideal for high sensitivity applications, but it is challenging to process.

3.2. Harvester Geometry:

The geometry of the harvester, including its shape, size, and stiffness, should resonate with the predominant vibration frequencies for maximizing energy conversion.

3.2.1. Modeling of Wheel Spoke mounted PEH:

A novel design of piezoelectric energy harvester (PEH) for smart tires which is seen as a major innovation in automotive engineering seeks to capture and convert the rotational mechanical energy generated by wheels as meters per revolution. This system employs a cantilever beam structure that is located within the wheel spokes and differs from the fundamental base-excited beam harvesting designs. In this unique design, the base of the PEH is firmly attached to one of the Spoke of the wheel. Moreover, this fixed positioning does not call for regular base excitation as is customary with some of the conventional designs. The gravitational forces acting upon it changes as the vehicle functions, the cantilever beam that is in turn, rotates along with the wheel axis. These forces produce vertical & horizontal oscillations at the free end of the beam which in turn creates mechanical stress which is than transduced into electrical energy with the help of piezoelectric disk fixed at the end of cantilever.

It became clear that for the realistic applications and high energy conversion efficiency, a though provoking yet simple mathematical model should be established. This model will provide a basic framework of analysis when designing the energy harvester and predicting its behavior during various operations such as at varying speeds and on different terrains. The original model is designed to achieve a high extent of realism and be as simple as possible so that it may be easily applied in practice. The integration of the PEH within the wheel spokes imposes specific dimensional constraints that must be carefully considered to ensure compatibility with the wheel structure and optimal performance. The dimensions of the PEH are chosen based on the average rim poke depth, which is approximately 21.6 mm across different vehicles. The length of the cantilever beam is crucial for capturing maximum vibrational energy and is therefore set at 120 mm, which is within the range of typical wheel radius from 15.24 cm to 27.94 cm (corresponding to R12 to R22 wheel sizes). The width of the beam is determined to be 20 mm, taking into account the depth limitations of the rim[41].

The following table provides a detailed overview of the critical dimensions of the piezoelectric energy harvester, ensuring that the design is adaptable to various wheel sizes while maximizing the energy conversion efficiency:

When wheel is rotating then the displacement of mass with respect to origin is w(t) and angle made by displacement with y-axis is θ(t) then displacement in cartesian plane is

$$w_x = \mathrm{w}\ \sin\theta$$

$$w_y = -\ \mathrm{w}\ \cos\theta$$

Taking derivate of eq1 yields speed of the system which is given in eq2

$$\dot{w}_x = \dot{w}sin\theta + \ w\dot{\theta}cos\theta$$

$$\dot{w}_y = -\dot{w}cos\theta + \ w\dot{\theta}sin\theta$$

Then the kinetic energy is given by

$$T = \frac{1}{2}m(\dot{w}^2{}_x + \dot{w}^2{}_y)$$

$$T = \frac{1}{2}m(\dot{w}^2 + w^2\dot{\theta}^2)$$

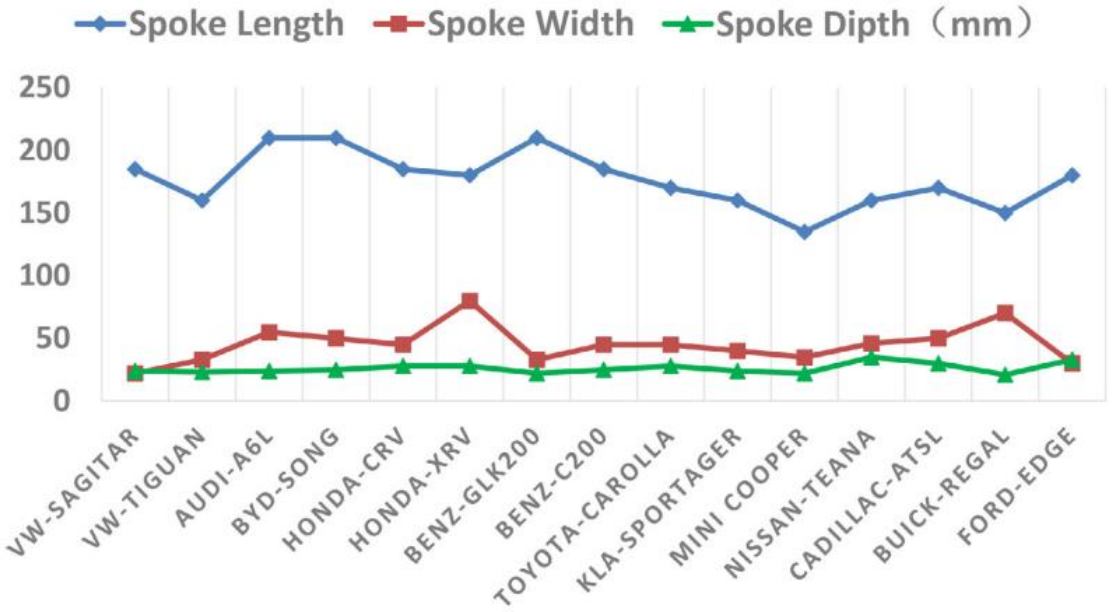


Figure 32: Characteristics of spoke [65]

As the harvester will be mounted inside the wheel spokes, hence its size should not exceed than the parameters of wheel spokes. Rim spoke depth length and width of different car wheels is given in Figure 32 and the avg depth is 21.6mm. For the length as the harvester is fixed along with the radius of the rim hence it should not be longer than radius of the tire. Keeping in mind the radius of the wheels range from 15.24 to 27.94 cm of R12-R22 wheels. In order to benefit from the maximum vibrations the length of the beam should be as long as possible. Hence the length of beam is set for 120mm. Width of the beam is set to 20mm keeping the depth constraint of rim in mind. Table shows the dimensions of the harvester

Table I: Dimensions of Cantilver type PEH

Parameter	**Symbol**	**Value**
Length of substrate beam	l	120 mm
Radius of piezoelectric disk	r_p	20 mm
Thickness of piezoelectric	h_p	0.47 mm
Width of substrate beam	b	20 mm
Thickness of substrate beam	h	0.5mm

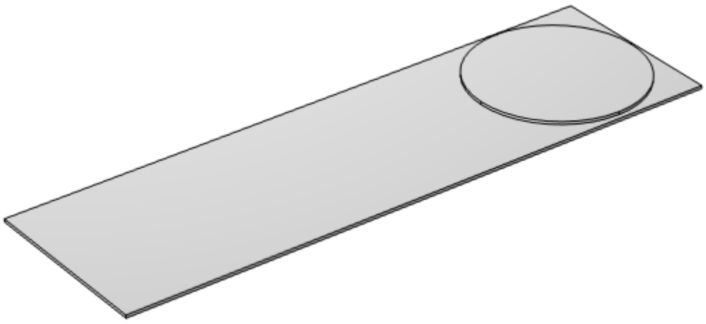


Figure 33: CAD Design of Cantilever type PEH

3.2.2. Modeling of PEH mounted on the inner surface:

Piezoelectric energy harvester is designed so that it can be mounted on the inner surface of the tire. Designed harvester converts mechanical energy into electric power from the rotating motion of tire. Low power sensors that are incorporated in tire can be operated by the generated power hence providing self sufficient system and the surplus power can be used to charge the battery. Proposed design is illustrated in fig. A thin metal host of aluminum is designed with masses on four corners and a piezoelectric film is placed on the center beam as shown in Figure 34 . Table shows the thickness of each part.

