Piezoelectric Energy Harvesting from Vehicle Wheels

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***Abstract*-Since the advent of modern civilisation, humans have always being depended upon the fossil fuels as the source of energy for their daily requirements. With the exponential growth in the 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 minimise 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. Of them, piezoelectric materials have gained the popularity in this niche of energy harvesting solutions and have resulted in promising possibilities of efficient tapping of waste energy for future use. In this paper, a technique of application of piezoelectric material for harnessing energy i.e. along the circumference of the inner lining of the tyre and rough calculations has been made to project the probable energy tapped and its usage. The current work describes a sample arrangement of crystal and various new arrangements based on maximum power output can be made.**

Keywords:- Energy Harvesting , Piezoelectric Effect, Piezoelectric crystals, Capacitor

I. INTRODUCTION

With the increase in the concern for the alarming depletion of fossil fuel reserves and its adverse effects on the surrounding environment, the alternative non-conventional sources of energy have gained popularity in the society. Starting from the well-known solar cells to the wind turbines, hydroelectric power generation, biodiesel and biogas plants have already being successfully proven and implemented for the same. For power supply needs of the portable gadgets the human use, new ways have been found out to cater the need. Piezoelectric materials and the effect itself have played a major role in solving such problems. Energy harvested from the vibrations is one of the easiest and omni-usable techniques. These vibrations can be from human motion, vehicular motion, machines and any other surface under vibrations. The conversion of mechanical energy into electrical energy can be done by the use of piezoelectric materials. Some of the natural piezoelectric materials already in use is quartz. Some artificial piezoelectric materials like $BaTiO_3$, Lead Zirconium Titanate etc. find their applications in modern electronic circuits.

Vehicle tires are subjected to normal and shear loads under static and dynamic conditions. The load can be used as a source of mechanical stress for the piezoelectric crystals. The piezoelectric crystals can thus be aligned along the inner lining of the tire where the air pressure does the work. In this paper, different applications of piezoelectric energy harvesting are being illustrated and an attempt has been made to conceptualise a new way of application of the same and certain calculations has been made to visualise the probable energy output from the system.

A. Piezoelectric Materials

Piezoelectric Materials are the smart materials which convert mechanical stress or strain into electrical potential and vice versa i.e. application of electrical potential to the material yields to mechanical displacement. While the former is known as direct piezoelectric effect, the latter is reverse piezoelectric effect.

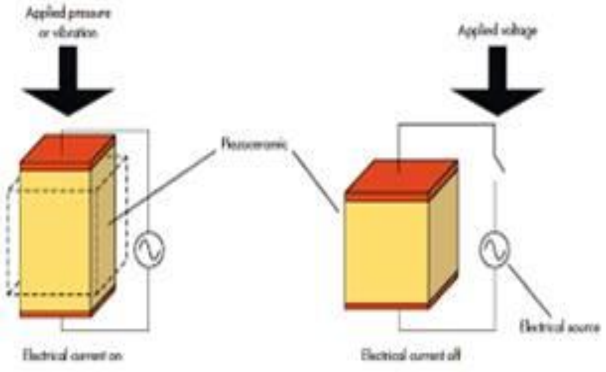

Figure 1- (a) Direct Effect (b) Reverse Effect

The piezoelectric material in the piezoelectric system has different modes of operation. The modes are characterized by piezoelectric strain constant d_{ij}, mechanical strain to electrical voltage. The subscript 'i' denotes the direction of electrical voltage output and 'j' denotes the direction of application of mechanical stress or deformation. There are predominately two constants d_{33} and d_{31} with the poling direction being the 3-axis.[1]

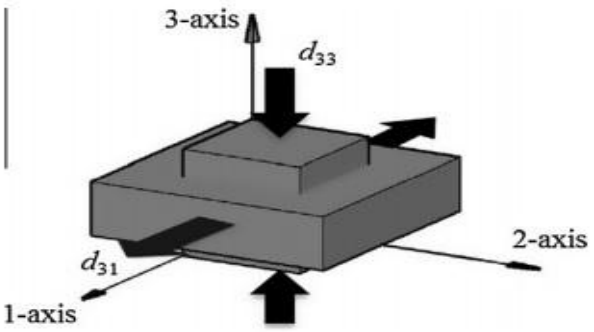

Figure 2- Operation modes of piezoelectric material and its axis reference system.

I.

B. Areas of Implementations

Piezoelectric materials have found their place in the energy harvesting sector for harnessing power ranging from nanowatts to some watts i.e. from micro-scale to macro-scale energy production. There have been some implementations over the globe based on this concept. Piezoelectric floors concept utilises the footfall energy of the human population in generating electrical energy and catering the power needs. The concept has been successfully implemented in the Tokyo Station, Japan[2] where the ticket gates are floored with these tiles and the power output is used to supply to the electronic circuits of the gates.

