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Piezoelectric Energy Harvesting using PZT in Floor Tile Design

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ABSTRACT: Energy Harvesting has experienced significant attention from researchers over the past few years .When humans walk in surroundings, some force exerts on the surface, this force can be used to generate electricity. The idea of converting pressurized weight energy into the electrical energy is possible by piezo-electric crystal. The power generating floors can be a major application if we use piezoelectric crystals as an energy converting material. The piezoelectric crystals have crystalline structure and ability to convert the mechanical energy (stress and strain) into the electrical energy. In this paper, a new prototype of PZT based mechanical vibration energy harvester for power generating floor tile is presented. The comprehensive floor tile design and results are tabulated which gives promising results.

KEYWORDS: Energy Harvesting, Piezoelectric, Piezo, Vibration.

I.INTRODUCTION

The total world energy consumption will increase from 575 quadrillion British thermal units (Btu) in 2015 to 736 quadrillion Btu by 2040, which is an increase of 28%. Most of the world's energy growth will occur in countries outside of the Organization for Economic Cooperation and Development (OECD). Non-OECD countries in Asia (including China and India) alone accounts for more than half of the world's total increase in energy consumption over the 2015 to 2040 projection period. By 2040, energy use in non-OECD Asia exceeds that of the entire OECD by 41 quadrillion Btu [1].

With the conventional source of generation of electricity being either polluting or non reusable (example: Coal, fossil fuels etc) search for a clean, reusable source of energy has caused a spike an interest in the exploration of piezoelectricity. Mechanical vibration is a wasted energy which presents around most machines and the motion of biological systems. The idea of vibration-to-electricity conversion was proposed by Williams and Yates. In general, there are three mechanisms to harvest the electrical energy from the vibration energy: electrostatic, electromagnetic, and piezoelectric [2]. Piezoelectricity is appearance of electric potential across the sides of crystal when subjected to mechanical stress. Thus by making use of human movements, movements of automobiles, piezoelectricity can be generated to a commercially usable extent. The recent development of ultra low power microelectronic devices has led to the design of self power devices using energy harvesting techniques. Energy harvesting is a method to generate electrical power from natural (green) energy sources such as: Solar, wind, wave energy, and hydro-electricity for high power generation in megawatts whereas vibration, geothermal, light, and RF for low power generation in milliwatts.

Piezoelectricity, which originates from the Greek word "squeeze or press", describes materials in which electric charge (electricity) is generated as a result of mechanical pressure. Historically, the direct piezoelectric effects were discovered by Pierre and Jacques Curie in 1880 in generation by crystals such as quartz. Since then, piezoelectric materials have become widespread as induced-strain transducers over the last few decades [5]. The piezoelectric materials that exist naturally as quartz, which possess properties for the production of electricity in very small quantity, however, compare to quartz, an artificial piezoelectric materials such as PZT (Lead Zirconate Titanate) present advantageous characteristics of generating more electricity.With technology advancing Japan has already started experimenting use of piezoelectric effect for energy generation by installing special flooring tiles at its capitals two busiest stations [3]. Tiles are installed in front of ticket turnstiles. Thus every time a passenger steps on mats, they trigger a small vibration that can be stored as energy. Energy thus generated by single passenger multiplied by many times over by the 400,000 people who use Tokyo station on an average day, according to East Japan Railway, which generates sufficient energy to light up electronic signboards. An average person weighing 60 kg will generate only 0.1 watt in the single second required to take two steps across the tile, but when they are covering a large area of floor space and thousands of people are stepping or jumping on them, then significant amount of power can be generated. This energy created is sufficient to run automatic ticket gates and electronic displays [3].

Piezoelectricity encompasses the two kinds of linear electro-mechanical coupling: the direct piezoelectric effect and the converse piezoelectric effect as shown in Fig. 2. The direct piezoelectric effect generates an electrical charge in response to applied mechanical stress or strain. In this case, crystal structures internally develop electric polarization which is linearly proportional to mechanical stress within the limited range of deformation behavior. The converse piezoelectric effect produces mechanical strain when electrical voltage (or electrical field) is applied along a certain direction. In this paper, we are presenting a new design approach is implemented in Energy harvesting using prototype floor tile.

