Effect of Variation in Tire Pressure on Power Generation From A Pre-Stressed Piezoelectric Element Installed in A Car Tire

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Abstract:- **Power generation from piezoelectric elements has been done quite extensively in the recent past. Of great interest have been the factors that affect power generation from different piezoelectric power harvesting systems with an aim of optimizing the harvesting process. In this paper the effect of variation in tire pressure on the power output is investigated for a tire in which elements are placed between an introduced inner tube and the tire carcass (referred to as a pre-stressed tire). The results are then compared with those of a tire in which the elements are glued inside the tire without any inner tube. From the tests, it was found out that both tires give progressively better output with increasing tire pressure up to a maximum pressure beyond which the output drops for excitation forces below some established value. This optimum pressure was found to be 20 psi for the tire with an inner tube and 10psi for a tire without an inner tube. Though the tubeless tire was found to give better outputs at lower pressures, the pre-stressed (tubed) tire was found to give out the highest overall power output and would be more suitable for actual application in cars.**

Keywords— Power harvesting, mechanical vibration, piezoelectric materials, tire pressure and physical modeling

I. INTRODUCTION

The recent fluctuations in the price of petroleum products have affected worldwide economics which has directly led to increase in the price of other items including food[1]. The underlying reason for this fluctuation has however always been uncertainties in the supply of fossil fuels sparking wars and all sorts of human conflicts worldwide.

As the world continues to develop both socially and technology wise, the need for clean sources of energy remains a priority to ensure sustainability of the developments being witnessed. Piezoelectricity has always been one of the above desirable non-conventional sources of energy in mobile system applications due to its compactness and ability to work in almost any environment at all times. Piezoelectricity as a source of energy is however critically limited in terms of the quantity of energy given out which is typical of any emerging energy source. The above limitation makes it necessary to establish and document the conditions(both operation and material) that could either increase or compromise the power output. Such information would give critical guidance on the precautions to take to avoid system underperformance as well as the measures to take to maximize the output.

One of the operation conditions that require study in the case of piezoelectric generation from car tires is the influence of tire pressure on the output.

II. LITERETURE REVIEW

The desire to try and make piezoelectric energy harvesting cost effective and easy to implement has been a shared idea for tens of years [2] . In the case of cars, piezoelectric harvesting could be achieved by mounting harvesters on the chassis, suspensions system, engine block, engine mounting, pneumatic tires etc. This paper will concentrate on pneumatic tires.

Pneumatic tires as a component began in Great Britain during the late 1800s as an upgrade from solid rubber tires[3]. Each pneumatic tires has a footprint at the contact point, of an area about the size of an average man's hand[3]. This could however change with the tire pressure. It is therefore the same footprint affected by the tire pressure which can be expected to provide cyclical stresses on installed piezoelectric material whenever a car tire is used for power generation.

The load carried by a vehicle as well as the weight of the tires themselves causes tires to deflect until the average contact area pressure is balanced by the tires' internal air pressure. Larger loads require more contact area or higher tire pressures [3]. These loads acting on the tire result in normal and shear stresses under static and dynamic conditions[4]. Piezoelectric elements could therefore be aligned along the inner lining of the tire to tap these loads and generate energy.

Piezoelectric materials convert mechanical energy surrounding a given system into electrical Energy. The output is always an alternating voltage which requires further rectification as well as a DC to DC converter to improve source current characteristics[5]. In this paper a DC to DC converter was not used since the interest was on instantaneous energy generation.

A. *Piezoelectric Materials*

A wide range of piezoelectric materials exist for energy harvesting. These include topaz, quartz, Barium titanate ($BaTiO_3$), Lead titanate, Lead zirconate titanate (PZTs) etc. Out of these, quartz gives the highest electrical output voltage per unit force applied, but it is not feasible due to its high cost [4]. The next best material in terms of output is PZT which unlike Quartz comes at low cost and is therefore the most widely used and readily available piezoelectric material today. PZT also occurs in different forms with some of the most widely used forms being PZT-4, PZT-5A, PZT-5H.

In this research PZT-5A was used because of its superior temperature properties as well as availability. This made it very suitable for tires which are known to experience elevated temperature particularly under aggressive acceleration and braking.

