Design and Simulation of Model for Energy Harvesting from Vehicle Tires Using Piezoelectric Modules

Madan Mohan Behera[1], Asish Mishra[2] , Pininti Purushottam[3], Sarthak Rout[4]

[1]Department of Mechanical Engineering, Veer Surendra Sai University of Technology, Odisha, India

[2]Department of Electrical and Electronics Engineering, Veer Surendra Sai University of Technology, Odisha, India

[3] Department of Mechanical Engineering, Veer Surendra Sai University of Technology, Odisha, India

[4] Department of Mechanical Engineering, Veer Surendra Sai University of Technology, Odisha, India

Email address:

madan.sipun@gmail.com (M. M. Behera), asishcooldood@gmail.com (A. Mishra), purus12@gmail.com (P.Purushottam) ,
sarthakrout1994@gmail.com (S.Rout)

Abstract: Piezoelectric materials hold the unique feature of development of electric potential upon application of mechanical stress and vice versa technically known as direct and indirect effect respectively. Many developments in the field of vibration-based energy harvesting in past few decades has been done and the accelerated depletion rate of conventional sources of energy in the recent years has drawn attention of science community towards sustainable energy development and researchers towards development of new energy harvesting techniques to tap the energy lost to the environment. This paper proposes a new design to harvest energy from vehicle tires by the use of PZT modules in the tire carcass utilizing the stresses developed at the tube and tire interface. The design has been modelled in MATLAB Simscape and simulated using COMSOL Multiphysics 5.0. The output voltage can be used to charge batteries for energy storage for future use.

Index Terms— Piezoelectricity, PZT, Direct Stress, Energy Harvesting, Tires, Wheels

———————————— ◆ ————————————

1. Introduction

With the mushroom growth of global population, the energy needs has nearly quadrupled since mid-20th century. The depletion of the reserve of conventional sources of energy and the deadliest effects of the same on the environment has been the major concern among the scientists and researchers on the globe in the recent time. A large number of new techniques have been developed in the past decade to tap the wasted energy in various processes and use it to cater small electronic circuits or used in large-scale energy storage systems. Piezoelectric materials are one such material which possesses the potential to tap the vibrational energy (or mechanical stress instead) in the form of electrical energy and used directly or stored in various fuel cells for future use. The basic concept of piezoelectric material is that when a mechanical stress is applied to the material, an electric potential is generated at the output terminals which is known as the Direct effect (Fig. 1a) and the vice versa i.e. possession of an electric voltage at the ends of the materials leads to deformation in the material, is known as Converse effect or Indirect effect (Fig. 1b).

When the vehicle wheel is unloaded, the tube doesn't exert much of load on the inner carcass of the tire but, when loaded, due to the sprung mass of the vehicle, the tube exerts an appreciable amount of load on the inner carcass of tire. Also, this load varies in different running conditions mainly different vehicle velocities [1]. While entering a corner or simply load transfer conditions, the load at the aforesaid interface increase. Therefore, if piezoelectric modules are placed at this interface, a lot of energy can be tapped and stored in batteries. A lot of designs have been proposed for tapping the energy with the use of piezoelectric modules. Noaman Makki and Remon Pop-Iliev [1] used piezo ceramics, namely PVDF and PZT, both at the tread walls and sidewalls and investigated the comparative results in energy harvesting technology from the vehicle wheels. They found that PZT has better power output per unit area and more cost effective than their PVDF counterparts but offers lesser flexibility as compared to the latter. T.Madhuranath et. al [2] placed a thin layer of a piezoelectric material of thickness 50mm at the tire-tube interface and analyses the results in COMSOL Multiphysics. They concluded that reducing the radius of the tire and thickness of the piezo layer, better results can be obtained. Kunchala Anil and N.Sreekanth [3] modelled the design of piezo ceramic placement at the tire-rim interface in MATLAB/Simulink and concluded that

the output voltage is increases linearly with the input force, thickness and the capacitance of the piezoelectric device and decreases with the increase of the area of the piezoelectric disc i.e. diameter of the disc.