II.FUNDAMENTALS OF PIEZOELECTRICITY

A. Piezo Electricity

Piezoelectricity describes the conversion of mechanical energy to electrical energy or vice versa. The total mechanical stress is the sum of the mechanical stress due to the mechanical strain and the mechanical stress due to the electric field. Analogously, the total electric charge is the sum of the electric displacement due to the mechanical strain and the electrical displacement due to the applied electrical field. This relationship is summarized in Equations below.

$$T = C^E.S - e^T.E \qquad \text{eq. (1)}$$

$$\mathrm{D} = \mathrm{e.S} + \in^S.E \qquad \text{eq. (2)}$$

$$S = S^E.T - d^T.E \qquad \text{eq. (3)}$$

$$\mathrm{D} = \mathrm{d.T} + \in^T.E \qquad \text{eq. (4)}$$

$$\text{Where } e = d.S^{E-1} \quad \text{and} \quad \in^S = \in^T - d.S^{E-1}.d^T$$

Alternative forms of piezoelectric constitutive equations are summarized below:

Strain-Voltage form:

$$S = S^D.T - g^T.D \qquad \text{eq. (5)}$$

$$E = -g.T + \in^{T-1}.D \qquad \text{eq. (6)}$$

$$S^D = S^E - d^T.\in^{T-1} \quad \text{and } \mathrm{g} = \in_{T=0}^{-1}.\mathrm{d} \qquad \text{eq. (7)}$$

Stress-Voltage form:

$$\mathrm{T} = c^D.S - h^T.D \qquad \text{eq. (8)}$$

$$\mathrm{E} = -\mathrm{h.S} + \in^{S-1}.\mathrm{D} \qquad \text{eq. (9)}$$

Here T is mechanical stress vector component, S is mechanical strain vector, D is the dielectric displacement matrix, E is the electric field matrix, C is the young's modulus matrix ,s is the compliance co-efficient matrix ,ε is the dielectric permittivity matrix ,d is piezo strain co-efficient matrix , e is the piezo strain constant matrix ,g is the piezo strain voltage constant matrix, h is the stress voltage constant matrix. If T=0,it is the value taken at constant stress , if S=0,it is the value taken at constant strain and if E=0,it is the value taken at constant electric field.

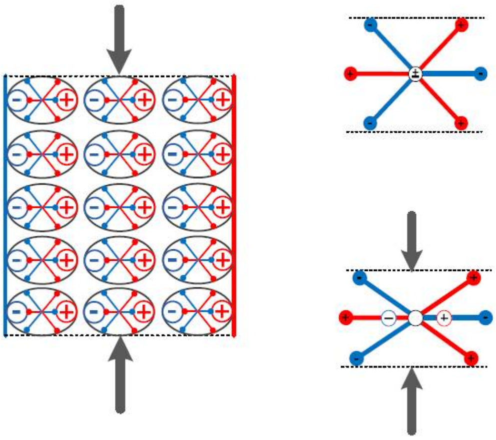


Fig. 1: Simplified Molecule Structure Before mechanical stress (upper right), after mechanical stress (lower right)

Fig. 1 shows Simplified molecule structure before and after mechanical stress is applied. The piezoelectric strain constant measures the strength of coupling between mechanical and electrical fields. This constant is generally defined as the ratio of the strain developed in the j-axis to the electric field applied in the normal direction along the electrode of i-axis. eq. (10) represents the fact that the large piezoelectric constant results in large deformation when the generated voltage is applied [5]

$$d_{ij} = \frac{Mechanical\ Strain}{Applied\ Electric\ Field} = \frac{m}{v} \qquad \text{eq. (10)}$$

B. Piezo Electric Sensor

A piezoelectric sensor is a device that uses the piezoelectric effect to measure pressure, acceleration, strain or force by converting them to an electrical signal. A piezoelectric transducer has very high DC output impedance and can be modeled as a proportional voltage source and filter network. The voltage *V* at the source is directly proportional to the applied force, pressure, or strain. The output signal is then related to this mechanical force as if it had passed through the equivalent circuit. The piezoelectric effect exists in two domains as shown in Fig. 2

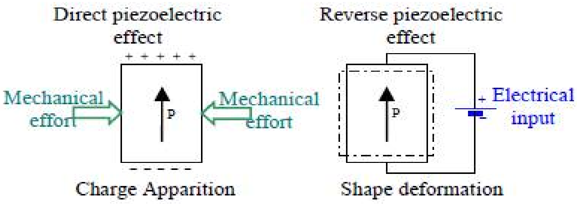


Fig. 2: Effects of Piezo

III.LITERATURE SURVEY

With the increase in energy consumption due to ever growing number of electronic devices, the concept of harvesting renewable energy in human surrounding arouses a renewed interest. In this context, this paper highlighted use of piezoelectricity and its generation. Energy harvesting, as opposed to the vibration absorbers, often employ electrical shunt systems across piezo structure to capture and store energy. These circuits have some characteristics of vibration absorbing in that they collect strain energy of the structure. Sometimes, this effect is called shunt damping. Electrical shunt circuits always induce some damping into the structure, which decreases the amount of vibration

