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Piezoelectric Effect: Smart roads in green energy harvesting

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Abstract— **The following piece is intended to take you away from the present scenarios of energy crisis and falling resources for sometime. It opens the doors of opportunities to the much dreamt greener future. Piezoelectricity, a centuries old discovery, and it was still buried under grounds of doubt and inefficiency. But the recent advents in the field of electronics and allied streams of electricity harnessing and storage technology have made it possible to capture the energy that always went unnoticed so far. Energy that is in fact invisible- energy that can be triggered by applying pressure on some specific substances, with pressures varying from that due to the flick of a finger to the landing of heavy aircrafts. Thus, making the Piezo-effect a very utilitarian concept. Recent developments in different parts of the world have shown how much impressive this new technology is. Piezo-tiles are now increasingly used in places ranging from train stations to dance floors, making them self-sustained units in terms of energy and costs. The following research successfully highlights how such pressure switches can be deployed in the airports too. Using some standard data and assumptions, the yearly average electricity produced and running costs are calculated. What is more interesting to observe is, when the energy savings outweigh the initial investments in a matter of just 10 years, let alone the crores of money to be saved in the years to come, gallons of fossil fuels and the thousands of flowers that will blossom in a much cleaner air. The following will explain the science of piezoelectricity and how it can be put into the desired uses. Piezoelectricity can become a very reliable form of energy with proper optimistic advances in the field of research. As humans, we have only taken from the nature so far. It is time to replenish and refurbish, and to re-darken the fading line of ecological balance. This can only be made possible through newer ventures in green energy. For whom only sparks have been enough to produce what not, let this spark lead to greener strides in the world of energy.**

Index Terms— **crystal structure, eco-friendly, high pressure, piezoelectricity, stacked structure, surface charge density.**

I. PIEZOELECTRIC EFFECT

The *Piezoelectric effect* was first discovered in 1880 by the brothers Pierre and Jacques Curie. This two French physicists, discovered that piezoelectric materials can produce electricity. They discovered that when *certain crystalline minerals are subjected to a mechanical force, the crystals became electrically polarized*. Shortly later, the French Gabriel Jonas Lippmann discovered the converse effect; how certain materials physically change when a charge is applied.

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Despite these exciting discoveries, it wasn't until the early twentieth century that practical devices began to appear. Today it is known that many natural materials like Quartz, Topaz, Rochelle salt & synthetic materials as PZT have this effect.

"Piezo" means pressure in Greek language. *Piezoelectricity is the relation between pressure (or mechanical stress) and electrical voltage*. When a force is applied on a piezoelectric material, this results in the development of a charge in this material. The activating force can be caused by deforming its crystal lattice without fracturing its structure. When there is no applied stress, the material is in balance and the positive and negative charges are evenly distributed. During the application of force, the lattice of the piezoelectric material is changed slightly, whereby a charge imbalance is created, which results in a potential difference. This resulting voltage, can be as high as several thousand volts. Since the current is extremely small, the generated power is also limited. The electrical polarization of the material & the resulting voltage, are in proportion to the applied force. Tension and compression generated voltages of opposite polarity. This principle, of creating a charge difference in response to applied stress, is known as the *direct piezoelectric effect*.

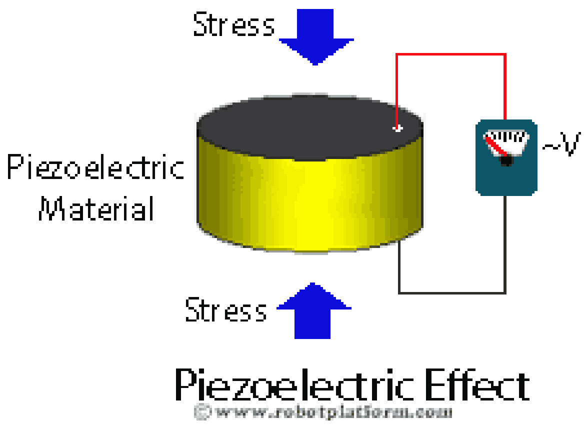

Fig 1.1 A simplified graphical representation of the mechanism of the direct piezoelectric effect

The process whereby the piezoelectric effect takes place is based on the fundamental structure of a crystal lattice. Crystals generally have a charge balance where negative and positive charges precisely nullify each other out along the rigid planes of the crystal lattice. When this charge balance is disrupted by an external force, such as, applying physical stress to a crystal, the energy is transferred by electric charge carriers, creating a surface charge density, which can be collected via electrodes.