B. Previous Research

Khameneifar and Arzanpour developed an approach for energy harvesting from pneumatic tires using PZT piezoelectric transducers modeled as a cantilever inside the tire[6]. The model predicted that 2.95 mW of useable power can be gained from a PZT mounted in a tire yet more than 1 KW energy wastes because of deflections of tires in an average passenger car[6]. This observation suggested the presence of several underlying factors which needed to studied individually in order to improve the output, one of them being tire pressure

In a study of the effect of pressure on resonant frequency of PZT 5 and PZT 4, Upadhye and Agashe[7] observed that as the pressure increased from 0 to 1Kg/cm^2 , the resonant frequency increased from 82 to 87 KHz. The effect of this on power generation depended on the frequency characteristics of the vibration source. The closer the source frequency to the final value of 87 KHz, the better the power output became and vice versa.

In 2018 Kurian et al [8] on a similar mission tried to harness power from a bicycle tire using piezoelectric patches on the rims of the wheel to generate electricity. The output was however so little that they opted not to talk about it quantitatively.

Sanjay in 2019 reviewed power generation from car tires [9]. He observed that the power generated from a piezoelectric tire depends on three factors, namely; tire surface area, rotation speed, and the deflection achieved. This review however failed to capture the effect of tire pressure because of lack of sufficient information on this area which makes the current research vital.

III. METHODOLOGY

The piezoelectric elements were soldered into arrays of 6 (based on space limitation) connected in parallel.

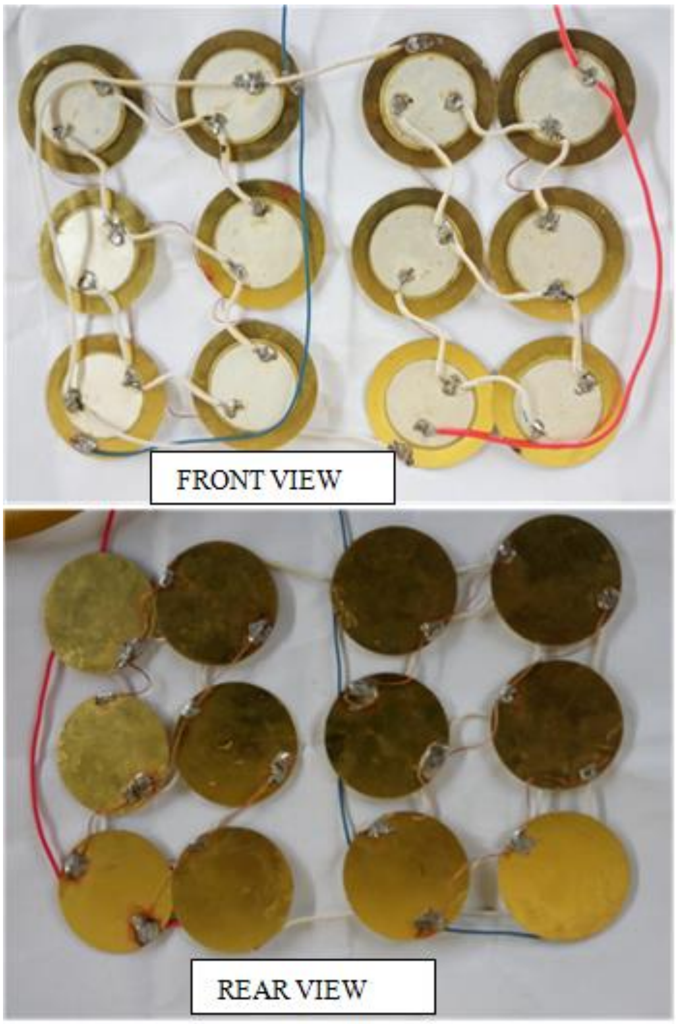

Figure 1: Wiring of the piezo discs

The six members in each array were connected to each other via short flexible connecting wires in such a way that each disc was provided with two alternative paths through which the output could be delivered. This ensured that in case any of the connection fails, the power production from the patch is not adversely affected. Two individual arrays were in turn connected in series with each other via similar flexible connecting wires to form a cluster of 12 as illustrated in **Figure 1**.

After developing the element assembly above, each cluster of 12 was provided with its separate rectifier, then encased with heat glue (Ethylene-vinyl acetate). The purpose of this heat glue blanket on the elements include:

- It protects the elements from each other's sharp edges.
- Protect the tires surface from the disc's sharp edges which under high pressure can easily transform into shear cutters

