ENERGY HARVESTING USING PIEZOELECTRIC PLATES IN LEAF SPRING

Sanjana Mann¹, Isha Garg², Arushi Singh³, Preetika Verma⁴, Ravinder Kumar⁵

¹Wz 37B Janak Park Hari Nagar, New Delhi-64, India
²G-3 Type 5(B) Hudco Place Extn. Andrews Ganj, New Delhi, India
³House No. 4, Vyas Kunj Appartments, Dwarka Sector 11, New Delhi-110075
⁴B-2 U.G Freedom Fighters Enclave Neb Sarai Igun Road, New Delhi - 110068
⁵MAE Department, IGDTUW, Kashmere Gate, New Delhi-110006

mannsanjana@gmail.com

ABSTRACT

This paper is designed to lay emphasis on a regenerative form of power generation. A conventional leaf spring is taken and its plates are replaced with piezoelectric plates in order to convert vibrational energy obtained from unevenness and bumps on the road into electrical energy to feed the battery. The plates are replaced alternatively to ensure that the overall structural integrity of the model is not affected negatively. The model is created in SolidWorks and static evaluation is carried out in ANSYS. The stress acting on each piezoelectric leaf is obtained. The stress so obtained is used to calculate input AC voltage for each plate and this voltage is used to estimate DC voltage and DC current using NI MULTISUM software. The procedure is repeated with varying the basic parameters like the thickness of plates and the number of plates to find the optimal case in which maximum voltage generation is observed. Further, the time required to charge the on-board lead battery and the auxiliary battery is calculated. The project aims to find out the optimal case for an Indian road scenario, which will be able to feed the on-board battery of an E-rickshaw to enhance its average running time.

Keywords: Piezoelectric, leaf spring, power generation, PVDF, energy harvesting

1. Introduction

With depleting fuel reserves and increasing population, it is necessary for humans to find novel power generation methods or to make the existing ones more efficient. One such material is piezoelectric which generates an electric charge when a load is applied. Out of the many possibilities this can have, one way to overcome this challenge is by making our vehicles more efficient. Energy harvesting in Electric vehicles could make use of piezoelectric material and generate electric current when the vehicle is running and even when the vehicle is at rest. The electric charge generated by the
piezoelectric material can further be used to charge the battery of E-vehicle resulting in better ecological performance through optimization. Our research aims to find solutions to what impact on voltage will be there when the leaf spring orientation i.e. no. of plates and thickness is varied and henceforth the manipulation of the voltage is done to charge a battery.

2. Literature review

Mohibb E Hussain Jamadar and Dr. B. S. Manjunath (2016) studied a leaf spring incorporated with piezoelectric material to find the voltage generated. Static analysis was done on the modified leaf spring to find the ability to withstand stress for a four-wheeler vehicle under typical road conditions. The voltage generated was enough to charge a cell phone battery in 15 hours, but at the same time, the stiffness and comfortability of the vehicle were compromised.

Zhoetal (2019) designed a harvester which converted the vibrations developed in piezoelectric material to electric energy. He used a dual-mass suspension system of an electric vehicle to see the extent of energy potential under different conditions. These conditions included random and pulse excitations. Harvested power was found to be 18.83W in the case of random road and 102.24W in the case of pulse road.

Yang H, Wang L, Zhou B, Zhao Q (2018) experimented by applying a piezoelectric energy harvester (PEH) in the road which could generate energy enough to light a LED signboards. The testing site consists of prefabricated PEH which had piezoelectric crystals, circuits, and packaging to seal the circuit. The Toyota SUV ran over the road at different speeds varying from 20-80 km/hr and generated a voltage of around 250V to 400V sufficient enough to light up the sign. The PEH installed converted the wasted mechanical energy into utilized electrical energy.