Table II: Thickness of each component

Part	Thickness (mm)
Piezoelectric Film	0.4
Host	0.5
Mass	1.5

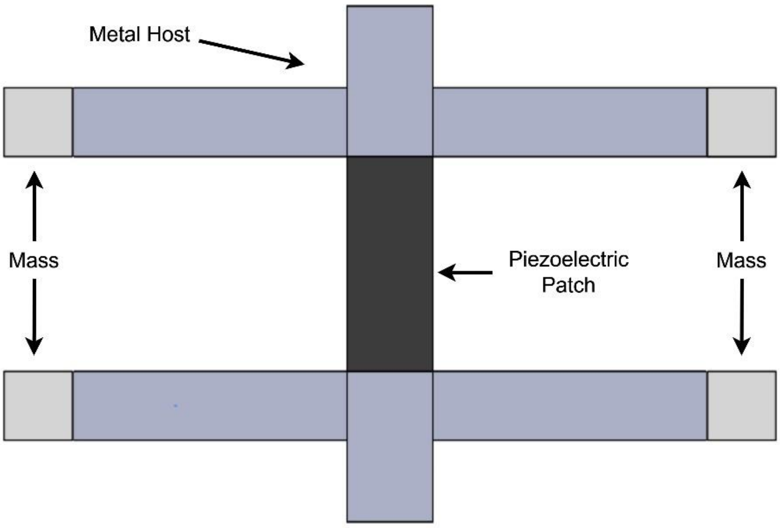


Figure 34: CAD design of Proposed Energy Harvester

Thickness of each component is provided in Table II .Dimensions of Proposed Energy Harvester are provided in Table III. Isometric view of proposed model is depicted in Figure 35

Table III: Dimensions of Proposed Model

Parameter	**Value**
Length of Piezoelectric	20 mm
Length of metal host	40 mm
Length of side beams	20 mm
Length of Mass	5mm
Width of piezoelectric	10 mm
Width of side beams	5mm
Width of Mass	5mm
Thickness of Piezoelectric	0.4mm
Thickness of metal host	0.5mm
Thickness of mass	1.5mm

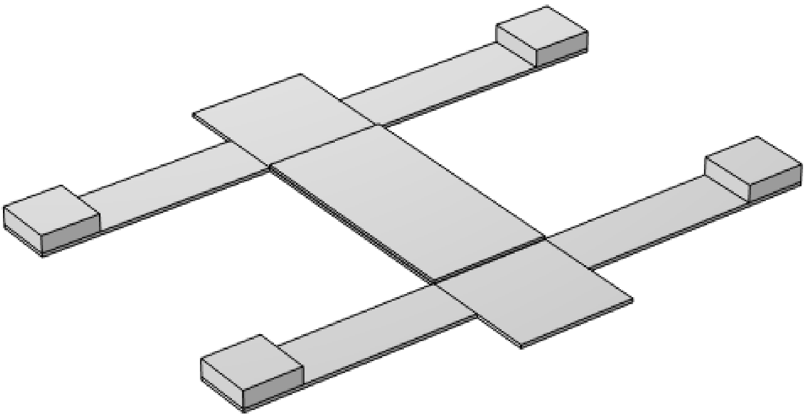


Figure 35: Isometric View of Proposed design

3.2.3. Placement:

Placing piezoelectric elements into the tire structure strategically is necessary to maximize energy conversion efficiency. Every viable placement has certain benefits and disadvantages that affect energy output and the overall viability of the system. Because of their flexibility and vibration sensitivity, wheel spokes are a popular option. They can be mounted either along the spoke's length or across its breadth to take advantage of the twisting and bending motions that occur while the vehicle moves. During tire rotation, the tire sidewall also experiences significant deformation, which makes it a potential source of energy. Piezoelectric patches can be mounted to the surface or embedded in the sidewall material to take advantage of the cycles of expansion and compression. The optimum substance to absorb vibrations caused by the road is tread blocks, as they are in continual touch with the surface. Utilizing the deformations from road contact, piezoelectric devices may be included into the tread blocks during tire manufacture. Despite the rim's milder vibrations, it may still be utilized for energy harvesting by mounting piezoelectric components to either its inner or outer surface. This will allow rotational and radial vibrations to be converted into useful energy. The tire's inner surface is subjected to significant strain due to inflation and compression during rotation, potentially leading to higher energy output than in any other placement option, making it most optimal option. Hence PEH is proposed to be placed on inner surface of the tire as shown in the Figure 36.

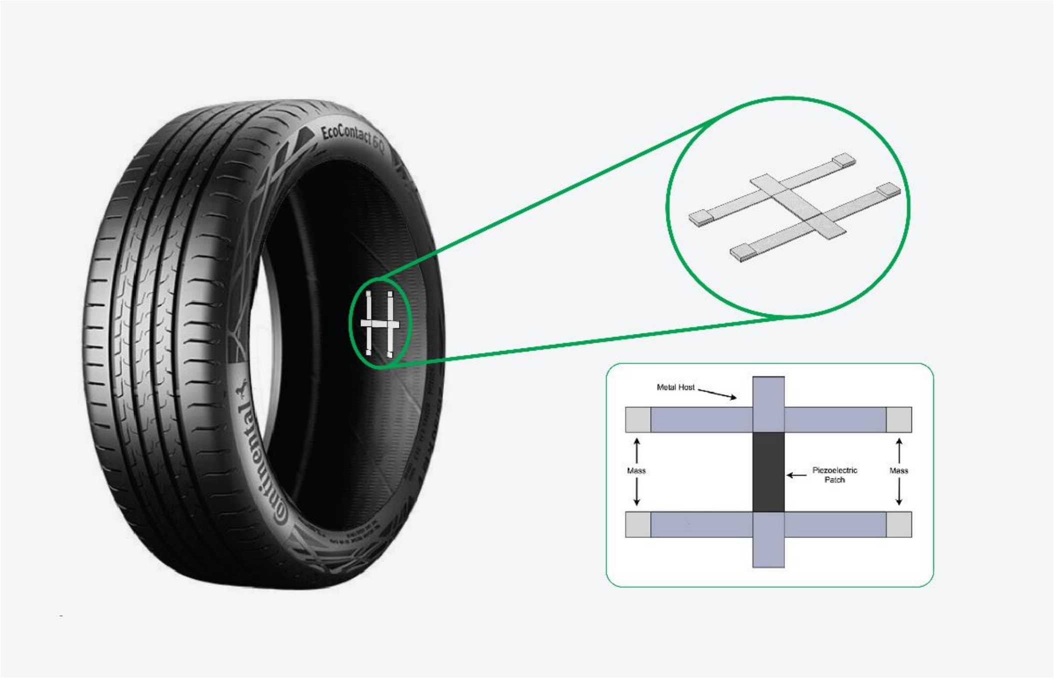


Figure 36: Placement of the PEH on inner surface of the tire

The second design that is designed to be placed on the wheel spoke. Several factors are considered for the optimal placement of the harvester. The harvester is aligned to the axis of the rotation of the wheel such that the piezoelectric disk is closer to the rim as centrifugal force is maximum closer to the rim. The orientation of the beam also play a significant role, it's orientation should be such that it bends/deflect when the tire rotates in response to the centrifugal force. It should be aligned perpendicular to the wheel spoke so that centrifugal force will cause it to bend outward. Fig shows the placement of the harvester on wheel spoke.

Chapter 4: Results & Discussion

Finite Element Method (FEM) is implemented on COMSOL Multiphysics. The proposed design is subjected to FEM simulation in COMSOL Multiphysics 3D plane. to analyze the strength and comprehensive simulation. The proposed design is subjected to the. Piezoelectric solid study is carried out on COMSOL Multiphysics in 3D Plane to simulate the behavior of piezoelectric material inside complex vibrational environment the tire. Rectangular Mesh is generated as shown in the figure

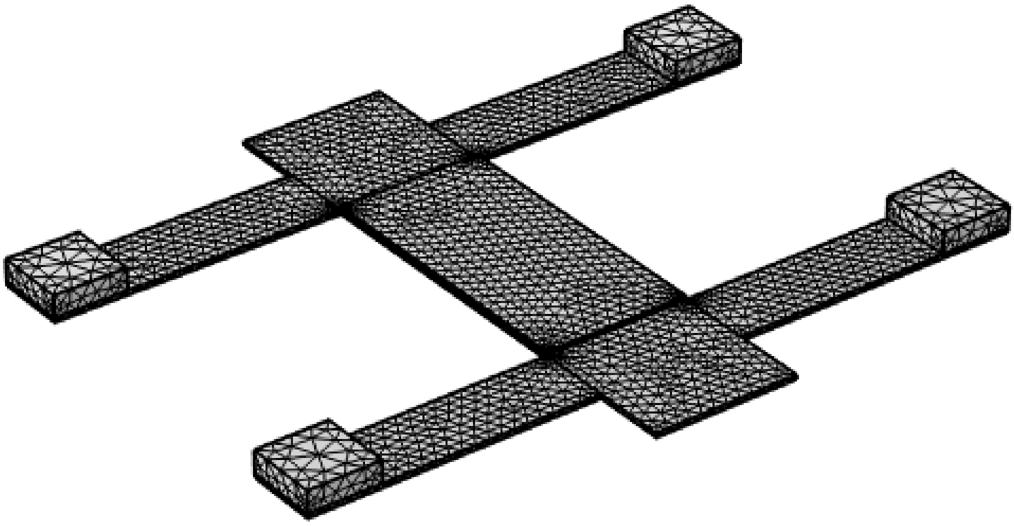


Figure 37: Mesh generation

Eigen frequency analysis is carried out as it is the key factor while designing piezoelectric energy harvester. To maximize the output of PEH, it’s eigen frequency should be aligned with the dominant frequency. Mode shapes are plotted on the respective eigen frequencies that illustrates the areas which are subjected to vibrations and deformation and plays a significant role in deciding the placement of piezoelectric for optimal performance.