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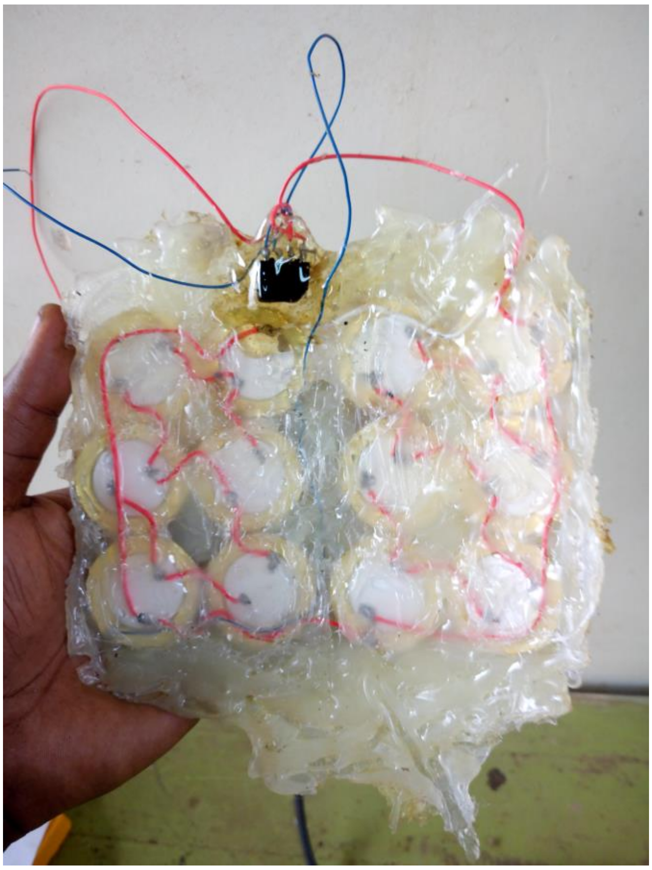

Figure 2: Piezo patch held together with heat glue

- Reduce chances of short circuiting when in operation by keeping the elements at a fixed distance from each other
- Develop a patch that can be easily moved from one tire to another or retrieved in case it is damaged
- Provide each element with an extra layer of damping to protect it from excessive impact forces expected in the course of operation

Figure 2 shows the patch with the heat glue applied.
Two tires were then assembled. In the case of the first tire, contact glue was applied between the tire and the patch. For tire 2, the patch was placed between the tire and an introduced inner tube without any additional adhesive.

This was done in order to provide a comparison between the performance of the pre-stressed element and the regularly installed elements. The tire was then pressurized to hold the patch in place. Two additional nozzles were used to get power from the tire as explained in [10].
The tires were then taken through a drop test from pre-determined heights (2 cm, 4 cm, 6 cm, 8 cm, 10 cm and 12 cm) and the peak output voltage and current measured. This was done with the patch located directly at the impact position, referred to as the zero degrees position. Figure 3 shows the zero degrees position of the harvester which was maintained throughout the experiment.

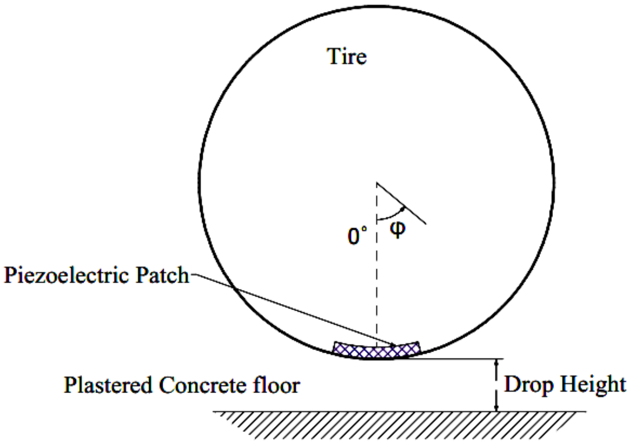

Figure 3: The zero position of the piezoelectric patch

In order to determine the actual impact forces, following relation was used:

$$\textit{Impact force} = \frac{m \times g \times h}{d}$$

Where **m** is the mass of the tire, **g** is the force of gravity, **h** is the drop height and **d** is the deflection of the tire after impact. Details on how h was experimentally achieved can be found in [10].