Figure 1. *Diagrammatic representation of (a) Direct effect (b) Converse effect [4].*

The piezoelectric modules are subjected to direct stress dominantly. The output voltage is made to pass through a rectifier to get a steady non-phase changing voltage at its output. This voltage is further fed to a capacitor bank or fuel-cell batteries for storage or can be used directly without any provision for storage (Fig. 2).

In the succeeding sections, the CAD design, the MATLAB/Simscape model and COMSOL Multiphysics simulations have been done to investigate the output voltage obtained in the applied conditions and possible utilization of the energy tapped has been discussed.

Figure 2. *Block diagram of working of the energy harvesting system.*

2. Methodology

2.1. Material

The material chosen for the piezoelectric module is PZT-5A. Both PZT-5A and PZT-5H share similar properties like high resistivity and high sensitivity [5]. Though, PZT-5H possesses better charge coefficients in the direct stress (d_{33}) condition (which is the working condition in the present model), it is practically unstable with the temperature [6]. However, PZT-5A has high time stability and comparatively high curie temperature than other available materials. Therefore, the material chosen for the model is PZT-5A.

2.2. Design

2.2.1. Piezoelectric Module

The structure or the contour of the piezoelectric module used in the energy harvesting system is a frustum (Fig 3). The variation of the output voltage with the change in the upper face diameter for a fixed base diameter of the module is shown in Fig. 4. The output voltage is obtained from the simulation in COMSOL Multiphysics software for a direct load of 500N (compressive) on the upper face with the base fixed for PZT-5A material (Fig. 5). From the figure, it can be inferred that with the increase in the upper diameter of the frustum-shaped module, the output voltage decreases and also with decrease in the base diameter, the output voltage increases. The simulation results were carried out for a module height of 30mm.
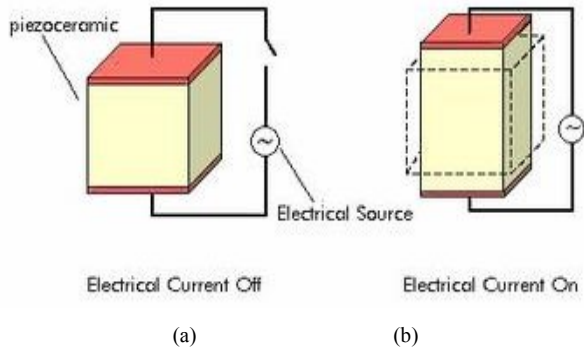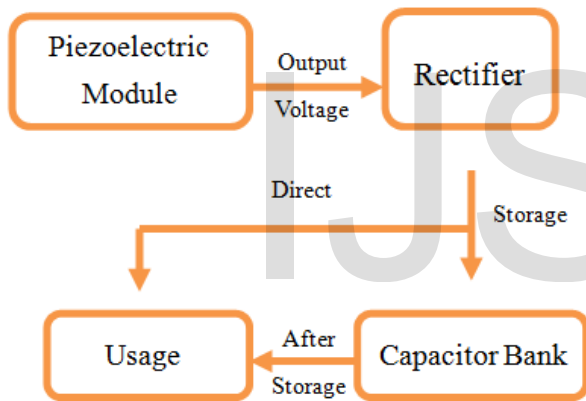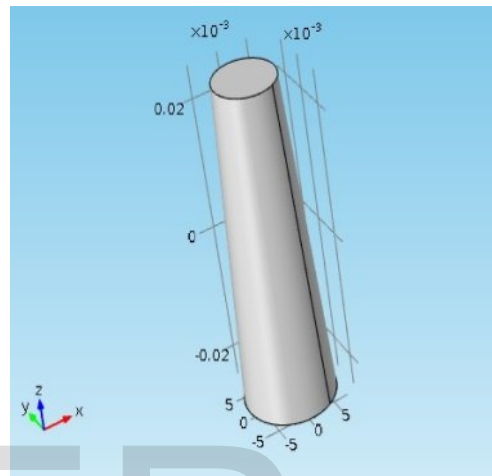

