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PIEZOELECTRIC ENERGY HARVESTING IN AUTOMOBILE WHEELS

Ayan Bhattacharya
B.Tech in Mechanical Engineering,
Maulana Abul Kalam Azad University of Technology (MAKAUT), Kolkata, India
abhbuna@gmail.com

Abstract: Humans have always being depended upon the fossil fuels as the source of energy for their daily needs. With the exponential growth in population, the dependence on these conventional sources for the daily energy requirements has led to the depletion of the same and adverse ill-effects on the environment. To lessen the burden and if possible minimize to zero, energy harvesting has become the need of the hour and the development of the different energy harvesting technologies has been the prime area of research. Piezoelectric materials have gained the popularity in this niche of energy harvesting solutions. The aim of this research work is to make power generation more sustainable, economical and ecological by utilizing the advancement in the technology. In this paper, an effective method for producing usable electrical energy from available mechanical stress (using piezoelectric material along the circumference of the inner lining of the tire) has been show. The output of conversion circuit is sufficient to charge a rechargeable DC battery where a fully discharged 9 volt dc battery was found to be fully charged within half an hour. The proposed electric power supply can be used to run low power electrical equipments like light, fan etc within the vehicle.

Keywords: Capacitor, Electrical Energy, Energy Harvesting, Mechanical Stress, Piezoelectric effect, Piezoelectric harvester, Power, Transducer, Vehicle tire.

I. INTRODUCTION

Piezoelectricity stands for the electricity generated from applied pressure .It is the ability of certain materials (notably crystals and certain ceramics) to generate an electrical potential in response to an applied mechanical stress. The phenomenon that produces an electric charge when a force is applied to a piezoelectric material is known as the piezoelectric effect. This is due to compression or stress applied to the piezoelectric crystal which changes the distance between the negative and positive charges of crystal, resulting in development of electric field on the surface of the crystal.

MECHANISM OF PIEZOELECTRIC EFFECT

Piezoelectric ceramics belongs to the group of ferroelectric materials. Ferroelectric materials are crystals which are polar without any electric field being applied .The piezoelectric effect is common in piezoceramics like $PbTiO_3$, $PbZrO_3$, PVDF and PZT elements. One of the defining traits of a ferroelectric material is that the molecular structure is oriented such that the material exhibits a local charge separation, known as an electric dipole.

Throughout the artificial piezoelectric material composition the electric dipoles are orientated randomly, but when a very strong electric field is applied, the electric dipoles reorient themselves relative to the Electric field; this process is termed poling. Once the electric field is extinguished, the dipoles maintain their orientation and the material is then said to be poled.

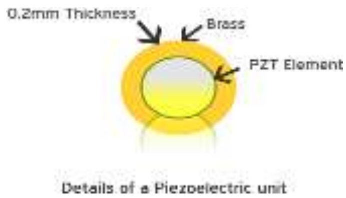

Figure 1:

After the poling process is completed, the material will exhibit the piezoelectric effect. The mechanical and electrical behavior of a piezoelectric material can be modeled by two linearized constitutive equations. These equations contain two mechanical and two electrical variables. The direct effect and the converse effect may be modeled by the following matrix equations:

Direct Piezoelectric Effect: $D = d.T + \varepsilon T.E$ (1)
Converse Piezoelectric Effect: $S = sE.T + dt.E$ (2)

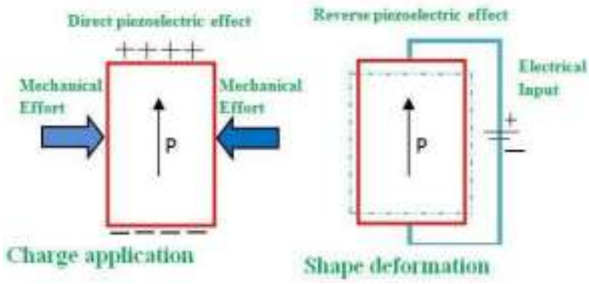

Fig. 2:
Electro-mechanical conversion in piezoelectricity phenomenon.