Antonino Proto, Karel Vlach, Silvia Conforto, Vladimir Kasik (2017) a PVDF transducer was used to utilize human movements. The transducer was placed in 4 main parts of the bodysuit worn by the person whose movements were tracked. The placement of the transducer was at elbows, shoulder, knees, and ankle. The power generated by movement up down the stairs, running, and walking was of range 0.1 to 10 microwatt.

Hiba Najini and Senthil Arunugam Muthukumaraswamy (2017) presented a paper on energy generated from vehicle traffic using piezoelectric material along with a Techno-economic assessment. Simulation of generated power was done on MATLAB-Simulink. A piezoelectric transducer implanted 5cm below the asphalt road surface was used to convert the kinetic energy from the traffic into a usable form of DC power for average speeds of 60, 80, 100, 120 kmph. Further, the economic analysis revealed that the system could be used in developed countries a yearlong loan with AED 550,000 and an interest rate of 7%.

Ratnesh Srivastava, Navneet Tiwari, Abhishek Kumar, Debojoyti Sen (2017) devised an economical and easy to implement a model of a footstep piezoelectric energy harvester. The model harvests mechanical and vibrational energy by a piezoelectric disc. This energy is used to extend the operation life of common portable electronic devices.

In contrast to a conventional energy harvesting system which simplifies the energy harvesting circuit into a simple resistor or a combination of linear elements, Daniel Motter, Jairo Vinicius Lavarda, Felipe Aguiar Dias, and Samuel da Silva (2012) provided a comprehensive study for the energy harvesting system describing the chosen capacitance and resistive loads. Experimental and theoretical results are compared for a non-parametric model of a cantilever beam having electrodes of piezoceramic layers connected to a standard rectifier circuit.
Raghu Chandra Garimella, Dr. V.R. Sastry, and Mohammed Shoeb Mohiuddin (2015) designed piezoelectric power generators that generated electrical energy using unwanted ground vibrations and converted them into Alternating power supply and later into DC supply. The generated output was stored in a battery for further use, minimizing dependence on fossil fuel for energy needs.

Kyu-Han Kim, Si-Bum Cho, Hyun-Dong Kim, and Kyu-Tae Shim (2018) applied piezoelectric materials to wave reducing the structure to harvest the wave energy hitting the structure. A physical model was tested with varying wave energy. The conclusion drawn was that there was an increase in wave pressure and voltage while increasing wave energy.

Kiruhaveni Savarimuthu et.al (2017) designed a generator with a power line conditioner using a piezoelectric material. The results concluded that at a frequency of 21.4Hz a 65.9mW of power could be harvested.

Dayou et al (2009) discussed how electricity can be harvested using piezoelectric material. They modeled different mechanisms for the generation of power using this material. The results concluded that a battery can be fully charged by generating electricity from this material.

3. METHOD
3.1. THEORETICAL CALCULATIONS

Problem statement:
An E-rickshaw weighing 380kg has a total capacity of 5 passengers with 70 kg of weight each. The wheelbase of the vehicle is 2110mm and the center of gravity is 1200mm beyond the front axle. The e-rickshaw is supported by 2 identical semielliptical carriage springs each of length 600 mm between the shackle pins. There are 3 full-length leaves and 7 graduated leaves.

SOLUTION:
Load calculation:
Weight of an E-Rickshaw = 380Kg
No. of passengers= 5
Weight of passengers = 70kg*5 = 350Kg
Total weight = 730 Kg = 750(approx.)
TOTAL LOAD = 750 * 9.81 = 7357.5 N

Load acting on rear axle = \( R_B \):
\[ L \times 1200 = 2R_B \times 2110 \]
\[ R_B = 0.28 \times L \]

LOAD ON ONE LEAF SPRING
\[ 0.28 \times 7357.5 \text{N} \]
Load on each spring = 2060N
Leaf Span = 2L
Length = 600/2 = 300mm
Value of stress and deformation:
\[ \sigma = \frac{6WL}{nb^2t^2} \]
\[ \delta = \frac{6WL}{3nEb^3} \]
\[ \sigma = 73.136 \text{MPA} \]
\[ \delta = 4.8 \text{mm} \]
Where
\( W \) = load acting on spring = 1030mm
\( 2L \) = Master leaf span = 600mm
\( n \) = No. of leaves in leaf spring (variable)
\( b \) = spring width = 60mm
\( t \) = leave thickness (variable)