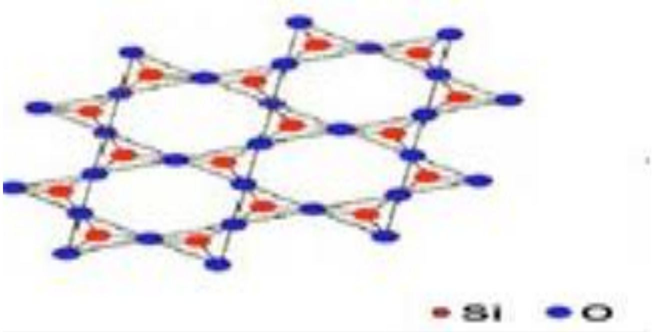

Figure 1.2 Crystal structure of Quartz

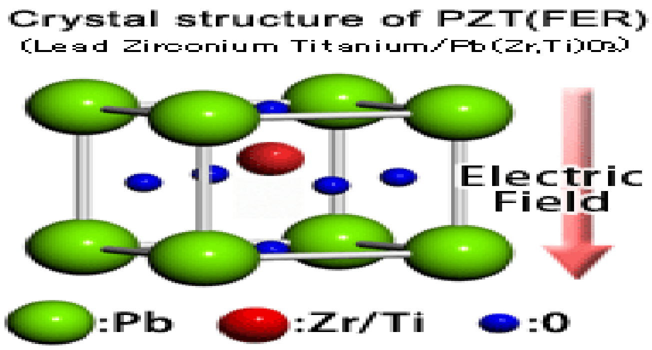

Fig 1.3 Crystal structure of Lead zirconate titanate (PZT)

II. PIEZOELECTRIC MATERIALS

A wide range of materials is available for the use in piezoelectric devices. The important criteria behind the selection of a material are *Piezoelectric Voltage Constant*, availability & productivity, cost effectiveness, sustainability. Considering the above mentioned factors Quartz is as most suitable which can be reclaimed most easily and is also abundant on earth's surface. Lead zirconate titanate (PZT) is also considered as one of the most economical piezoelectric materials because it is physically strong, chemically inert and relatively inexpensive to manufacture. Plus, it be easily tailored to meet the requirements of a specific purpose. PZT ceramic is revered because it has an even greater sensitivity, a

high piezoelectric charge constant (d_{33}); a higher mechanical quality factor that reduces mechanical loss, a low dissipation factor that ensures cooler, more economical operation; high dielectric stability; and low mechanical loss under demanding conditions, a higher operating temperature than other Piezo ceramics. Piezoelectric materials are generally utilized for applications where there is a low power requirement. They include portable electronic devices such as mp3 players, mobile phones, GPS receivers or sensors of remote sensing systems or transmitters which are conventionally powered by batteries. The amount of pressure required for distortion of a piezoelectric ceramic element by 0.05mm can generate nearly 100 kV, however the electric current generated is of the order of mA to µA. Key factors involved in the amount of energy produced by a piezoelectric material have to do with the stress on the element, which is the ratio of the applied force to the surface area of the element. When the composition of the ceramic, the volume of the ceramic element, and the applied force are constant, the element that has the smallest surface area will generate the most electrical energy. Very high amounts of electric energy are obtainable with piezoelectric elements when the amount of stress applied to it is very high or very frequent. For example, a 2 kN force properly applied to a cubic-centimeter sized quartz crystal produces over 12.5 kV. The amount of energy will increase linearly with the amount of stress applied to it, so the more pressure there is on the piezoelectric material, the more power will be generated.

III. CONCURRENT APPLICATIONS

The most primitive example of an application of Piezoelectricity is a *BBQ lighter*, the popping noise which is heard when depressing the lighter button is a little spring-loaded hammer hitting a crystal and generating thousands of volts across the faces of the crystal. A voltage this high is identical to the voltage that drives a spark plug in a gasoline engine. The crystal's voltage can generate a nice spark that lights the gas in the grill.