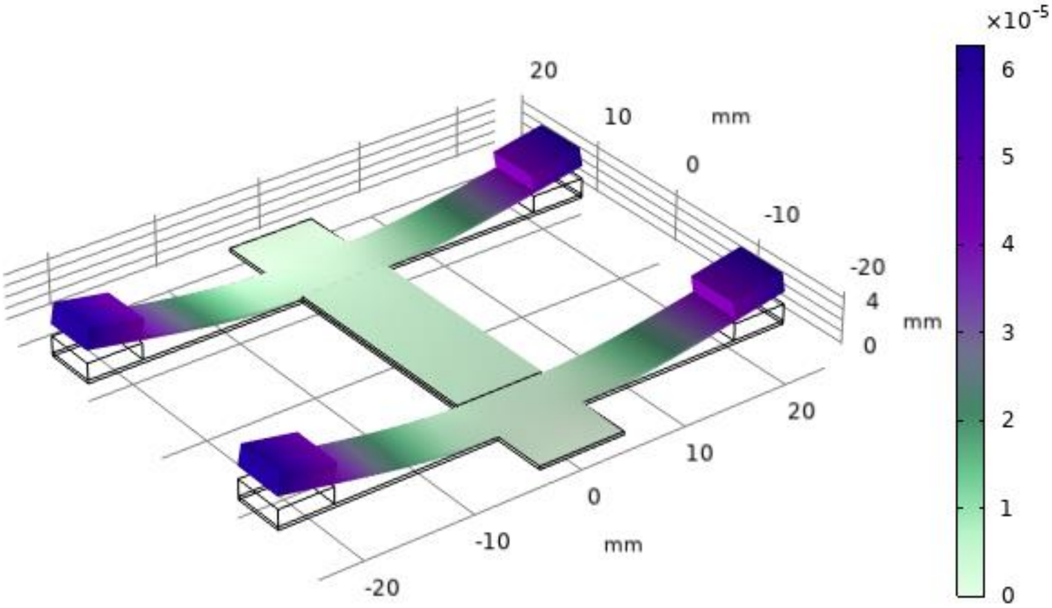


Figure 38: Mode Shape at the first eigen frequency at 16 Hz

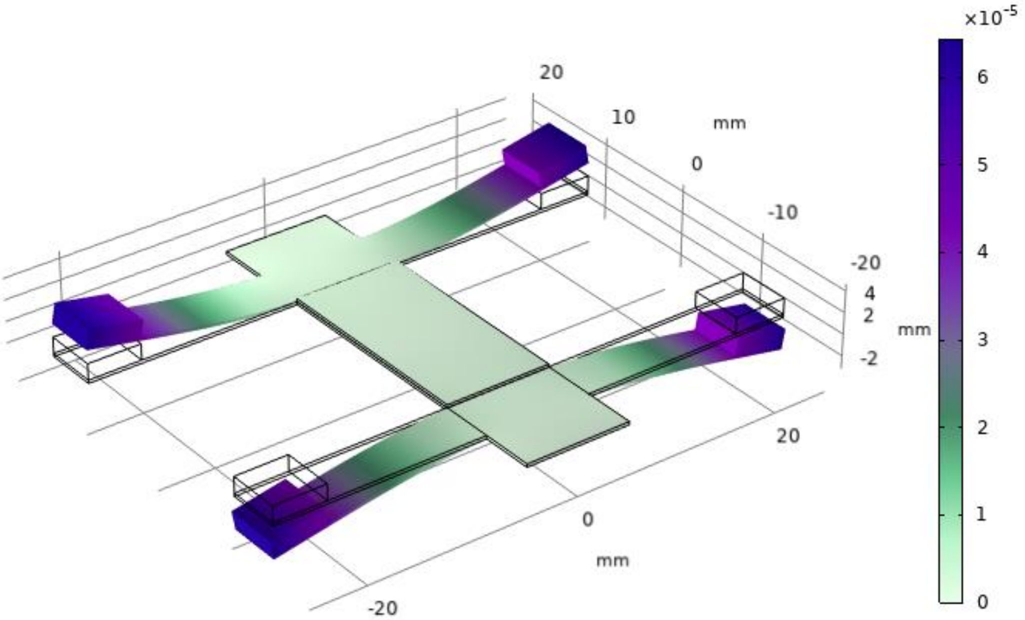


Figure 39: Mode Shape at the first eigen frequency at 22.81 Hz

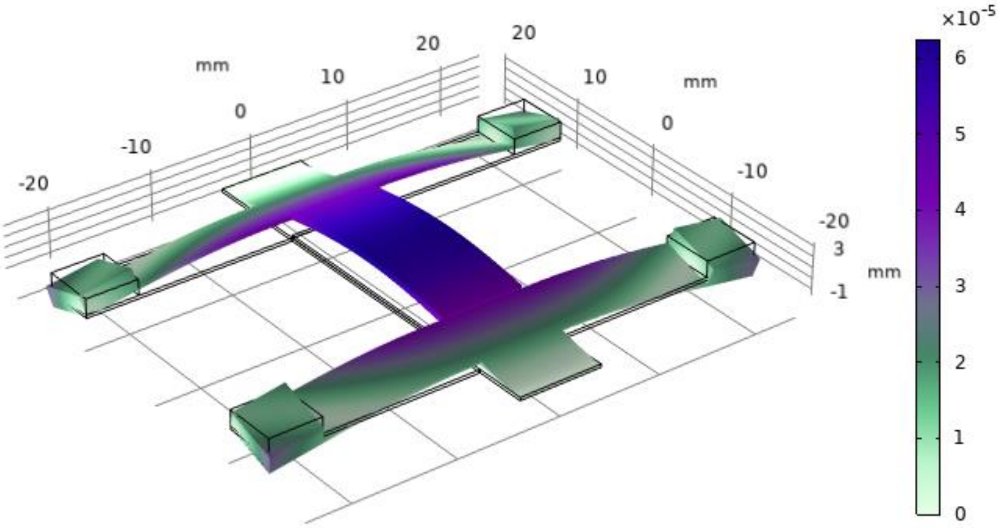


Figure 40: Mode Shape at the first eigen frequency at 39.7 Hz

Every time the tire patch makes contact with the ground, the PEH inside the tire is subjected to force. The PEH is subjected to force from this contact as the tire bends. The PEH experiences this bending with each rotation of the tire. Suppose the car is moving with a speed of 40km/h the number of tire revolutions that occur at a speed of 40 km/h must be calculated in order to determine the frequency at which the force should be delivered to the PEH. In order to calculate the distance covered by 215/55R16 tire with rim of 7Jx16 ET45 in one rotation, circumference of tire needs to be calculated. The circumference is given by Eq (6).

$$Circumference\ of\ tire = 2\pi r \tag{6}$$

Where r= Overall Radius of tire, Let's first calculate the overall radius of tire.