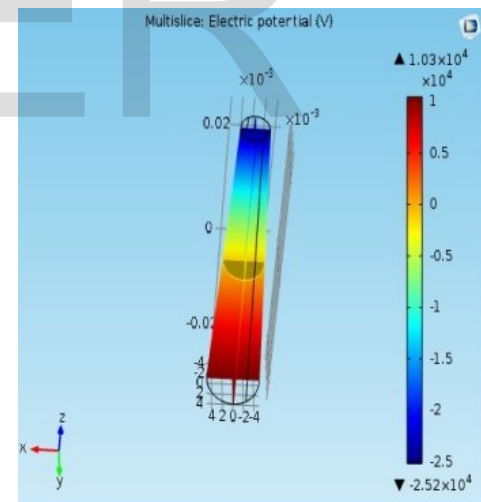**Figure 3**(a). *CAD model of the piezoelectric module under simulation.*

Figure 3(b). *Electrical potential distribution throughout the module.*

The mesh size used for the simulation is free-tetrahedral and physics-controlled mesh and 'stationary' study and

'piezoelectric devices' as physics module were chosen. From the graph plotted in figure 4, the piezoelectric module with base diameter 15mm and top face diameter 10 mm is chosen as the test module.
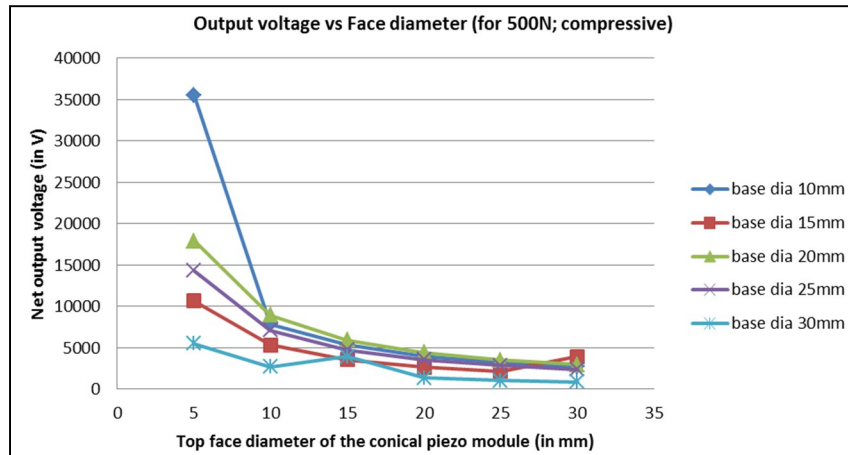

Figure 4. *Relationship between output voltages and face diameter of the piezoelectric module.*

2.2.2. Arrangement of Piezoelectric Module

The piezoelectric modules are arranged along the circumference of the tire (Fig. 5(a)). The dimension of the piezolectric module, as inferred from figure 4, has a base diameter of 15mm and a top face diameter of 10mm and a height of 30mm. The tire chosen for the purpose is designated as 165/80 R14. The modules are arranged in 5 circular columns with each column consisting of 30 PZT modules.

The modules are then covered by a layer of tire material of thickness equal to the thickness of the tire carcass. The remaining arrangement of the wheel i.e. the placement of tube and rim remains the same (Fig. 5(b)).
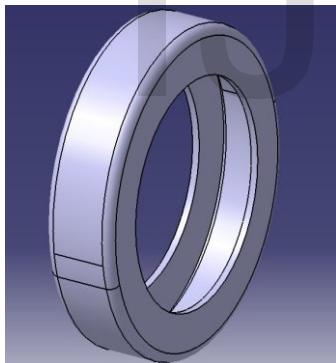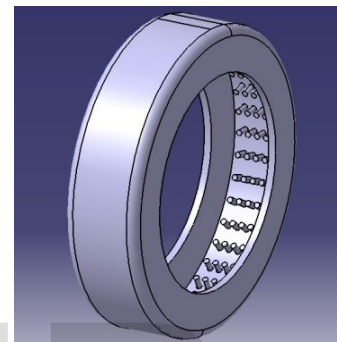