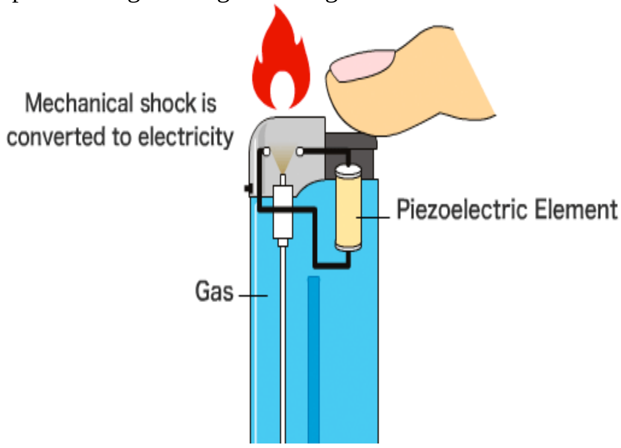

Fig 3.1 Application of Piezoelectricity in a Cigarette Lighter

Fig 3.2 Piezoelectric tiles embedded floor at Tokyo Station

Club Watt in Rotterdam, The Netherlands utilizes a spring-loaded flooring system of independently moving tiles. Inhabitant claims that each tile can compress up to 2cm, activating a flywheel mechanism which powers a small electrical generator. It also claims that LEDs embedded in the floor are sustained entirely by the approximately 20 watt generated by each dancer. The owner is said to have paid $257,000 for the 270 square foot floor. While he does not expect to recoup his investment through energy generation, he expects to recover 10% of the club's electrical requirements through the flooring system. Engadget covered a similar club in the United Kingdom. Named Club4Climate, it utilizes piezoelectric materials in the flooring to generate higher amounts of electricity. Harvesting power from the dancers, the energy is stored in batteries, which are emptied into the grid to help directly offset the costs of electricity usage. Mail Online cited the owner, Mr. Charalambous, claiming that vigorous dancing could generate as much as 60% of the energy needs for the club.

Fig 3.3 Dance Floor installed with Piezoelectric Crystals in WATT club, Netherlands

The East Japan Railway Company (JR East) conducted a demonstration experiment from January 19 to March 7, 2008, at Yaesu North Gate, Tokyo Station, on a new power-generating floor. Installed at the ticket gate area, it generates electricity from the vibrations created by passengers walking through the ticket gates. The power-generating floor is embedded with piezoelectric elements, which are 35 millimeters in diameter, and disc-shaped components used for loudspeakers. It uses 600 of these elements per square meter. While the loudspeaker creates sound by converting electric signals to vibrations, the floor adopts the reverse mechanism that produces electricity by harnessing the vibrational power generated from passengers' steps. It is being developed by JR East with the aim of making stations more environmentally friendly and energy efficient (Japan for Sustainability, 2008). JR East has been trialing these systems for the past year. They have recently improved and expanded the system by changing the floor covering from rubber to stone tiles, and have improved the layout of the mechanisms to improve energy generation. The total amount of floor-space will add up to around 25 square meters, and they expect to obtain over 1,400 kW per day – more than sufficient to power their systems.

IV. POTENTIAL SCENARIOS FOR LARGE-SCALEGENERATION OF ELECRICAL POWER FROM PIEZOELECTRICITY: 'MAKE IN INDIA'

A. Highways

Motor vehicles are in today's society one of the most indispensable means of transportation, it is very convenient & flexible. The density of motor vehicle ownership per capita is escalating in a rapid rate in our country. The number of motor vehicles is significant on the road, every day which generates million joules of mechanical energy which is wasted in form of heat energy which should not be underestimated. Traffic at roads and highways varies throughout the day, with more traffic during the day than at night, and in certain time durations throughout the day. By incorporating piezoelectric generators in the roads we can convert the vibrations caused by the vehicles into useful electricity. Present day the most commercial ones are asphalt roads (Tar road) on which thousands of vehicles run on it. At first the first layer is laid with fine gravel and sand content. Then a thin layer of asphalt is laid which acts like a strong base for the generators. Piezoelectric generators are placed in quick drying concrete as per design and left for 30min. Then all the generators are wired in series to get collective output. A bitumen sheet is used to cover all the generators to provide better adhesion of concrete to asphalt. Finally a thick layer of asphalt is laid which finishes the construction. Recent experimentations carried out by Innowattech in Israel, consists of putting IPEG (Innowattech Piezoelectric Electric Generators) 6cm under the road level and at a distance of 30cm apart, the piezoelectric system being covered by a layer of asphalt. From these trials, it has been seen that a truck weighing at around 5 tons can generate 2000 V, and a 1 km stretch of generators along a dual carriageway (assuming 600 vehicles go through that road segment in an hour), can generate about 200 kWh, enough energy to power 600-800 homes. Similar method we have adopted for in country India. We have considered the Outer Ring Road project of Hyderabad to compare. The overall budget of this project is 6700 Crores. In this 8 lane road of 158km stretch, if a piezoelectric road is laid, the overall cost & energy generation scenario has been outlined below :-