Tire width = 215, Aspect Ratio = 55%, Rim Diameter=Rrim =16 inch = 406.4mm. Side wall height is given by Eq (7)

$$Side\ wall\ height = H_{Sw} = \ Tire\ width\ \times Aspect\ Ratio \tag{7}$$

$$H_{Sw} = \ 215\ \times 0.55 \approx 118\ mm$$

As illustrated in fig overall radius of tire is

$$Overall\ Radius\ of\ Tire = r = R_{rim} + H_{Sw}$$

$$r = 203.2\ mm + 118.25mm = 321.45\ mm = 0.321m$$

Substituting r in eq we get the circumference is 2020mm. So the tire covers the distance of 2020mm in one revolution. Number of rotation that a tire make in one second if a car is is given by

$$No\ of\ rotaions\ per\ second = \frac{Distsance\ traveled\ per\ second}{Circumference\ of\ tire} \tag{8}$$

Figure shows the relationship between speed and frequency.

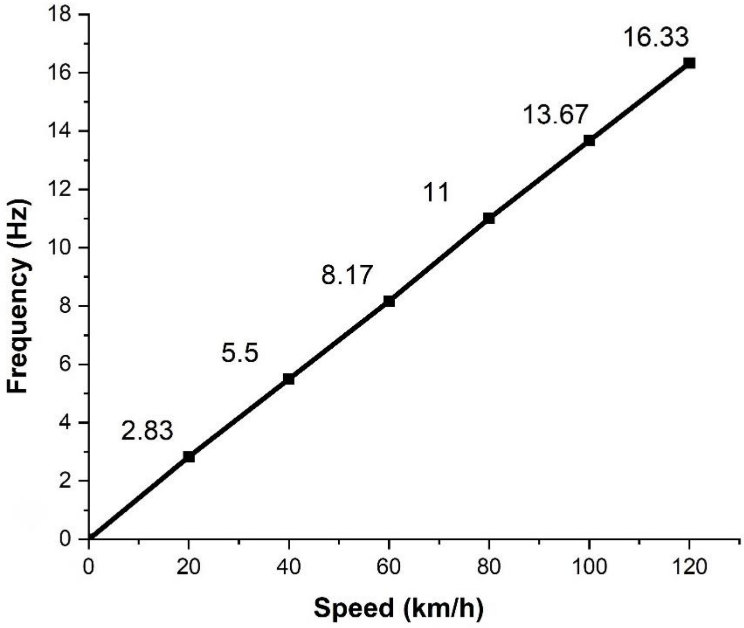


Figure 41: Frequency vs Speed relation

Hence the force should be applied at a frequency of 11Hz while simulating speed of 80km/h. Car weight is assumed to be 1500kg, as load is equally distributed on all four tires, so there is 375Kg of weight on each tire.

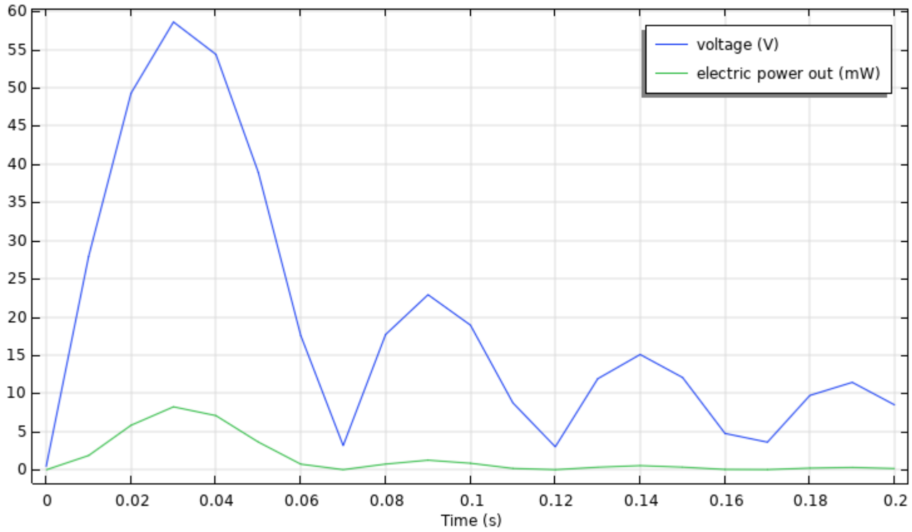


Figure 42: Voltage and electric power output for one complete rotation of tire at a speed of 40Km/h

Figure 42 shows the voltage and electric power output of the proposed PEH at a speed of 40Km/h. It can be seen that the voltage and electric power output is maximum at when the patch of tire.   where PEH is mounted is in contact with the ground and gradually decreases as the tire rotates. Peak voltage of 60V is achieved for 40 km/h of speed with peak electric power out of around 8mW Figure 43 demonstrate the output voltage and electric power output of the proposed PEH at different speeds of car ranging from 0 km/h to 130 km/h. Voltage and electric power output gradually increases as the speed increases. Peak electric power output of 14.6mW is generated at the speed of 90 km/h. Max power consumption of TPMS is when it is in active mode and is sending pressure data to the receiver in the car at 434 MHz is around 5dBm [66] which is equivalent to 3.16mW. As the proposed design is generating more power than to operate TPMS, remaining power can be stored in battery and can be used to run additional sensors Including accelerometer load and temperature sensor.

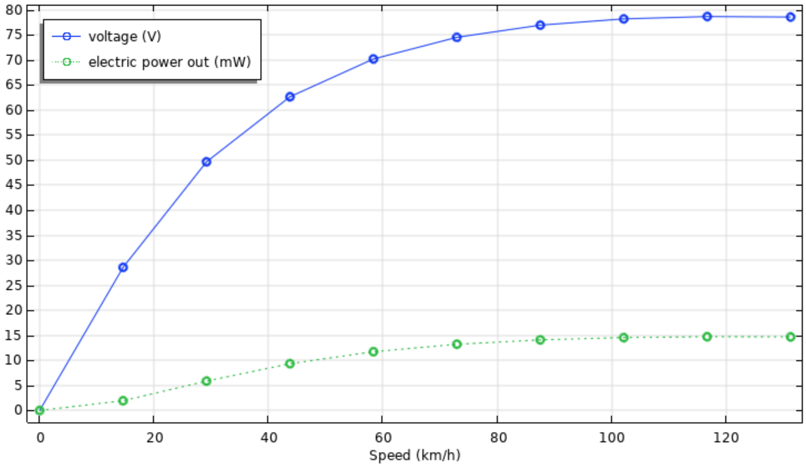


Figure 43: Voltage & Electric power output of proposed PEH at different speeds of car

Impedance analysis of piezoelectric disk is done using LCR Meter MCR-6200A as shown in the figure below. LCR meter and data is recorded using LABVIEW.

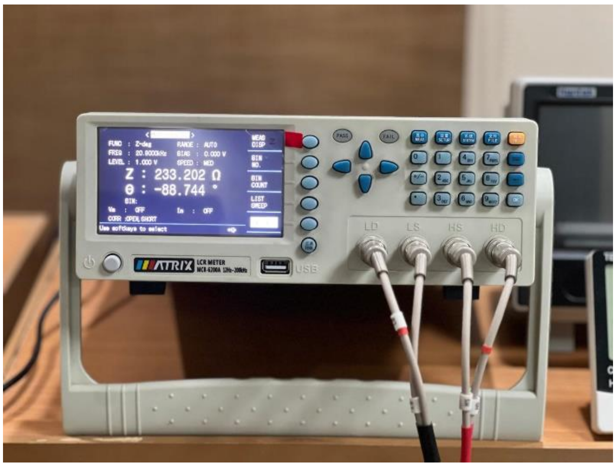

FUNC : Z-deg
RANGE : AUTO
FREQ : 20.0000kHz
BIAS : 0.000 V
LEVEL : 1.000 V
SPEED : MED
Z : 233.202 Ω
θ : -88.744 °
BIN:
Vm : OFF
Im : OFF
CORR :OPEN, SHORT
Use softkeys to select