Figure 5(b). *CAD model of PZTs covered with another layer of tire rubber.*

The arrangement of the modules is represented through a CAD drawing in Fig. 6. The hatched lines represent the tire rubber material and the side and front view of the assembly is shown in the figure.
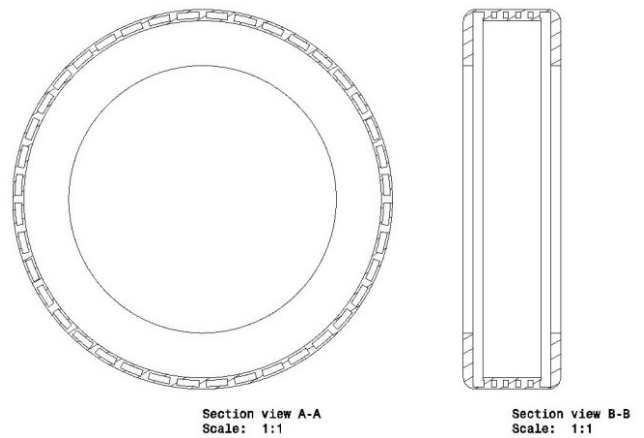

Figure 5(a). *CAD model of PZT-5A module arrangement in the tire.*

Figure 6. *CAD drawing of the assembly of PZT module inside the tire.*

3. Calculations

The tire pressure of a passenger vehicle is about 32 psi [7]. Assuming the weight of the vehicle along with the passengers be 1000 kg with an equal weight distribution both at the front and rear, the load acting on each of the tire is identical i.e. 250 kg or 2453 N.

For the approximate calculation of contact area of the tire when loaded, the following relation is used [8]:-

$$\text{Contact patch area} = \text{force applied/tire pressure}$$

$$= (2453 \text{ N})/(0.2206 \text{N/mm}^2) = 11120 \text{ mm}^2 \quad (1)$$

The tire pressure is converted from psi to N/mm^2. Since the base diameter of each of PZT module is 15mm, the area covered at the base by each module is given by the area of the circular base i.e.

$$\text{Area of circular base} = 0.25 \text{ x } \pi \text{ x (base diameter)}^2$$

$$= 0.25 \text{ x } \pi \text{ x } (15)^2 = 176.25 \text{ mm}^2 \quad (2)$$

Therefore, the approximate number of modules that will be under the load can be calculated as:-

Number of PZT modules= (Contact patch area) / (area of circular base of a single module)