Where D is the electric displacement vector, T is the stress vector, εT is the dielectric permittivity matrix at constant mechanical stress, sE is the matrix of compliance coefficients at constant electric field strength, S is the strain vector, d is the piezoelectric constant matrix, and E is the electric field vector. The subscript t stands for transposition of a matrix. When the material is deformed or stressed an electric voltage can be recovered along any surface of the material (via electrodes).

Therefore, the piezoelectric properties must contain a sign convention to facilitate this ability to recover electric potential. The piezoelectric effect is the process of internal generation of electrical charge resulting from an applied mechanical force. The origin of the piezoelectric effect was, in general, clear from the very beginning. The displacement of ions from their equilibrium positions caused by a mechanical stress in crystals that lack a centre of symmetry must result in the generation of an electric moment, i.e., in electric polarization.

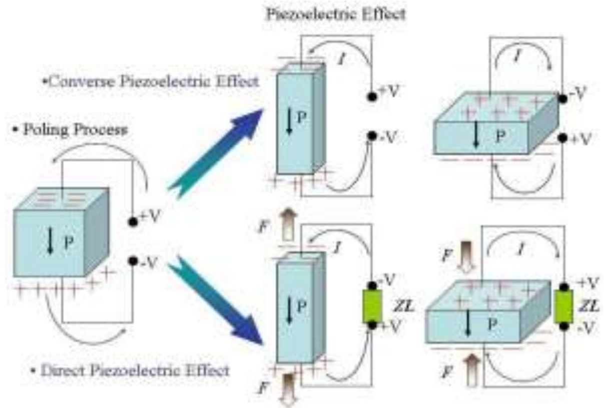

Fig. 3: Origin of piezoelectric effect and polarization.

The above figure shows the piezoelectric material without a stress or charge. If the material is compressed, then a voltage of the same polarity as the poling voltage will appear between the electrodes.If stretched, a voltage of opposite polarity will appear.Conversely, if a voltage is applied the material will deform. A voltage with the opposite polarity as the poling voltage will cause the material to expand, and a voltage with the same polarity will cause the material to compress. If an AC signal is applied then the material will vibrate at the same frequency as the signal.

II. COMPARISON OF PIEZOCERAMICS TO BE USED FOR APPLICATION

Table 1:
Comparison of Energy Harvesting on per unit Area basis:

Sl. no	Element	Dimension	Area (mm2)	Power (mW)	Power/Area (mW/mm2)
1.	PZT	25mm disc	491	4.3	0.009370
2.	PVDF	40x40mm	1600	0.85	0.000531
3.	PVDF	15x40mm (3pieces)	1800	0.23	0.000127

The thickness of the elements used in these three(3) methods were omitted since the thickness of PZT(0.1mm) and PVDF(0.11mm) elements are almost equal. PZT Elements have the highest power output capacity per unit area.

Besides power output, there are other important factors on which PZT and PVDF elements should be compared regarding their usage in tires. Some of these are compared in Table 2.

Table 2: Comparison of PZT and PVDF elements on some basic criteria:

Criteria	PZT element	PVDF element
Deformability	Low	Very Low
Piezoelectric charge constant(d33)	High (110)	Low (33)
Cost ($)	$2 per element (25mm dia,449mm2)	$2.8per element (449mm2)
Temperature Range(C)	High (upto 130)	Low (upto 80)

After a long drive, the tire temperature can rise up to 70 C and so the piezoelectric materials being used must be able to withstand such high temperatures without failure. Both PZT and PVDF have operating temperatures that exceed this temperature and are usable inside the tire for energy harvesting. PVDF elements being more flexible do hold the potential of providing more deformation cycles than PZT without degradation in the quality of output power. A very important factor involved with the use of piezoelectric materials for energy harvesting is that of cost; high cost of harvester can prove to be a major hurdle in their wide scale usage and replacement of permanent power storage medium such as batteries.