Figure 44: LCR Meter

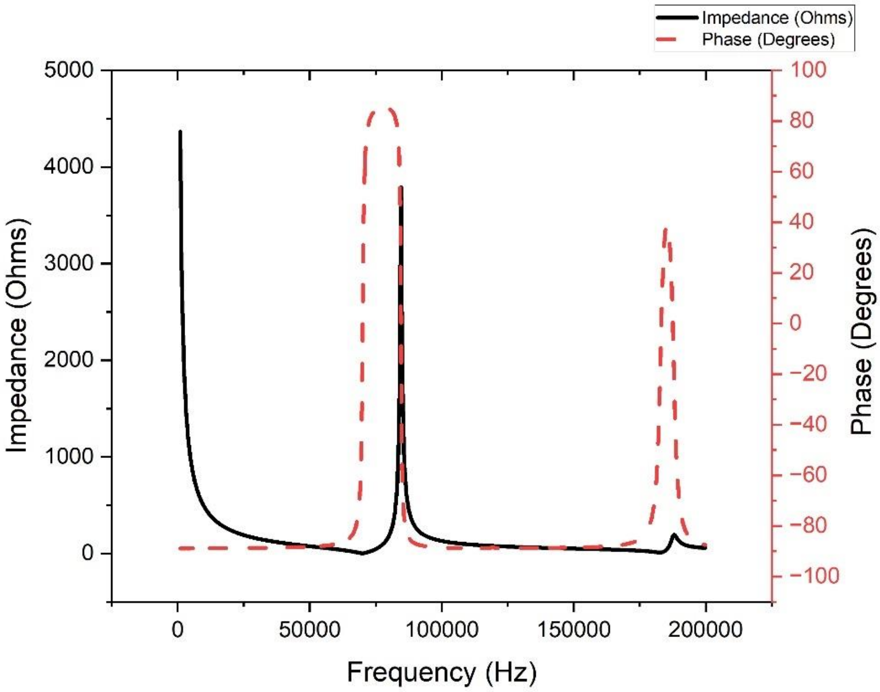
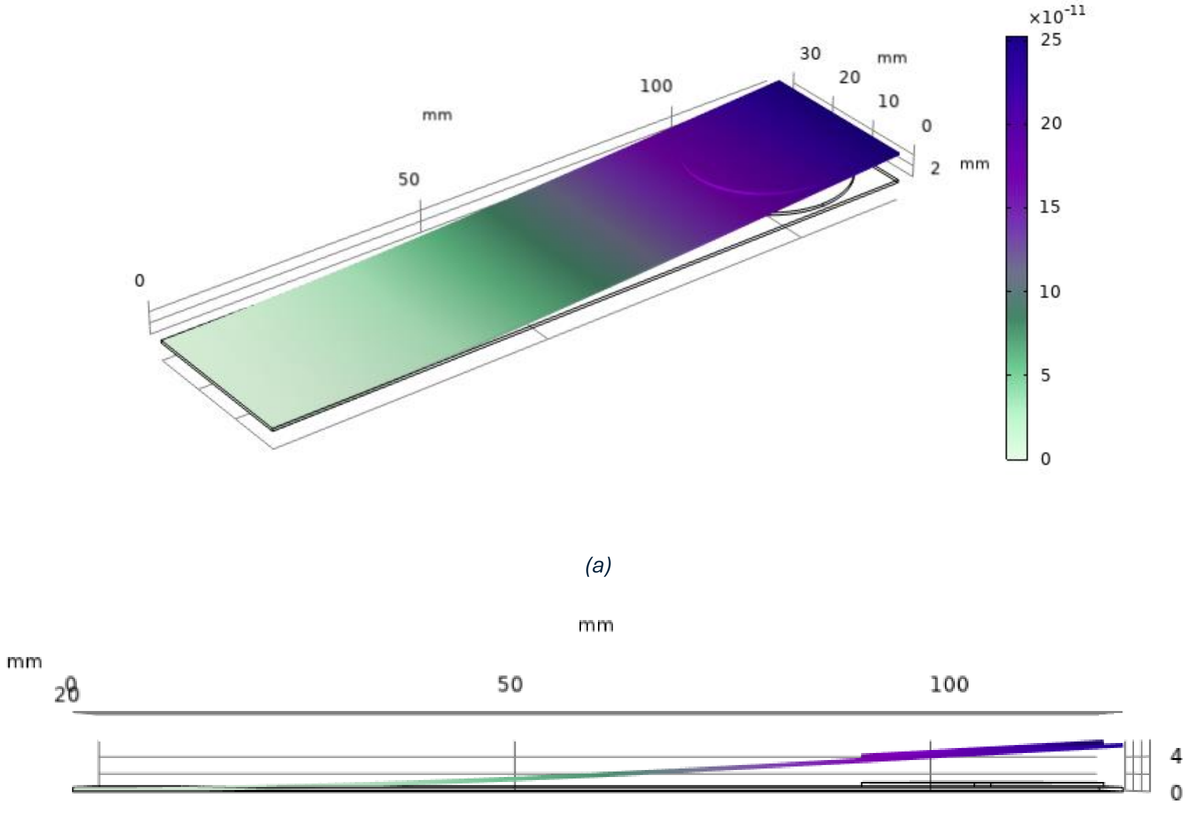


Figure 45: Impedance and frequency relation of PZT disk

Figure 1 indicates the impedance and phase characteristic plot of PZT-5H material that had been carried out using LCR meter, across a wide range of frequency. The black solid line on the graph shows the impedance in ohm while the red dotted line shows the phase shift in degrees between the voltage and current. With reference to the real part of the model impedance at low frequencies, the impedance is high but as the frequency increases, it sharply decreases then sharply rises to form a fairly pronounced peak at about 100 kHz. This is associated with the resonant frequency at which transformation of mechanical energy to electrical energy is at its best and the impedance is high. Following this, the impedance reduces and another peak arises at about 190 kHz and these are classified as the anti-resonant frequency at which the material exhibited high impedance but with a different phase characteristic. The phase response is depicted by red dashed line which is started at -88 degree at lower frequency and experiences considerable amount of phase shift at the resonant frequency and ends at approximately +89 degree phase angle. The phase shift behavior is associated with the fact that the material behaves as capacitor and inductor in turn, especially at the frequencies close to the resonance frequencies. This detailed impedance and phase information is pretty much pertinent for or PEH, sensors, or actuators that utilize PZT-5H and focuses on the superior frequencies that should be applied for increased efficiency.

Simulation of second PEH is also done on COMSOL. FEA analysis is done in COMSOL Multiphysics using Piezoelectric Study. One end of cantilever beam is given a fixed constraint and a rotating frame is applied to mimic the tire rotation. First mode shape and displacement at eigen frequency of 10.34 is given below in the Figure 46.