Supplied Data: -
Generator size: 1 Square feet
Cost of one generator = Rs.2000
No of generator needed = 3280 (for 1km of road.)

So, Total Cost estimation for that 8 lane road of 158 km stretch = 800 Crores. The overall budget becomes 7500 Crores which is about 12% increase in overall budget. Every year 12000 (Average) Kwh can be generated in one km single lane road. So if we calculate for the considered road total energy generated = 158km x 8 lane x 1,20,000 Kwh = 15,16,80000 Kwh can be generated. In general, Govt. of India charge Rs.5.50 on an average per 1Kwh, so total electricity bill worth of Rs.80 Crores can be saved. By this means, the amount invested on this road returns in just around than 10 yrs. The average life of this piezoelectric road is 30 years so the income generated in the next 20 years would be a profit. The most beneficial sides of this projects are green solution for power generation, minimization of centralization of power, reaching to the even most remote & undeveloped areas, minimization of dependence on thermal electricity. The only disadvantage is that the maintenance of these roads is a bit difficult and constant inspections are to be made.

Fig 4.1 Outer Ring Road project of Hyderabad

B. Runways

Airports in India are vital transportation hubs that will greatly benefit from new energy technologies. Lower costs along with cleaner day-to-day operations with green forms of energy shall allow airports in India to operate more efficiently and effectively. Furthermore, implementing these technologies at airports would have an added benefit of improved relationships with airport neighbours; the green technology used at the airports would set an example for the surrounding communities and would show that airports are concerned about the environmental impact that they have on the surrounding areas. When an aircraft takes off or lands, a massive amount of pressure is exerted on the runway, which is equivalent to the take-off weight of the aircraft. The huge amount of mechanical energy involved can be converted by placing an arrangement of piezoelectric materials at a certain distance below the runway. This arrangement will act as a form of piezoelectric generator, and the efficiency can be increased with a stacked structure, which consists of many layers of piezoelectric materials and are suitable for handling a large force and collecting a huge amount of charge. Piezoelectricity could also be harnessed from high traffic areas such as the check-in station, these areas often have large lines of passengers waiting to check in baggage and obtain boarding passes. Piezo devices could also be installed under the baggage weighing scales in the check-in areas to harness the energy from placing luggage on these platforms. Another high traffic area is the security line; the Piezo devices could be located under the floors along these lines to capture the foot traffic in these lines. Concession areas and advertising signs would also benefit from having the power-generating floor. Billboards could be light up by people passing by and lighting in the concession areas could be partially powered by the flooring. Similar method we have adopted in our country India. We have considered the New Delhi Indira Gandhi International Airport to compare. A vivid calculation (using some available data & making some assumptions) to estimate the energy generation per year due to piezoelectric energy harvesting from Airport's runways has been the central idea of our study. It is presented below:-

***Supplied Data**: -*

Piezoelectric material considered is: PZT-5H
Mass of average commercial aircraft: 100,000 Kg
Landing velocity of aircraft: 140 $Km\cdot h^{-1} \approx 40\ m\cdot s^{-1}$
Dimensions of tire: mean diameter = 0.96 m, width = 0.36 m,
Piezoelectric charge coefficient (d_{33}) = $560 * 10^{-12}\ C\cdot N^{-1}$
Volume of one Crystal plate = 1 m^3
No. of aircraft landing on one Average aviation day = 500

Formula for *direct Piezoelectric effect:* - $D = d_{33} * T$

where D = Electrical Surface Charge Density, T = Applied Mechanical stress.