The PZT elements are relative cheap at $2 per piece (from digikey.ca) for a 491 mm2 ceramic area, while a 216 x 280 mm PVDF sheet costs $330 or $2.71 per 491 mm2. However, PZT elements offer a greater return due to their higher power output per unit area or cost.

In order to understand the output voltage corresponding to the various forces applied, the V-I characteristics of PZT and PVDF elements were plotted .Voltmeters are connected across both of them for measuring voltage and an ammeter connected to measure the current. For each voltage reading across the force sensor, various voltage and current readings of the piezoelectric materials are noted.
The graphs below show that voltage obtained from PZT element is around 2V where as that of PVDF element is around 0.4 V.

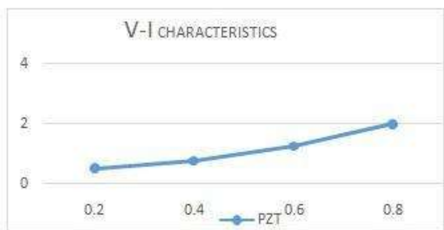

Figure 4: Voltage Current Characteristics for PZT Element

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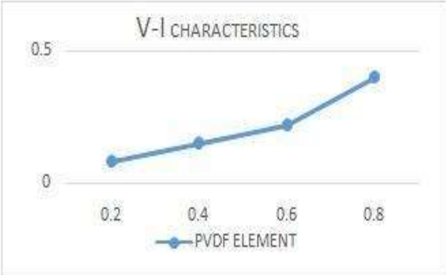

Figure 5: Voltage Current Characterstics for PVDF Element

Thus, PZT element application can be used in automobile wheels for energy harvesting.

III. PZT ELEMENT FUNDAMENTALS

PZT, or **lead zirconatetitanate (Pb[Zr(x)Ti(1-x)]O3)**, is one of the world's most widely used piezoelectric ceramic materials. When fired, PZT has a perovskite crystal structure, each unit of which consists of a small tetravalent metal ion in a lattice of large divalent metal ions. In the case of PZT, the small tetravalent metal ion is usually titanium or zirconium. The large divalent metal ion is usually lead. Under conditions that confer a tetragonal or rhombohedral symmetry on the PZT crystals, each crystal has a dipole moment. Each PZT element has a thickness of 0.2mm with a 0.1mm thick circular ceramic plate of 25mm diameter.

IV.ARRANGEMENT

It was noted from experiments that voltage from PZT units connected in series connection is good but current obtained is poor, whereas from PZT units connected in parallel, the current obtained is good but the voltage is poor. Developing a piezoelectric energy harvesting system is challenging because of their poor source characteristics (high voltage, low current, high impedence). So here we use 4 stacks of piezoelectric systems equidistant to each other attached to a circular strip arranged in between the inner layer of tyre and outer surface of wheel rim.

Piezoelectric unit application in tyres
Figure 6:

Each PZT unit is connected with other two PZT unit in series connection. So each row has 3 piezoelectric units connected in series like shown in the figure (1) below. These rows (total 16 rows, 4 in each stack) of PZT units connected in series are connected to the rectifier circuit (individually) in a parallel connection. So arranging the piezoelectric system in a series-parallel connection produces good output voltage and current, required for proper energy harvesting .The output of the system is not a steady one. So a full wave bridge rectifier is used to convert this variable voltage into a linear one. The rectifier circuit is also used to convert the AC output of a piezoelectric system into DC voltage. The rectifying circuit consists of 4 diodes.