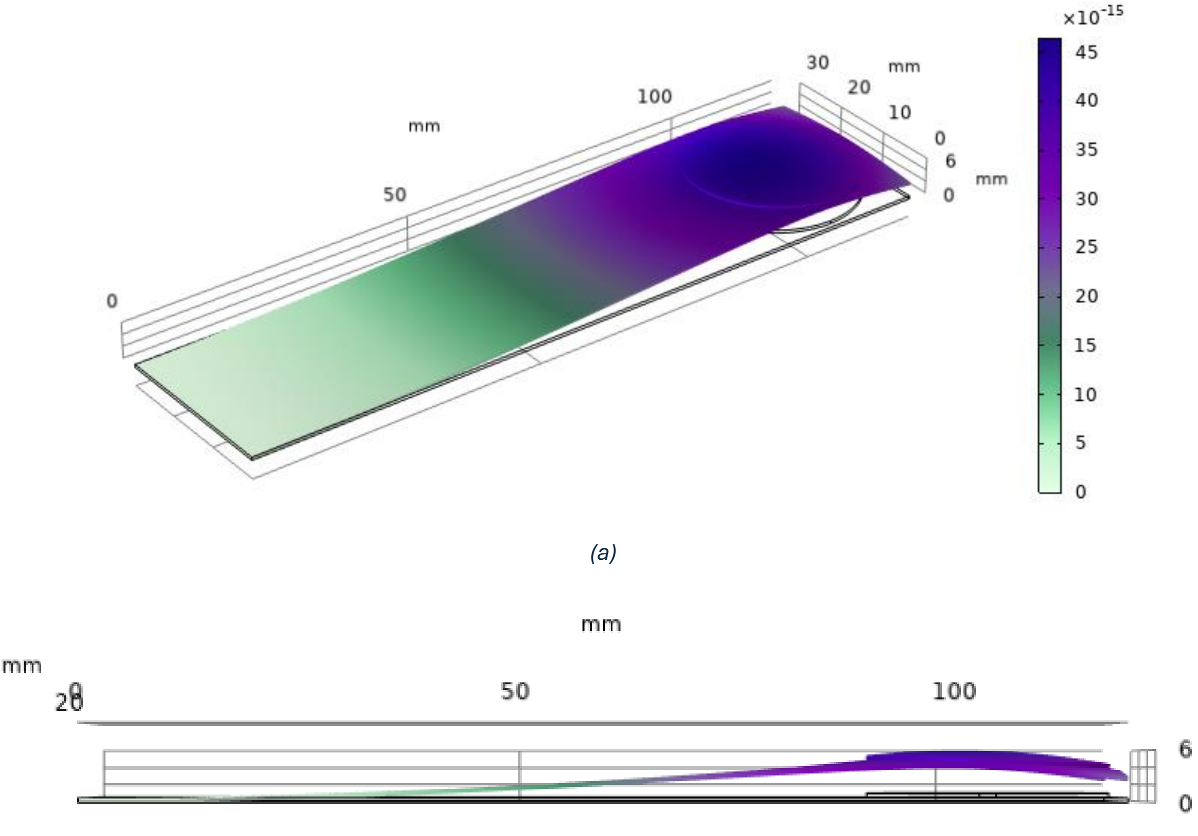


(a)

(b)

Figure 46: (a) Mode shape (b) Total displacement at first Eigen Frequency at 10.34 Hz

From the graphs presented above in Figure 46 a & b, this mode shape indicates the first or fundamental bending mode of cantilever. In this mode, the whole cantilever bending in simple arc like motion but the maximum deflection is observed in the free end in which piezoelectric disk is fixed. This mode is particularly important for energy harvesting because it usually produces the largest stress across the piezoelectric material and, thus, the highest energy conversion. The displacement gradient also varies smoothly in the direction of the free end and remain maximum at the section where the bending stress associated with the electric output of the piezoelectric material is also highest.

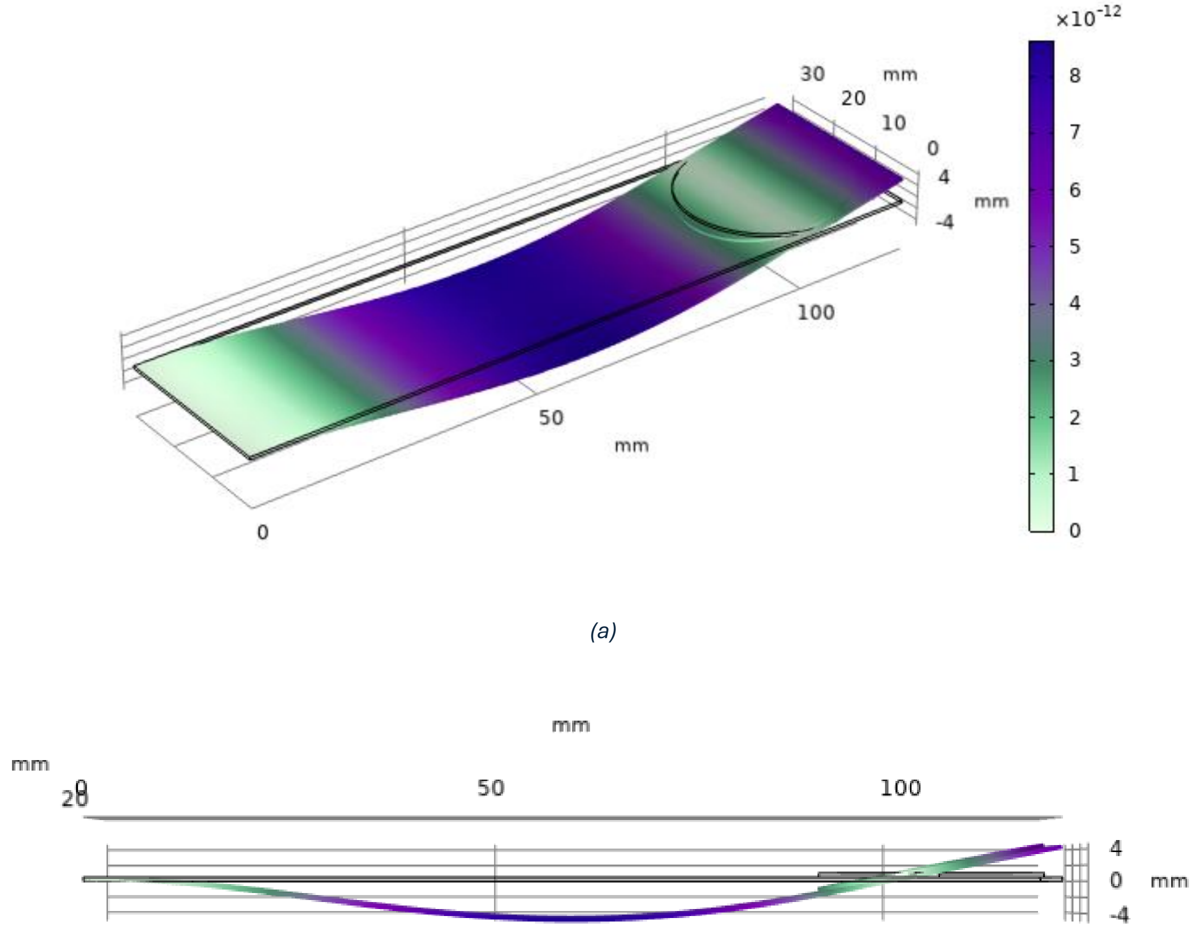


(a)

(b)

Figure 47: (a) Mode shape (b) Total displacement at Eigen Frequency of 22.91 Hz

The second mode shape indicates one of the first overtone of the bending mode. Special points here include the node, which is around the midpoint of the beam, and large displacements on the left side of the beam with moderate displacements at the right side, specifically, at the free end of the cantilever. This mode can also be used for energy harvesting even though, it may not as effective as the first mode of operation because of the effect of the node in reducing the length of the beam that contributes to energy production. But it can still work at other frequencies, especially if the harvester that is used is tuned to work at higher frequencies.



(a)

(b)

Figure 48: (a) Mode shape (b) Total displacement at Eigen Frequency of 163.93 Hz

This is the higher frequency mode shape educed for the cantilever beam and it show a two nodal points along its length Thus the beam is divided in three segments that vibrate out of phase. Displacement is maximum in the case of free end and it is minimum in the case of fixed end. This mode has higher frequency and energy output which increase with the rate of oscillation but the use of multiple nodes mean that less of the material volume contributes to energy transfer. This mode may not be optimal for energy harvesting except if the circuit was designed with specificity to operate at high frequencies.

For the piezoelectric energy harvester which is mounted on the car wheel spoke, frequency range that is generated due to the tire is 0- 15Hz. This range is near to the natural frequency of the first mode shape of the harvester which is about 10.23 Hz. It is most advantageous to operate the harvester near this natural frequency since it matches with the maximum on the resonance curve, which depicts the amplitude of the oscillations. To ensure that the mechanical strain experienced by the piezoelectric material is maximized the amplitude should also be maximized to achieve an optimum conversion of energy. Any design of the harvester, therefore, must ensure that the design natural frequency of the device coincides with the usual mode of vibrations of the car wheel in order to enable the devise to harvest most of the mechanical energy during any driving situation. This capability is necessary for the high efficiency of energy harvesting because the vibrations frequencies generated by the wheel depend on the speed of a vehicle. When incorporating the cantilever design into the harvester, it is possible to obtain maximum capacity for receiving the rotational kinetic energy produced by the wheel movement and convert it into electrical energy. This approach ensures that the actual vibrational energy harvester, namely, piezoelectric energy harvester, is not only proficient at the exact resonance frequency but also acceptable and capable of conforming to the dynamic frequency range as usually observed in automotive wheel applications while optimizing its usability and efficacy in field conditions.