IV. RESULTS

1.1. Variation of Power Generation with Changing Pressure for 0.3 mm Discs In a Tire With an Inner tube

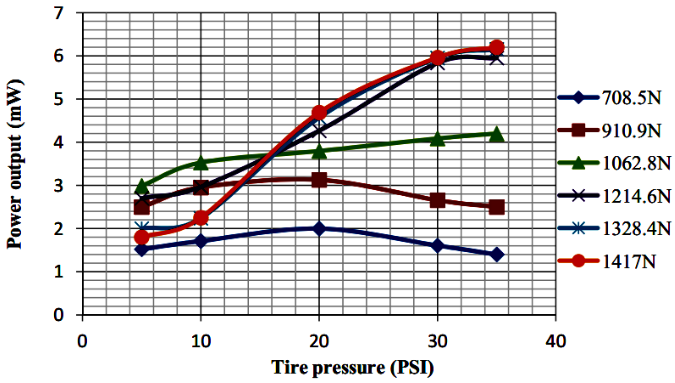

Figure 4: Effect of increasing pressure on a piezoelectric tires with inner tube and 0.3mm discs

From the graph shown in Figure 4, increasing tire pressures in a piezoelectric tire having an inner tube produces continuously increasing power irrespective of the load size up to 20 psi. This is mainly because as the pressure increases from 0 to 20 psi, the patch is held against the tire carcass more firmly making transmission as well as distribution of the applied force to the elements more effective hence better power generation. This deduction agrees with the observation made by Farsworth et al.[11] where they observed that, in order to optimize the efficiency of power generation, it is important that the energy harvesting system should maximize the coupling between the kinetic energy source and the transduction mechanism. Li et al. [12] in their paper also noted that aside from the resonance matching between the energy harvester and the primary input frequency of the host, strain distribution within the piezoelectric material is also an important aspect in achieving maximum efficiency when harvesting piezoelectricity.

From the same graph in Figure 4 the intersection at 16 psi implies that at this pressure, the tire used (185/70r14) behaves as an energy sink for any forces above 1062 N. As a consequence, the amount of energy output witnessed for a force of 1062 N, continues to be the same amount given out no matter how much the impact force is increased. This information could be used in the design of luxury cars (with further research) to ensure the ride is smooth and as comfortable as possible.

From the graph shown in Figure 4 , any further increase in pressure from 20 psi was accompanied by an increase in the output only if the force at the contact point is above 1062 N, otherwise the output power decreased. This could be because at 20 psi, the best physical coupling possible for the elements in the 185/70r14 tire has already been achieved. Further increase in pressure therefore demands that bigger forces are applied to counter the additional pressure applied in the tire before gaining additional power output. As a result the rate of increase in power output with increasing tire pressure starts going down if the force is above 1062 N, otherwise the power output starts decreasing with increase in pressure. Garimella et al. [13] on an almost similar research, investigated the effect of pressure loading on PZT. They observed that when the pressure exceeded 50 kbar, the output current and hence the power dramatically decreased. They concluded that this could have resulted from internal short circuiting of the generator due to massive generation of electrical charges.

Figure 4 however suggests that though some form of short circuiting might be taking place at pressures beyond 20 psi, the occurrence affects very small isolated portions of the harvester in a gradual manner as the pressure increases. This allows forces that are big enough (above 1062 N) to continue generating higher power output with increasing pressure up to 35 psi while forces that are below this value start experiencing a decline in output with increasing tire pressure from 20 psi as shown in Figure 5

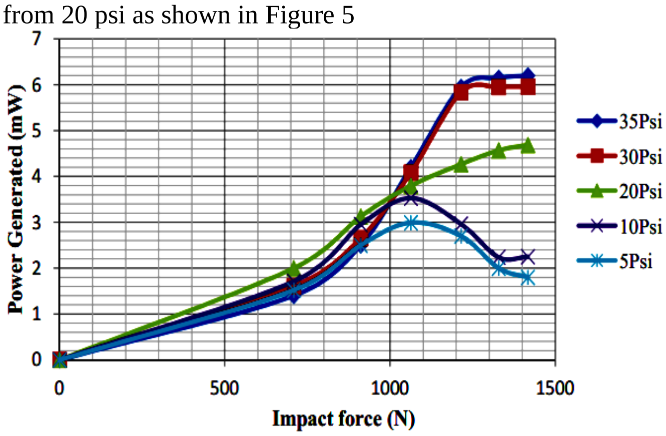

Figure 5: Effect of increasing impact force on a piezoelectric tires with inner tube

It can therefore be concluded that if the design of a 185/70r14 piezoelectric tire allocates each layer of piezoelectric discs between 1062 N and 1200 N of the force expected at the tire-road interface, then the best operation range of the tire is between 20 psi and 35 psi. The actual optimum pressure is however 30 psi.