The piezoelectricity of PVDF was first observed and described by H. Kawai in 1969. In their investigations the dynamic compression of parquet floors, is presented. The piezoelectric foil material for this approach is a mono-axial stretched fluoropolymer PVDF (Polyvinylidene fluoride). This type of PVDF has an amorphous phase with partly crystalline areas which could be piezoelectric. In [4] PZT have been investigated experimentally and numerically. A different electric generation characteristic was further observed depending on the stress conditions: generation of positive and negative electric voltage. Here PZT ceramic was subjected to mainly compressive and tensile stress, respectively.

In [8] describes a Quickpack QP20W which is used as the piezoelectric energy source and a full wave bridge rectifier circuit is used in harvesting energy. This paper propelled our idea of using full wave bridge rectifier circuit in harvesting circuit and further carry out experiment with piezo discs. In [9] energy harvesting from floor is described as a sustainable method to generate electrical energy. Design, fabrication and test of organic piezoelectric harvesting modules consisting of a polymeric thin film of PVDF is discussed. The Harvesting modules are built up as roller-type capacitors. In [10] a harvesting floor is designed with piezoelectric material, which can convert extra energy of walking motion into electrical energy. The generated electricity is then used to drive a wireless transmitter module to detect user's current position as shown in Fig. 3.

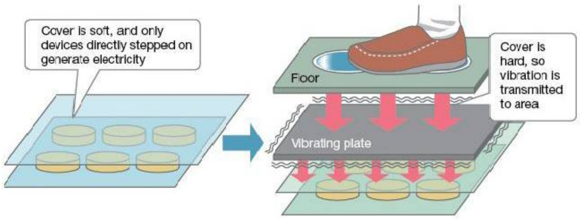


Fig. 3: Special Flooring Tiles with Piezoelectric Crystals.

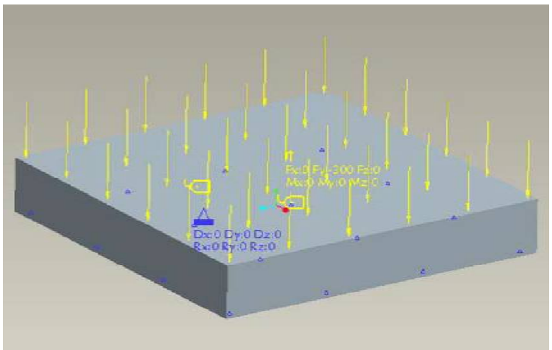
In [11], potential application of a commercial piezoelectric energy harvester is presented. The modelling results indicated that the total annual energy harvesting potential for the proposed optimized tile pavement model is estimated at 1.1 MW h/year.

In [12] paper presents designing of a low voltage energy harvesting circuits for generating rectified voltage into storage devices using vibrating piezoelectric element. A technique (i.e., DC-DC Step-Down converter) is chosen for designing the low-power circuit with low voltage energy

IV.ENERGY HARVESTING FLOOR TILE DESIGN

A. Tile Design

The tile went through various changes and improvements. The design of the floor tile as well as the setting up of the stress test was set up using Pro engineer. From the Fig. 4 below a 300 pound distributed load was placed on the tile. Once the tile set up was designed using Pro Engineer, Ansys was used to solve the system and evaluate the results as shown in Fig. 5. These results let us evaluate which areas of the tile would be affected most by the weight of a person being applied to it.



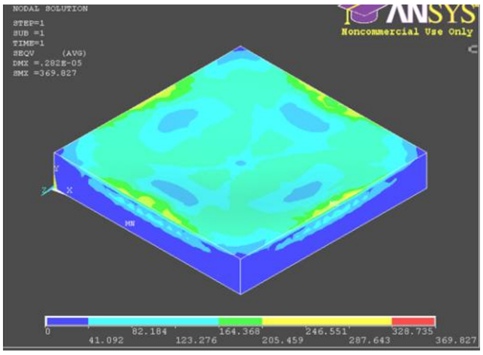


Fig. 4: Load Placed on Tile: FEM Analysis

Fig. 5: Evaluation of Result using Ansys

An FEM analysis was performed using Pro Engineer changing variables such as loading, constraint locations, wall thickness, material choices, and different casing dsetups. The model to the right went through multiple iterations with the different variables after testing several variables the maximum stress achieved was 2400 psi with a dimension of 22x14 inches. Based on the maximum stress the team concluded any of the proposed materials could be used: Aluminium, Wood, Steel, PVC, or polycarbonate plastic (Lexan).