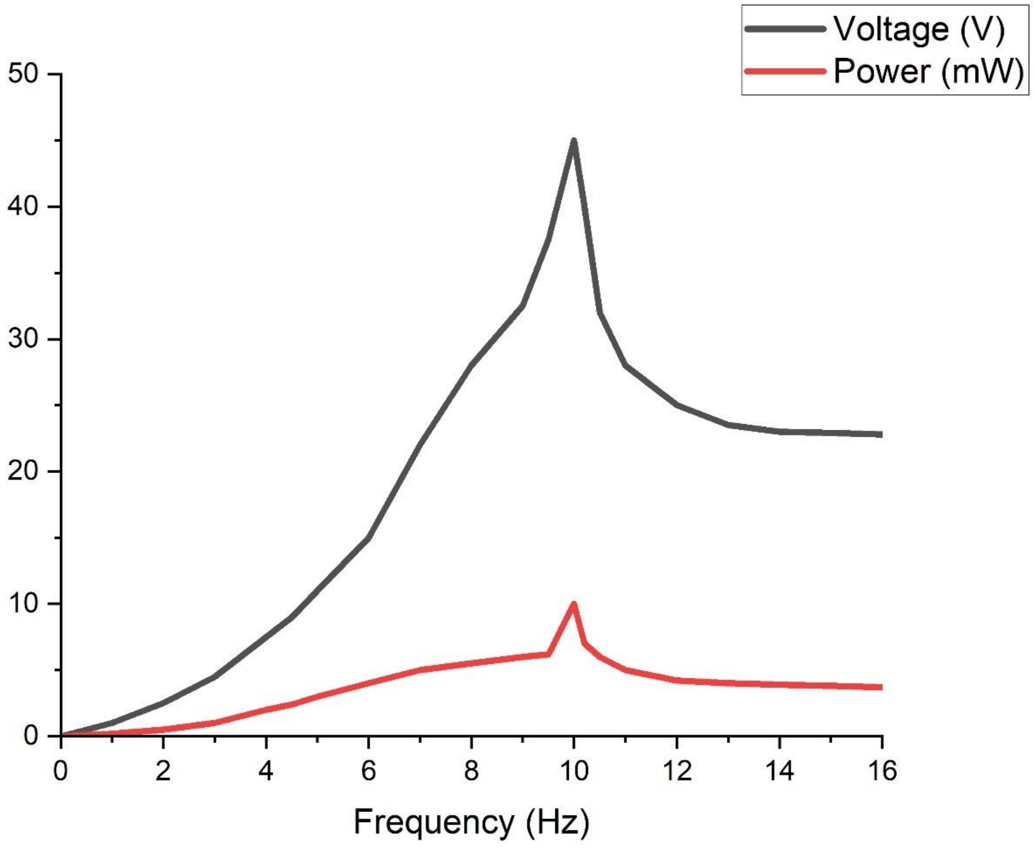


Figure 49: Voltage and power output of Cantilever PEH

With frequency increasing from 0 Hz, the output voltage and power both increase, which show that the piezoelectric harvester is capable of converting mechanical vibrations to electrical energy as the frequency is closer to its resonant value. The magnitude of voltage increases to about 45 V at the frequency around 10 Hz while the magnitude of power gets the maximum value of about 9 mW at the same frequency. The peak performance at 10 Hz shows that this is the optimum frequency of the energy harvester which has the maximum ac conversion efficiency of mechanical energy to electrical output. After that peaks the voltage and power outputs reduce as the frequency increases beyond 10 Hz. Across the frequency of about 15 Hz, the voltage output reduces to about 23V while the power output diminishes to 4mW, meaning that there is low efficiency. Such decrease in the performance after the resonant frequency is observed in the piezoelectric energy harvesters as the devices are designed to work at their optimal frequency band where mechanical resonance boosts the energy conversion efficiency.

A comprehensive lab prototype has been developed to simulate and evaluate the performance of a piezoelectric energy harvester designed for smart tire applications. The prototype is constructed using a 16-inch acrylic disk to represent the tire, which is mounted onto a motor that rotates the disk at varying speeds. The motorized setup effectively simulates the rotational motion of a tire in real driving conditions. A key component of the energy harvesting system is a cantilever beam, onto which a piezoelectric disk is attached at one end. This cantilever structure is mounted on the rim of the acrylic disk, positioned perpendicular to the spoke of the rim. As the motor rotates the disk, gravitational acceleration and centrifugal force caused by the tire's rotation, the cantilever beam bends under the forces exerted by rotation and vibration. The bending of the cantilever beam causes the piezoelectric disk to undergo mechanical stress, which generates an electrical charge due to the piezoelectric effect. This electrical energy is in the form of alternating current (AC), which is then rectified using a rectifier circuit to convert it into direct current (DC). The rectified voltage is subsequently fed into a voltage sensor, which continuously monitors and measures the generated voltage in real-time. To capture accurate readings, the voltage sensor is interfaced with the Arduino nano microcontroller, which has a 12-bit analog to digital converter (ADC). The sensor reading is processed through the formula given in equation (9) to determine the sensor voltage.

$$V_{sensor} = \left(\frac{ADC_{value}}{4095.0}\right) \times 5 \tag{9}$$

Here, ADC_{value} is a value from the ADC while 4095 is maximum value that 12-bit ADC can read. And the ‘5V’ is the reference voltage as the operating voltage of the Arduino Nano is 5V.

As the sensor measures the greater voltage the actual input voltage $V_{measured}$ is determined by scaling the sensor voltage using the equation (10)

$$V_{measured} = \left(\frac{V_{sensor}}{5}\right) \times 25 \tag{10}$$

This formula takes into consideration where the sensor can measure up to 25V and thus accurately measure the energy harvested by the piezoelectric.

Similarly to voltage controlling, the prototype acquires rotational speed data of the acrylic disk using an MPU-6050 sensor. The same as the MPU 9150, MPU-6050 is a combination of accelerometer and gyroscope where we put it on the rotating disk to measure angular velocity. The data obtained from the MPU-6050 gyroscope facilitates the determination of disk's rotation velocity in RPM hence giving an important assessment on the working velocity of the simulated tire. The MPU-6050 measures angular velocity in radians per second and using equation(11) , the value has been converted in RPM.

$$RPM = \left(\frac{AngularVelocity(rad/s)}{2\pi}\right) \times 60 \tag{11}$$

With the angular velocity thus converted to RPM, the speed of the rotating disk in this system can be measured and subsequently compared with the voltage output by the piezoelectric energy harvester. Since the efficiency of a harvester depends on its ability to deliver the highest energy output in the shortest time possible, this rate between speed and energy output is extremely vital for the determination of how effectively the harvester will be operating depending on the prevailing conditions. The voltage data obtained from the piezoelectric is measured and stored on an SD card module along with the speed data from the MPU-6050. The module for the SD card is integrated with the ESP32 microcontroller, making sure that all information is recorded in real-time that can be used later on for experiment analysis. This data logging ability enables a detailed analysis of the energy harvesting system efficiency as it is tested in varying speeds and mechanical loads.

The piezoelectric disk rotates on acrylic platforms, piezoelectric energy harvester, voltage sensor, MPU-6050, and the SD card module make the system mimic the realistic conditions that are experienced by a vehicle tire. This prototype is also essential for determining the applicability of piezoelectric energy harvesters in practical tire applications. From the analysis of the recorded data the efficiency of the energy output for the power of the system can be estimated and the feasibility of powering other onboard equipment like TPMS can be determined. Block diagram of the process is given in Figure 50.