V. VARIATION OF POWER GENERATION WITH CHANGING TIRE PRESSURE FOR 0.3 MM DISCS IN A TIRE WITHOUT AN INNER TUBE

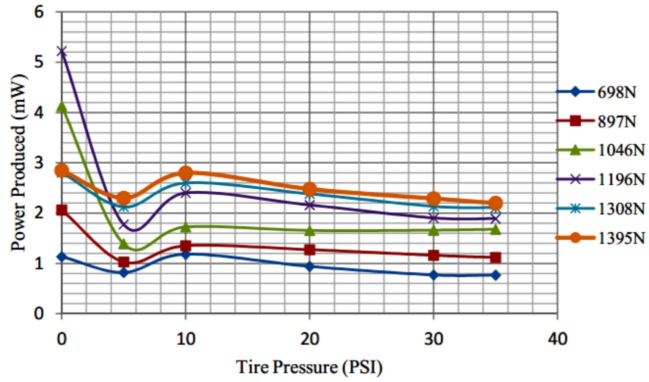

Figure 6: Power production in a pressurized tubeless tire with changing drop height

The patch as seen in Figure 6 appeared to give out highest amounts of power when the tire pressure is zero. Though it was expected that the output would increase with pressure, the observation can be attributed to the increased ease of deforming the patch considering the glued patch could easily follow the outer tire deformation without the need for supporting pressure. However at the same 0 psi tire pressure, forces above 1,196 N appear to give out less power as compared to lesser forces. This could be due to increase in non-uniformity of force distribution in the patch with the increasing impact forces. The power output then drops for pressures from 0 psi to 5 psi. The main reason for this is the increasing spring constant of the tire with the initial increase in the air inside which absorbs most of the impact. Between 5 psi and 10 psi the output increases as the rigidity of the host increases improving force transmission. After 10 psi the output however appears to continuously reduce. This could be due to the reduced deformation of the tire leading to less deformation of the patch since the holding conta glue imparts less pressure on the patch compared to an inner tube. All in all, the tire with an inner tube performs several times better than the one with contact glue when impact force is applied.

1.2. Stationary Tests for 2 mm Thick Disc

The earlier mentioned drop test was repeated with a patch composed of six pieces of 2mm thick piezoelectric discs. The performance was unexpected for two reasons

1. The electric current generated was so low that it couldn't be measured after going through the full bridge rectifier
2. The power output was less than that of the 0.3 mm thick piezoelectric elements for the same force

The poor performance in comparison to the 0.3 mm discs can however be partly explained by the research findings by Huidong et al.[12]. They found out that a thin and flat form factor allows a piezoelectric element to readily react to the motion of the host structure[12]. Thus, the piezoelectric materials used in most of the piezoelectric energy harvester designs and configurations explored to date, possess a thin-layer geometric shape. These findings encourage the idea of using several 0.3 mm disks as opposed to one thick piezoelectric element.

As shown in Figure 7, it was observed that for the 2 mm thick element in a tire with an inner tube, increase in tire pressure continuously improved the emf voltage generated. This could be attributed to the increasing efficiency in the coupling between the surface on which the tire is dropped and the element in the tire with the increasing pressure. Since the element is thicker, it also means the generated electrons require a relatively high electric potential to send them a cross the semiconductor PZT material [14].

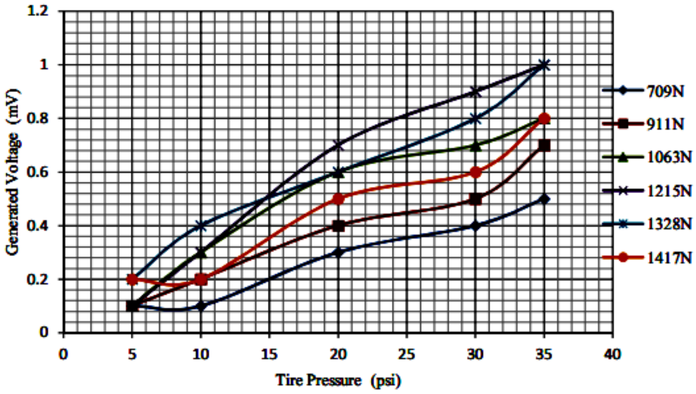

Figure 7: Power production with changing tire pressure

VI. CONCLUSION

From this study, a piezoelectric tire assembled with an inner tube produces continuously increasing power irrespective of the load size up to 20 psi. Any further increase in pressure from 20 psi is accompanied by an increase in the output only if the force at the contact point is above 1062 N, otherwise the output power decreases. The tire without an inner tube however generally gives decreasing power (from 10 psi onwards) with increase in tire pressure. There is however a slight increase in output with increasing pressure between 5 and 10 psi. From the results in this paper it can therefore be concluded that the tire with an inner tube is the best choice for power harvesting using PZT discs in any tire operating beyond 10psi tire pressure.

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