B. Material Selection

In this work we are using PZT (3B35+2.6EE) because of the availability of disc in India. The PZT ceramic has been employed widely for buzzers and ultrasonic sensors. The nominal grain size of this PZT is about 1 mm. The PZT ceramic is formed with dimensions of ϕ9.0 mm x 0.12 mm, which is attached to a thin brass plate (ϕ12.0 mm x 0.10 mm) as shown in Fig. 6.

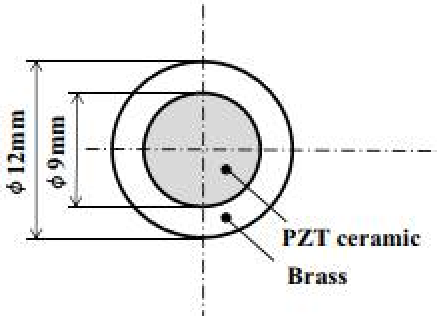


Fig. 6: PZT ceramic plate for investigation of electric power generation

Table 1: Typical piezoelectric materials coefficients

SL.No.	Material	d33 = 560 (10^{-12} C / N)
1	Quartz	2.3
2	$BaTiO_3$	90
3	$PbTiO_3$	120
4	PZT	560
5	PZN-9PT	2500

For the PZT, d33 = 560 (10^{-12} C/N) means that when1 Newton force is applied, the strain produces 560 x10^{-12} C electrical charge.It is the property of certain crystalline substances to generate electrical charges on the application of mechanical stress. A force is applied along a neutral axis (y) of a crystal and the charges are generated along the (x) direction, perpendicular to the line of force. The amount of charge depends on the geometrical dimensions of the respective piezoelectric element and the pressure applied.

V. RESULTS AND DISCUSSION

In the design 54 Piezo discs 3B65+FA are incorporated .Peizo plates or piezo stacks would have derived maximum output , but to minimize the cost and owing to availability, Piezo discs are adopted. To utilize maximum available peak voltage generated from piezo discs, full wave bridge rectifier circuit is used. Diode IN4148 is adopted which is a high signal frequency diode. It has the advantage of rectifying at all frequencies and less voltage drop as compared to diode IN4007. The selection of capacitor bank was essential in the final circuit design. The Peak voltage generated from the Piezo disc multiplied by a factor of two will give the voltage rating of capacitor. If the capacitors are connected parallel, it will add up to capacitance value, but voltage will remain same. Vice versa capacitors connected in series will add up the voltage where as capacitance will remain same. Initially low capacitance value of 10µF, 25V were used in rectifier circuit to check whether charges are stored in capacitor using 4 piezo discs. On getting satisfactory result that 10µF capacitor is holding charge, we started using higher capacitor value such as 47µF, 100µF, 1000µ, 2200µF, 4700µF. All capacitors from each rectifier is connected in series and then in parallel. Charge holding capacity in higher value capacitor is more and discharging time is more. It should be noted that, charge holding capacity of the capacitor bank should be more than that of battery, only then battery gets charged. Impendence matching should be there between piezo discs capacitor. If this is achieved then maximum power can be transferred. Here we have used Lead acid battery.

The Fig. 7 Shows the final design of the work. Initially Piezo discs were sandwiched between sponge and rubber and the outcome of the design was studied. However, instead of spring and sponge, high density foam was adopted after analysis. Sandwiched Piezo disc with foam is housed inside wooden box. Due to high rate of deformation and expansion of foam sufficient vibration was achieved hence more charges was produced by piezo discs due to the foot strike on the wooden plank tile. The complete set up of the design is shown in Fig. 8.