$$= 11120/176.25 = 63 \text{ (approx.)} \quad (3)$$

Therefore, the number of modules in the contact patch area is 63. The tire material can be modelled into an equivalent spring-damper system [9] whose spring stiffness and damping coefficient values are listed in Table 1. The piezoelectric module can also be modelled as a spring-mass system whose spring stiffness and equivalent mass values are listed in Table 1. The corresponding physical modelling of the assembly in MATLAB/Simscape workbench is shown in figure 7. The nomenclature of the symbols used in the model is inscribed in Table 2.
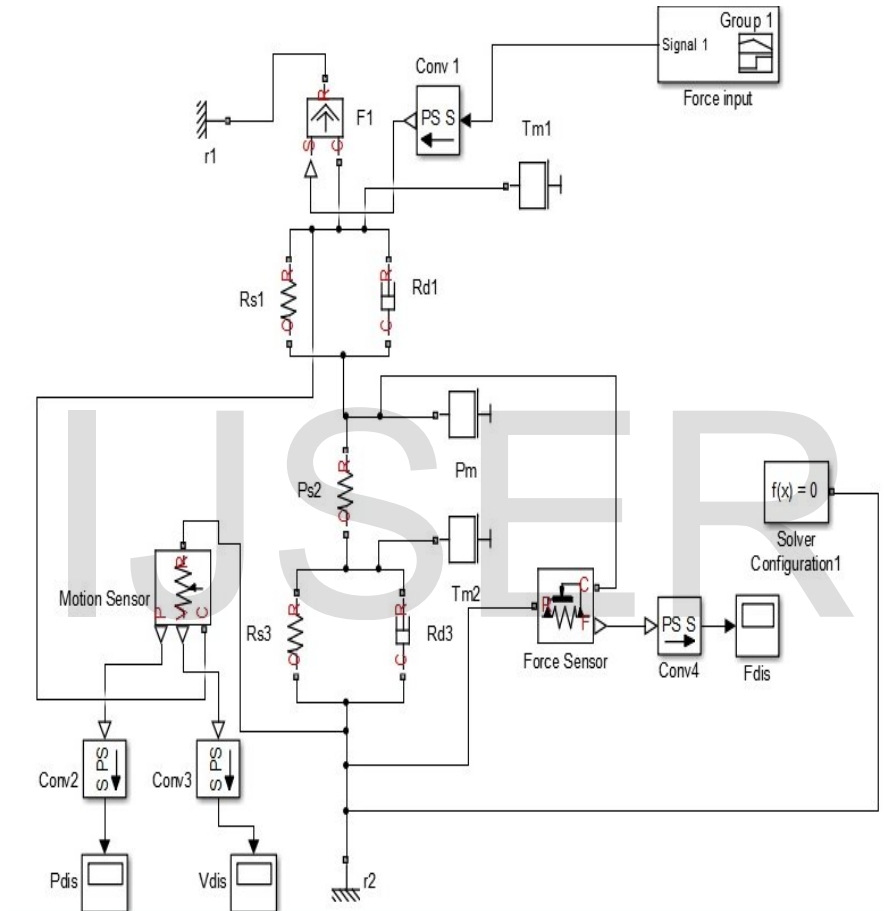

Figure 7. MATLAB/Simscape modelling of the assembly.

Since the force of 2453 N is acted upon 63 modules parallel, the force will be shared among the PZT module uniformly i.e.:-

Force on each module = Total force/ Number of modules

$$= 2453/63 = 39 \text{ N (approx.)} \quad (4)$$

Table 1. Numerical values of the components of the MATLAB/Simscape model of the entire assembly [5, 9-11].

| Sl. No.	Name of the component	Unit	Value

Sl. No.	Name of the component	Unit	Value
01.	Spring stiffness of tire	N/m	230×10^3
02.	Damping coefficient of tire	N-s/m	3440
03.	Mass of tire	kg	0.1
04.	Spring stiffness of piezoelectric module	N/m	38.63×10^6
05.	Mass of piezoelectric module	kg	0.028

Table 2. *Nomenclature of the symbols used in the physical modelling of the assembly.*

Sl. No.	Name of the component	Symbol
01.	Spring stiffness of tire	Rs1, Rs3
02.	Damping coefficient of tire	Rd1, Rd3
03.	Mass of tire	Tm1, Tm2
04.	Spring stiffness of piezoelectric module	Ps2
05.	Mass of piezoelectric module	Pm

The PZT module is simulated for a load of 39 N in COMSOL Multiphysics software (Fig. 8) and the output electric potential is found out to be 414 V which when connected to an external resistance will intend the flow of current through it. These piezoelectric modules are connected in parallel so the current just adds up and a greater value of power is produced as compared to the output of a single piezoelectric module.
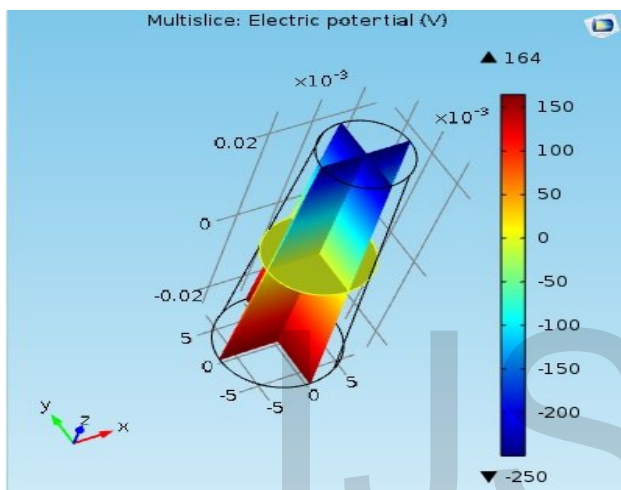
Figure 8. *Electric potential distribution throughout the piezoelectric module upon the application of 39N of compressive load.*