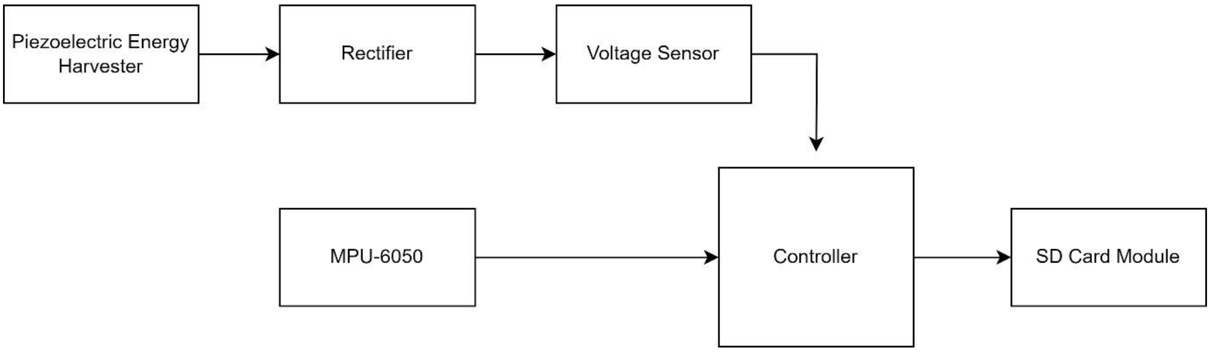


Figure 50: Block diagram

The setup proves that rotational energy from the tire rotations can be harvested and converted to electric energy for the efficient powering of smart tire systems in the future. Experimental setup is shown in the figure below.

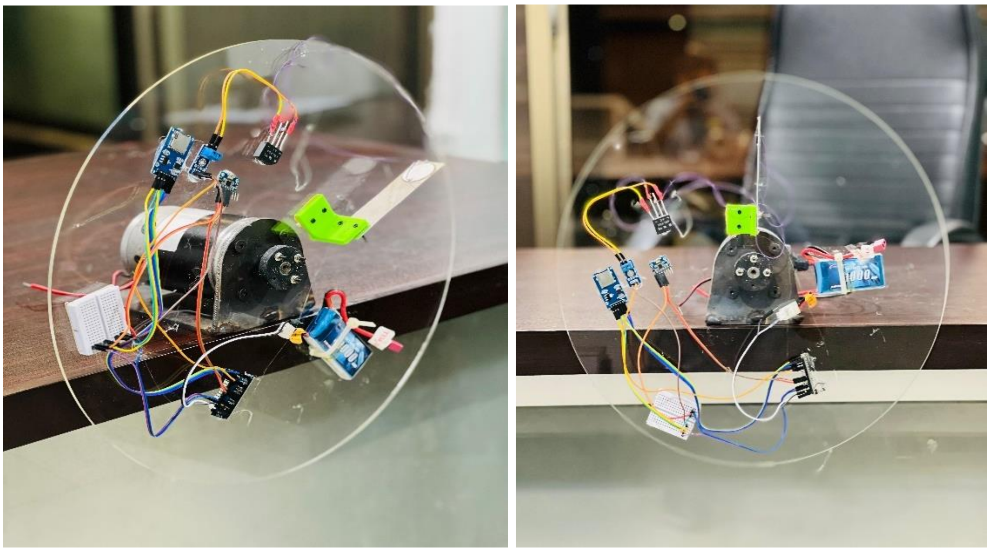


Figure 51: Experimental Setup

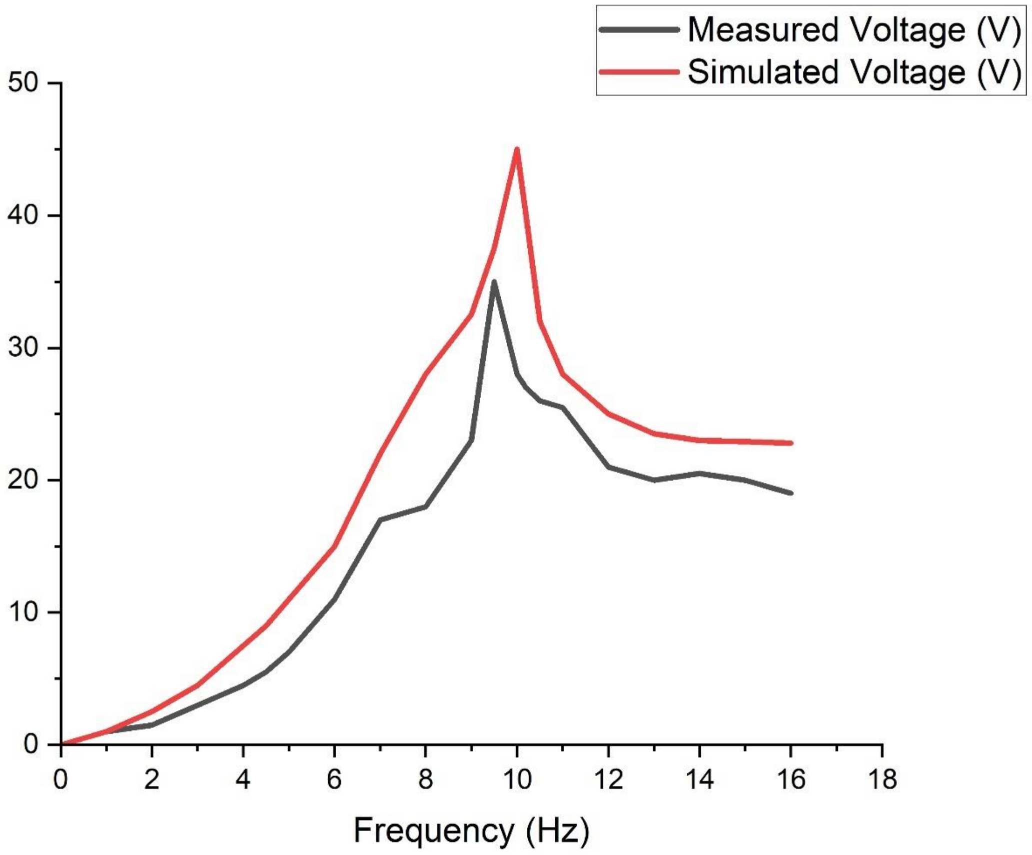


Figure 52: Measured and Simulated Voltage Output

In this graph, relationship between simulated and measured voltage frequency and frequency as parameters of the piezoelectric energy harvester is illustrated. Here the black line with square markers refers to the simulated voltage and the red line with circular marker refer to the measured voltage. As can be observed, both curves follow the same pattern with an increase of the voltage output as the frequency increases and with the attainment of the highest value at around 10 Hz. The simulated voltage varies and reaches its highest value which is about 45 V while the measured voltage is just about 35 V, thus implying that the performance that has been simulated is better than the one that had been realized experimentally possibly because of some losses or inefficiencies that have not been captured in the simulation due to system idealization. Beyond the 10 Hz, both the simulated and measured voltage outputs are coming down with similar trend in that respect. At 16 Hz also the simulated and measured voltages have reduced drastically. Based on this similarity, the author inferred that the overall trend of the simulation coincides with the experimental data although, the actual voltages are slightly different. The graph can also be explained by the voltage of the piezoelectric energy harvester where harvesting is highest at a resonant frequency of close to 10Hz for both the simulated and the measured voltage. It also shows the usual drop in voltage output as the frequency deviates from the resonant zone as covered in the explanation before. The discrepancies between simulated and measured results can be explained by some factors which are beyond the scope of the simulation; some defects in the materials, damping and environment effects.

Chapter 5: Conclusion

In this study, a piezoelectric energy harvester (PEH) specifically designed for smart tires is studied in terms of both design and performance analysis. This paper focuses on analyzing two different design concepts of PEH serving to charge TPMS systems in vehicles. The first design, anchored on the inner wall of the tire and using PZT-5H as the piezoelectric material with aluminum as substrate, is successful in converting the energy from tire pressure and road interaction. This design not only fulfills the power requirement of TPMS but also provides the storage capability for the excess energy, the power output rises with the rise in vehicle speed and maxes out at 90 km/h. The second design involved a cantilever beam with a PZT-5H disk located at 90 degrees with the rim spoke. However, this design is functional and produces power; yet its efficiency is somehow inferior to the tire-mounted PEH because of lower energy outputs from centripetal forces acting in every revolution of the tire. The comparative analysis obviously indicates that the tire mounted PEH design has better performance and efficiency due to higher deformations within the structure of the tire. This study also validates that the inner tire mounted PEHs can effectively operate TPMS while cutting down the environmental effects from the battery-operated system. Continued studies should therefore be directed towards experimental testing of these designs in order to understand how they perform in normal conditions. Therefore, the given PEH systems introduce a possible significant improvement in organizing sustainable energy solutions for the automotive business, which can replace batteries and reduce negative consequences on the environment.

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