Figure 3- Piezoelectric tiles at the Tokyo Station, Japan

Club4Climate, a dance club in United Kingdom [3], have their dance floors embedded with piezoelectric materials which converts the hops and dance of the crowd into electrical energy. According to the owner, these tiles can cater as much as 60% of the club power needs.

Figure 4- Concept of Piezoelectric Dance Floors

Innowattech, a company have implemented the piezoelectric tile concept beneath the road surface and railway tracks which absorbs the vibrations and generate electrical voltage which is stepped up and fed to the grid.[4]

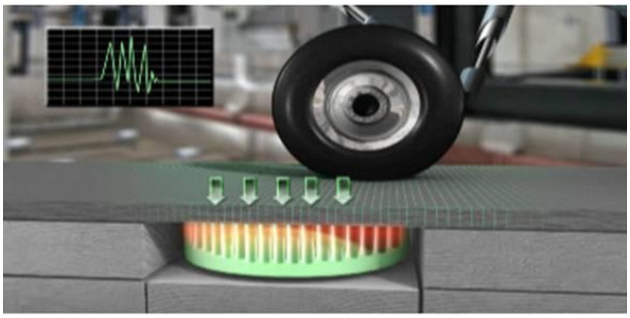

Figure 5- Concept for harvesting energy from road vibrations

II.MATERIALS AND METHODS

A. Materials

Piezoelectric materials include quartz, $BaTiO_3$, Lead ZirchoniumTitanate (PZTs) etc. Out of these quartz gives highest electrical output voltage w.r.t the mechanical stress applied but it is economically not feasible due to its high cost. The next is PZT which are readily available at low cost and gives impressible results. The following graphs [5] give a clear picture of different PZT materials under various working conditions in terms of temperatures.

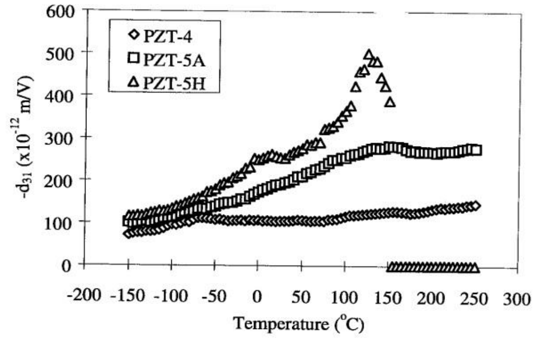

Figure 6(a) - Variation of d_{31} with working temperature.

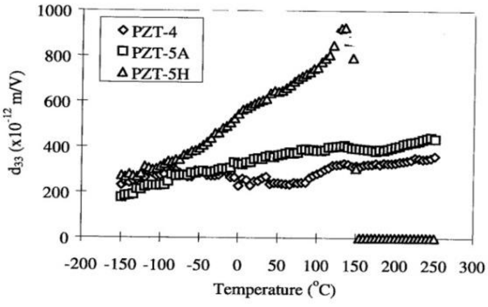

Figure 6(b)- Variation of d_{33} with the working temperature.

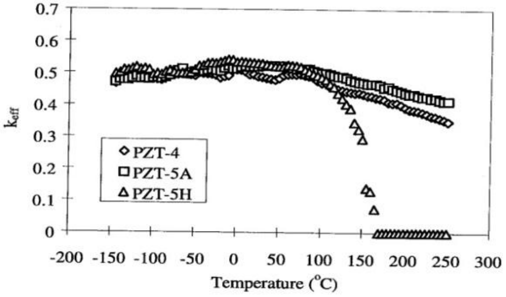

Figure 6(c)- Variation of effective electromechanical coupling coefficient with temperature.

From above graphs, it can be seen that PZT-5H has highest d_{31} and d_{33} values then, PZT-5A and PZT-4. Also, it can be seen that the strain constants of PZT-5A and PZT-4 are consistent over different temperatures. The availability and cost of the PZT-5A is more feasible than the other PZT materials. Therefore, PZT-5A material was chosen. The module chosen is of diameter 28mm and thickness 2mm.

B. Methodology

The PZT-5A modules are placed in three strips all along the inner circumference of the tire. The tire chosen has tubes in them. The load experienced by the tire is profound in the contact patch area where the modules also experience the mechanical stress. The electrical voltage produced in the modules is fed to the capacitor bank for storage. The flowchart of the working of the system is described in the following figure.

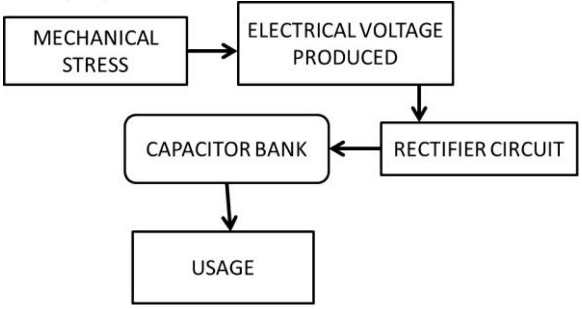

Figure 7- Flowchart of the working

The modules are arranged as shown in the figure 8 all around the inner circumference of tire. The modules can be arranged in a single strip or multiple strip (decided according to the contact patch area and tire width). In this calculation, 3 strips of the same is mounted.