4. Discussion and Recommendation

The piezoelectric modules carry a disadvantageous production cost which make them less popular among the public. But, the initiation of its use and commercialisation of the same will surely reduce its cost and make economically feasible for the customers. The conversion efficiency of the piezoelectric energy harvesters are practically found out to be an increasing curve up to a certain normalized resistance or load and beyond that the efficiency decreases with increase in the electrical load or resistance [12]. The resistance also known as the resonant resistance can be practically or theoretically determined to harvest maximum possible power from the above stated energy harvesting model.

Developments can be made in terms of the geometry of the

module chosen and the pattern of the arrangement of the module. Iterations can also be made in the dimension of the present shape module to observe the change in the output voltage and amount of power that can be harvested from it. Apart from the direct loading condition, the modules are also subjected to shear load to some extent and also, the loading conditions are different at different states of run i.e. the loading condition changes with velocity, during cornering or during a roll or pitch etc. which can be simulated or experimented practically to figure out the actual amount of the energy that can be tapped.

5. Conclusion

The model for tapping energy by the use of PZT modules from the vehicle tires was designed and simulated using COMSOL Multiphysics and MATLAB/Simscape. The module that was chosen for the model had a countour of that of a frustum with a base diameter of 15 mm and a top face diameter of 10mm. The force acting on each PZT module in the model was calculated to be 39 N and the output voltage was simulated to be 414 V. The output power, thus, can be tapped to be stored in batteries and can be a major boon in the hybrid vehicles. A lot of research on this field will result in the day where use of piezoelectric modules for power harvesting becomes popular among the public and technical enthusiasts.

Acknowledgement

References

[1] Noaman Makki and Remon Pop-Iliev, "Piezoelectric power generation in automotive tires", International Workshop Smart materials, Structures & NDT in Aerospace Conference NDT in Canada 2011 , 2 - 4 November 2011, Montreal, Quebec, Canada.

[2] T. Madhuranath, R. praharsha and Dr. K. Srinivasa Rao, " Design and simulation of piezotyres using Comsol multiphysics 4.3b software", Excerpt from the Proceedings of the 2013 COMSOL Conference in Bangalore.

[3] Kunchala Anil, N. Sreekanth, " Piezoelectric power generation in tires", International Journal of Electrical, Electronics and computer Systems (IJEECS), ISSN (Online): 2347-2820, Volume -2, Issue-2, 2014.

[4] Madan Mohan Behera, "Piezoelectric energy harvesting from vehicle wheels", International Journal of Engineering Research & Technology, Volume. 4 - Issue. 05 , May – 2015.

[5] D. Berlincourt and H. H. A. Krueger, "Properties of Morgan electro ceramic ceramics", Technical Publication TP-226 Properties of Piezoelectricity Ceramics.

[6] Matthew W. Hooker, "Properties of PZT-Based Piezoelectric Ceramics Between -150 and 250°C", NASA / CR-1998-208708.

[7] http://www.aa1car.com/library/tirepres.htm.

[8] http://www.performancesimulations.com/wp/fact-or-fiction-tire-contact-patch-size-is-determined-mostly-by-weight-and-tire-pressure.

[9] "The pneumatic tire", US Department of Transportation, National Highway Traffic Safety Administration, DOT HS 810 561, February 2006.

[10] onlinelibrary.wiley.com/doi/10.1002/...app5/pdf.

[11] www.riken.jp/epmrt/Hanaguri/Tech/tube_piezo.xls.

[12] Y C Shu and I C Lien, "Efficiency of energy conversion for a piezoelectric power harvesting system", Journal of micromechanics and microengineering, 16 (2006) 2429–2438; doi:10.1088/0960-1317/16/11/026.

IJSER