So, the momentum of the aircraft when it is about to land = 100000 ∗ 40 = 4000000 $Kg\cdot m\cdot s^{-1}$. The change in momentum is the initial momentum as it turns to almost zero immediately when the aircraft touches down onto the runway. An assumption had been made as the time of which the aircraft reaches 140 $km\cdot h^{-1}$ ($\approx 40 m\cdot s^{-1}$) is unknown; therefore an assumption has been made as the time period is very close to zero yet not quite zero. An assumption of an aircraft takes half a second to change its momentum from 4x 10^6 to zero, is used.

∴ Impulse generated = $4 * 10^6 / 0.5 = 8 * 10^6\ kg\cdot m\cdot s^{-2}$, through this calculation of the impulse, we know that the force the aircraft exerts on the Runway is 8 x 10^6 N.

The total area in contact with the ground (due to 4 tires) = $\pi * 0.96 * 0.36 * 0.15 * 4 = 0.65\ m^2$, because only 15% of the aircraft tire touches ground during landing.

∴ The pressure generated (or stress, T) = $8*10^6 / 0.65 = 12.3 * 10^6$ Pa = 0.0123 Gpa

∴ Therefore Surface Charge Density, D = $d_{33} * T$

$= 560 * 10^{-12} * 12.3 * 10^6$

$= 6.89 * 10^{-3}\ C\cdot m^{-2}$

For simplicity of calculation, the amount of time for the electricity to be generated is taken as one second hence, Charge= Current flow.

According to the assumed facts, the amount of voltage generated from a single aircraft landing would be approximately 100 kV, but depolarization occurs at 20-30% of the specified range so the voltage of 20 kV has taken for power generation condition.

Hence Power generated $= 6.89 * 10^{-3} * 20000 = 138$ W

Therefore 138 W is the amount of energy an aircraft can generate by landing on a one meter cubed of piezoelectric crystal plate.
Using the number of aircraft landings at the Indira Gandhi International Airport (500), a rough estimation of the amount of energy that can be generated on an *Average Aviation Day* is: 138∗500 = 69000 W = 69 MW, which in turn generates energy (per year) = 25,000 MW.

At present Piezo-generators have efficiency around 30% in micro scale which can be hovering around 20% for large scale power generation. Assuming that said efficiency of energy harvesting system, energy generated on a yearly basis could be 25000 $*$ .20 = 5000 MW, which should supplement the power requirement of around 15000 households outside the airport, as per average electricity consumption in India per household on a yearly basis.

Fig 4.2 Indira Gandhi International Airport runway 11/29, 4,430 m × 60 m with CAT IIIB instrument landing system (ILS) on both sides

V. CONCLUSION

The recent emphasis on eco-friendly sources of energy has opened new horizons for the global energy market. Piezoelectricity offers a viable alternative to conventional fossil fuels. It is relatively inexpensive and easy to install, and recycles otherwise wasteful forms of energy. However, it should be mentioned that the scenarios presented here are an approximation, and current experiments have shown that although large amounts of energy can be generated, the full amount cannot be used. The efficiency is low, in the range of 20-30%. Further work in this field is required to find out more efficient methods of utilization. With further advancement in field of electronics, better synthesized piezoelectric crystals and better selection of place of installations, more electricity can be generated and it can be viewed as the next promising source for generating electricity.

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REFERENCES

[1] Piezoelectricity. Retrieved March 13, 2011, from Wikipedia: http://en.wikipedia.org/wiki/Piezoelectricity

[2] Yang, J. (2005). *An Introduction to the Theory of Piezoelectricity*. New York: Springer Science + Business Media. Inc.

[3] http://www.innowattech.co.il

[4] http://www.nationmaster.com

[5] Halse, A. (2008, October 2). *The World's First Sustainable Dance Club Opens in Rotterdam*. Retrieved from Inhabitat: http://www.inhabitat.com/2008/10/02/sustainable-dance-club-opens-in-Rotterdam/

[6] How Stuff Works. (2000, May 18). *How Does The Lighter in a BBQ Grill Work?* Retrieved November 30, 2008,

[7] Japan for Sustainability. (2008, May 9). *Power Generating Floor Tested at JR Tokyo Train Station*. Retrieved November 30, 2008, from http://www.japanfs.org/en/pages/027023.html

[8] CIA World Fact book

[9] "Flight Radial Details." *Goodyear Aviation Tires*. Web. 03 Aug. 2011.

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