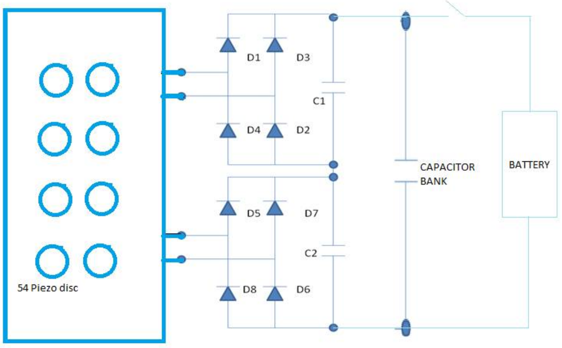


Fig. 7: Final Circuit design

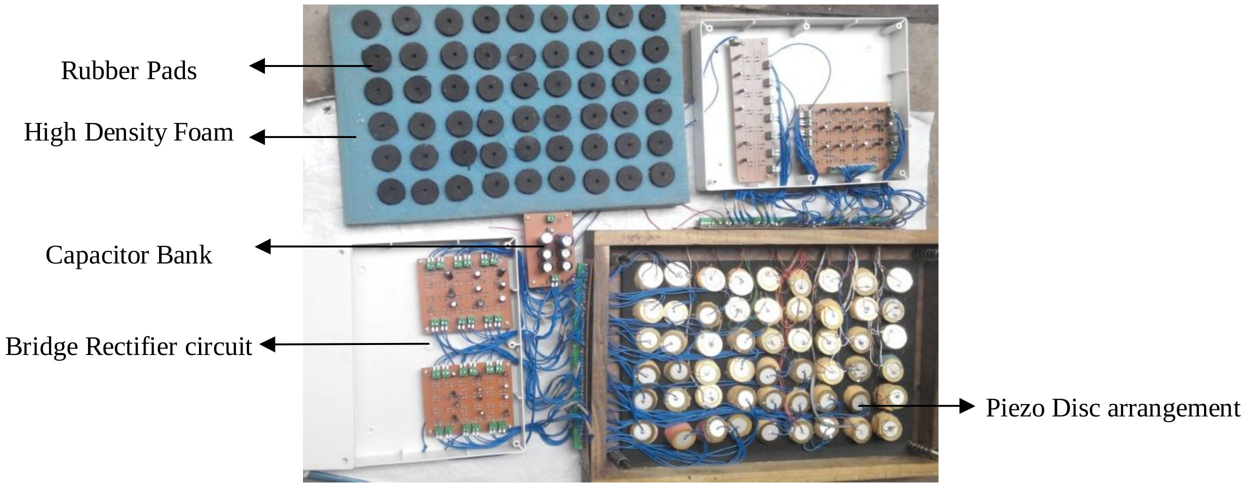


Fig .8: Final Module inside section

The mathematical analysis was performed to test the efficiency of the design.Since pressure is directly proportional to amount of power generated

$$P \alpha Wt \qquad \text{eq. (11)}$$

Here we take the constant proportionality as ‘K’, then equation becomes

$$P \alpha KWt \qquad \text{eq. (12)}$$

Where, K=Constant Proportionality, Wt-weight, P-power

For the verification of results, let us assume a case for wt=50kg,
We get the value of voltage V=4V and I =0.015A

$$\text{Power } P= V*I \qquad \text{eq. (13)}$$

$$= 4*0.015=\mathbf{0.06W}$$

Which means we can say that for 50kg we get power (P) =0.06W from this we can find the value of ‘K’

$$K = P/Wt \text{ from eq. (12)}$$

$$K = 0.06/50= \mathbf{0.0012}$$

The Table 2 shows relation between pressure and weight. For the final Floor tile dimensions of 22*14 inches the results is as shown in Table 3

Table 2: Comparison of results for different pressure and weight

SL No.	P in Watts	Wt in kg
1	0.012	10
2	0.024	20
3	0.06	50
4	0.09	75

Table 3: Final Floor Design result

SL.No.	No. of disc connected	Capacitor used at the output	Charging time in mins (upto 5.75V)	Discharging time in mins (upto 2V)
1	54	9500 µf, max 63V	90	30

Analyzing the results, use of PZT discs gave promising results which can be utilised for mass production and mass generation of energy. For more efficient output piezo strips and piezo stacks can be incorporated or material made with PZN-9PT.Ideal capacitor should be used for higher charging rate and high performance low power rectifiers could be used as an alternative.

VI.CONCLUSION

As a whole the team felt that we achieved the objectives set forth at the beginning of this design process. Through literature survey we came to know how ambient energy can be converted to electrical energy and then be used to supply a corresponding consumer under specific conditions using peizo electric material. There is no general energy harvesting solution that serves all purposes. The design of the piezoelectric floor tile, the electronics and the kind of excitation used substantially determine the outcome and need to be matched individually for a certain task. Though the output drawn may be minimum, it can be designed to harvest power in busy locations .The team feels the Piezo films can be used as a layer in road and the energy derived can be used for street lighting and other specific purpose in country like India where the potential of energy harvesting is more.

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