IV. EQUIVALENT CIRCUIT DIAGRAM OF PIEZOELECTRIC HARVESTER

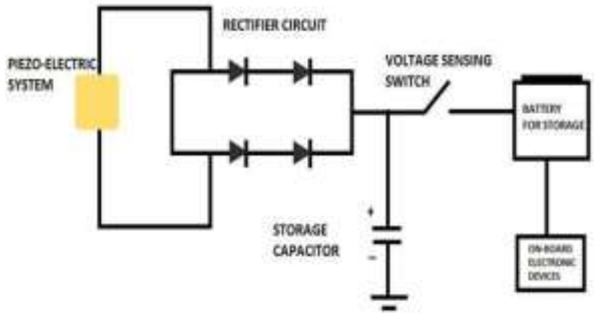

Figure 7: Circuit diagram of the piezoelectric system

V. WORKING

In our proposed method, for conversion of mechanical energy into electrical energy we used several piezoelectric transducers. For filtering, storing and prevent this ac voltage a 1 farad of 5.5 volt super capacitor has used. All super capacitors used in parallel to the piezoelectric material. The super capacitor is also known as Electrical Double Layer Capacitor (EDLC). Super capacitors are differs from other general capacitors. It can bridge the gap between capacitors and batteries with its high capacitance value. Super capacitors required short time to charged, that's why available mechanical energy can be easily stored as electrical energy. But it needs much longer time to discharge. So, the stored electrical energy can be hold for longer time than other capacitors. When one of the piezoelectric unit (4 different units placed at right angles to each other) comes in contact to the road surface (the contact patch area) , at any instance an electric voltage is produced in each of the piezoelectric unit .This AC output is converted into usable DC voltage using the rectifier circuit. This electrical voltage is fed to the capacitor bank for storage. A battery is also connected as shown in the circuit diagram (Figure 6) which cuts off from the circuit as soon as the battery gets full charged. The battery is then ready for usage. The generated DC voltage can also be used to run onboard electrical devices or other sensors in the car. This working process is applicable for each of the 4 wheels of an automobile fitted with piezoelectric modules.

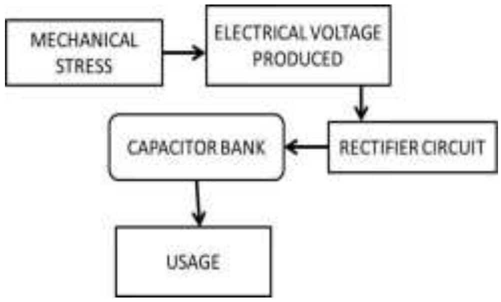

Figure 8: Block Diagram showing generation and storing electricity using mechanical stress

VI. EXPERIMENTAL ANALYSIS

Our proposed method was tested in outdoor environment to measure its performance. For calculations of the output voltage certain data indicated in Table 1 is required. The mechanical stress source is basically from the load on the tire which is predominantly the vertical load.

Parameter	Value
Weight of the vehicle (4-wheeler/ 5passengers)	1000kg
Weight distribution	50:50
Wheel Radius	153.62mm
Wheel Width	140mm
Tire Air Pressure	25psi
Dimension of PZT module	28mm dia, Thickness 2mm
d_{33}	350x10^{-12} C/m^2
g_{33}	16.6x10^{-3}Vm/N
Electromechanical coupling coefficient	0.69

Table 3: Data of working environment for calculations

Since, the vehicle is weighing 1000kg and 50:50 weight distributed, the load on each tire is calculated out to be 250kg(250x9.81=2452.5N). The modules are to be arranged such that 2mm gap is maintained between two successive modules.

Number of modules mounted on each wheel =
(Circumference of the wheel) /
(Diameter of wheel +gap between two modules)
=π x 153.62/(28mm+2mm) = 32 (approx)

Therefore, the total number of modules in each wheel is 32.

Contact patch area
= Load on the wheel/Air pressure in tire
=((250x9.81) /0.1724 N/ ²) =14225.64 ²

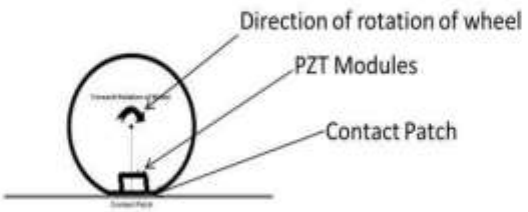

Figure 9: PZT module under stress at contact patch area

For the width of the contact area to be 140mm, the length of the contact area (assuming that the region is almost a rectangular one) is 102mm. Therefore, the contact area almost indulges 3 PZT modules which will be under stress once entering to the contact area zone as shown in figure 8.