3.2. SELECTION OF MATERIAL

Piezoelectric materials are those which generate an electric charge on the application of load. The following piezoelectric materials are considered:

CERAMICS: Generally, ceramics are of fine crystals and for each atom in a crystal, there is a positive or negative electrical charge. These are highly brittle and hence they do not find applications in high-stress conditions like this.

QUARTZ: It is a hard-crystalline mineral composed of silicon and oxygen. It is an expensive material and is used in the sand used for making glass. The hardness and stiffness of quartz make it unsuitable for energy harvesting in leaf spring.

POLYVINYLIDENE FLUORIDE: Also abbreviated as PVDF, this material is a polymer. It is elastic material and has elasticity similar to that of leaf spring material, therefore, it is selected for this project.
3.3. MODELLING OF LEAF SPRING IN SOLIDWORKS

The SOLIDWORKS CAD software is used as an application of engineering drawing and enables the user to sketch out components with varying dimensions to produce models along with intricate drawings. A 3D model of the semi-elliptical leaf spring is prepared in SolidWorks with the design constraints obtained from theoretical calculations which are as follows:

| Table-2. Design parameters for leaf spring |
|------------------------------------------|
| Sr No | Parameter                          | Value          |
| 1.    | Master leaf length                 | 600 mm         |
| 2.    | Free Camber (At no load)           | 81 mm          |
| 3.    | Full-length leaves                 | 3              |
| 4.    | Graduated leaves                   | 7              |
| 5.    | Width of leaf spring               | 60mm           |
| 6.    | Maximum load acting on the spring  | 1030 N         |
| 7.    | The internal diameter of the Eye   | 23 mm          |
| 8.    | The thickness of the leaf spring   | To be varied   |
| 9.    | Number of plates                   | To be varied   |

3.4. SIMULATION IN ANSYS

The SolidWorks model is imported to Ansys for further evaluation. The material applied is structural steel and PVDF (polyvinylidene fluoride). The master leaf, the 1st graduated leaf and the last leaf are always structural steel to ensure that the strength of the model is not compromised. The rest of the leaves are alternately applied with the material PVDF and structural steel. Mesh generation is carried out with Tetrahedral elements for master leaf and Hex elements for graduated leaves. After mesh convergence, the element size of 2mm is considered for meshing. The total number of nodes obtained is 1459241 and the total number of elements is 392768.

Boundary conditions are a critical aspect of FEA analysis. In this model, a force of 1030N each is applied to both the eye ends, and the inner holes of the spring are fixed for evaluation. Equivalent von mises stress is calculated for each case.

Table-1. PVDF material properties

| PROPERTY                          | VALUE |
|----------------------------------|-------|
| Density (kg/m3)                  | 1770  |
| Poison’s Ratio                   | 0.34  |
| Elastic Modulus (GPa)            | 2.4   |
| Young’s Modulus (MPa)            | 2450  |
| Tensile Yield Strength (MPa)     | 53.5  |
| Compressive Yield Strength (MPa) | 50    |
3.5. STRESS CALCULATION AT DIFFERENT PIEZOELECTRIC PLATES

To calculate voltage generation by a single leaf spring, the voltage at each PVDF plate is calculated and then added. For this, equivalent von mises stress is evaluated for the whole model, and the stress acting on each PVDF plate is calculated by the stress probe tool. This tool allows users to find the equivalent stress acting in the X/Y/Z direction. We find the stress acting along the Z direction as the Z-axis is perpendicular to the axis of force and in piezoelectric materials the charge is generated perpendicular to the application of applied force.