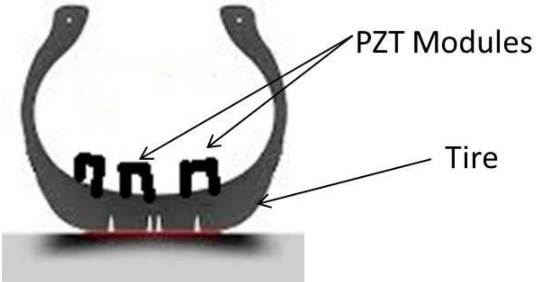

Figure 8- Mounting of PZT-5A modules on tire

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.

Table 1- Data of the working environment of the system

Parameters	Values
Weight of the vehicle(+5 passengers)(4-wheeler)	1000kg
Weight distribution	50:50
Wheel Radius	6'' (153.62mm)
Wheel width	145mm
Tire air pressure	25 psi
Dimension of PZT-5A module	Diameter-28mm; Thickness-2mm
d_{33} [5]	$350x10^{-12}$ C/m^2
g_{33} [5]	$16.6x10^{-3}$Vm/N
Electromechanical Coupling coefficient [5]	0.69

C. Output Calculations

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

Number of modules mounted on each wheel=$\frac{\boldsymbol{Circumference\ of\ the\ wheel}}{\boldsymbol{Diameter\ of\ each\ module+gap\ between\ two\ modules}}$

= π x 153.62/(28mm+2mm) = 32 (approx.).

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

The contact patch area= $\frac{\boldsymbol{Load\ on\ the\ wheel}}{\boldsymbol{Air\ pressure\ in\ the\ tire}}$

= $\frac{\mathbf{250\times9.81}}{\mathbf{0.1724}\ \boldsymbol{N/mm^2}}$ = 14225.64 mm^2.

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 9.

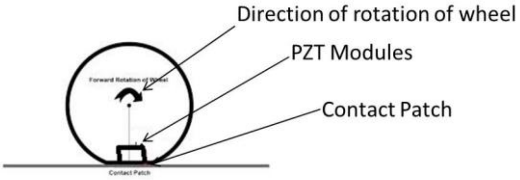

Figure 9- PZT module under stress at contact patch area

Assuming that the load is distributed uniformly in the contact patch area, the mechanical stress induced in each module will be :-

$=\frac{\boldsymbol{Force\ on\ each\ module}}{\boldsymbol{Area\ of\ application\ of\ the\ load}}=\frac{\mathbf{250\times9.81\times4}}{\mathbf{3\times\pi\times0.028^2}}$

=1327644.551 N/m^2

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 1327644.55 x 0.002

= 44 V (approx.)

Charge Density (CD) = d_{33} x σ

= 350 x 10^{-12} x 1327644.55

= 0.46 mC/m^2

Therefore, charge on each module=CD x π x $(0.014)^2$

= 0.283 μC = 0.283μA (for 1 sec)

Thus, the power output = VI= 44 x 0.283 μW
= 12.45 μW.

If the modules in the contact patch area are connected in series, then the voltage output of each PZT module just adds up. Therefore, the output voltage now becomes (44 x 3) V= 132V and power output is

37.4 μW. For one complete rotation of the wheel, the number of times the same power output is obtained is equal to 32. Therefore, the amount of power generated in total = 32 x 37.4 μW =1.2 mW (approx.)

Assuming the vehicle is running at a speed of 40kmph i.e. 11.11m/s, then, the number of wheel rotations per second is given by:-

$$=\frac{velocity}{radius\ \ of\ the\ wheel\ \times 2\times\pi}$$

$=\frac{11.11}{152.64\ \times 2\times\pi}$=11.6 rotations/second

Therefore, power output per wheel per second
= 11.6 x 1.2 mW = 14 mW (approx.).

If the vehicle runs for one hour, then the amount of energy that can be stored = 14 x 10^{-3} x 3600 = 50.4 J

Assuming, the similar conditions in all the four wheels, the total amount of energy that can be stored is
= 4 x 50.4 J = 201.6 J.

III. DISCUSSIONS

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 -5A 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 d_{31} and g_{31} 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.

IV. CONCLUSION

With the increase of popularity of non-conventional energy sources among the researchers all over the world, the possibilities of energy harvesting by the use of piezoelectric materials paves its way towards major green technology designs. Experiments and prototyping can lead to better collation of theoretical results and practical world outcomes. Great temporal and financial investments are required for the research of such promising outcomes of the piezoelectric energy harvesting concepts. Better materials selection, system design, efficient storage system and piezoelectric module design will guide this new concept of technology to be the next alternative source of energy in the near future.

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