Open Circuit Voltage (OCV) = g_{33} x σ x t
where,
σ = induced mechanical stress in the module t = thickness of the module
Therefore,
O.C.V = 16.6 x 10^{-3} x 995733.41 x 0.002
= 44 V (approx.)

Assuming that the load is distributed uniformly in the contact patch area, the mechanical stress induced in each module will be:
Mechanical Stress induced in each module
= (Force on each module / area of application of load)
= (250 X 9.81)/ (π X 0.028^2) = 995733.41N/ ²

Charge Density = d33 x σ
=350 x 10-12 x 995733.41N/ ²

Charge on each module
= charge density X π X 0.014^2 = 0.3 μA (for 1sec)
Thus,
Power Output =VI =44 X 0.3=13.2 μW

VII. OUTPUT CALCULATIONS

Maximum voltage that can be generated in each piezo module = 44 V
Output power in one unit = 44 x0.3 = 13.2μW
Output power in one strip = 3 x 13.2 =39.60μW

As there are total of 4 piezo stacks (4x12=48 total units) , For one complete rotation of the wheel, the number of times the same power output is obtained is equal to 48. Therefore,

Amount of power generated in total
= 39.60 x 48 = 1900.8μW = 1.9mW (approx.)
Output power in 4 wheels = 4 x 1.9 =7.6mW
Assuming that the vehicle is running at a speed of 45 km/hr (12.5 m/s),

The no of wheel rotations per second is given by:
= velocity /(radius of wheel X 2π)
= 12.5/(153x2xπ) x 1000
= 13 rotations / sec
Power output per wheel per second (car is in running condition)
= 13 X 1.9 =24.7mW
Therefore,
Power output for 4 wheels of the car /second
= 24.7 X 4 = 99mW (approx.)

If the vehicle runs for 1hour (3600 seconds),
The amount of energy that can be stored
= (0.0247 x 3600) J
=88.9Joules (each wheel)
Total Energy that can be stored from all the wheels
= 88.9 X 4
= 355.7Joules

VIII. RESULTS

It can be seen that the amount of energy that can be stored from an hour of driving with the present design of the system is enough for catering the power supply needs of various electronic circuits of the vehicle. Proper designing and experiments can lead to better results. Although the efficiency of such systems is around 30-40%, use of better quality PZT materials can yield better results.

The amount of energy that can be produced is enough to charge mobile phones or can be held as power store for the LED headlights which consume very less power as compared to the conventional headlights. The calculations shown above are theoretical ones which accounts for only the direct load. Practically, the vehicle tire also experiences shear loading which can contribute to the total power generated, taking into account the d31and g31 constants of the material. The connection of the PZT in the contact patch area can be iterated out, that means the modules can be connected in series, parallel or series-parallel connection for better output results. The shape of the piezoelectric modules can be altered and experimented best suited for its housing and power output results.

IX. CONCLUSION

Piezoelectric materials have the ability to transform mechanical strain energy into electrical charge. The amount of energy generated depends on the speed of the vehicle and the number of piezoelectric elements on the tires. In this paper a theoretical model for energy harvesting system using piezoelectric materials have been presented. It is evident that harnessing energy through piezoelectric materials provider a cleaner way of powering lighting systems and other equipment. It is a new approach to lead the world into implementing greener technologies that are aimed at protecting the environment. Piezoelectric energy harvesting systems are a onetime installment and they require very less maintenance, making them cost efficient. One of the limitations of this technology is that its implementation is not feasible in sparsely populated areas as the foot traffic is very low in such areas.

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