3.6. THEORETICAL AND SIMULATED VOLTAGE GENERATION

Voltage generation in a piezoelectric element can be found out by the formula:

\[ V = \sigma \times g \times t \]  \[3\]

Where \( V \) is the voltage generated, \( \sigma \) is the stress acting, \( g \) is the piezoelectric constant whose value is 0.22 N/m² for PVDF and \( t \) is the thickness of the plate in mm.

The theoretical voltage generated will be found out for each case and further evaluation is done for this case only. Further, the simulated voltage and the charging time will be calculated for the case with maximum theoretical voltage.

PIEZOELECTRIC POWER HARVESTING CIRCUIT

A method of power harvesting system is designed in NI MULTISM 14.0 software and is depicted in figure (2). The model consists of a piezoelectric material, mounted between a full-wave rectifier,
capacitor, and a resistor connected in a parallel combination. For measurement of voltage, a voltmeter is connected across the capacitor, an ammeter for current flow through the resistor, a wattmeter for power consumption, and an oscilloscope to achieve output waveform.

The piezoelectric material selected is PVDF (Polyvinylidene fluoride) which acts as RMS value for the system. The frequency of the suspension system is subjected to variation in the road surface. The average frequency of the road surface is taken as 12Hz which forms the base for comfortability. A capacitor of 82μF and resistor of 2kΩ are taken to be standard values for the system.

3.7. CALCULATION OF BATTERY CHARGING TIME

The lead-acid battery of Ah in the range of 90-105 is used in e-rickshaws. After obtaining the final current, battery charging time is found.

Charging time is also calculated for auxiliary battery with a 45 Ah rating.

4. RESULTS

4.1. VALIDATION:

![Stress for leaf spring (steel)](image)

**Fig-3. Stress for leaf spring (steel)**

| STRESS (N/mm²) | THEORETICAL VALUES (MPA) | ANSYS SOLUTION (MPA) | ERROR (%) |
|----------------|--------------------------|----------------------|-----------|
| 73.136         | 68.627                   | 6.16                 |

**Table-3. Validation of theoretical and analytical values**

4.2. SIMULATION RESULTS FOR STRESS:
CASE 1:

![Fig-4. Equivalent Von-Mises Stress developed for case 1](image)

CASE 2:

![Fig-5. Equivalent Von-Mises Stress developed for case 2](image)

CASE 3:

![Fig-6. Equivalent Von-Mises Stress developed for case 3](image)

CASE 4:
CASE 5:

Fig-7. Equivalent Von-Mises Stress developed for case 4

CASE 6:

Fig-8. Equivalent Von-Mises Stress developed for case 5

Fig-9. Equivalent Von-Mises Stress developed for case 6
CASE 7:

![Fig-10. Equivalent Von-Mises Stress developed for case 7](image)

CASE 8:

![Fig-11. Equivalent Von-Mises Stress developed for case 8](image)

|   | NO. OF PLATES | THICKNESS (mm) | Stress probe 1 (MPa) | Stress probe 2 (MPa) | Stress probe 3 (MPa) | Stress probe 4 (MPa) | Maximum total stress (MPa) |
|---|---------------|----------------|----------------------|----------------------|----------------------|----------------------|---------------------------|
| CASE 1 | 10 | 6.5 | 0.5797 | 0.45136 | 0.58667 | 0.83417 | 2.4519 |
| CASE 2 | 8 | 6.5 | 0.61137 | 0.55585 | 0.77962 | - | - | 1.94684 |
| CASE 3 | 6 | 6.5 | 0.86612 | 1.0084 | - | - | - | 1.87452 |
| CASE 4 | 10 | 7 | 0.5314 | 0.43573 | 0.53795 | 0.67308 | - | 2.17816 |
| CASE 5 | 10 | 7.5 | 0.4865 | 0.3954 | 0.5069 | 0.65656 | - | 2.04536 |
| CASE 6 | 8 | 7.5 | 0.47926 | 0.49068 | 0.78305 | - | - | 1.75299 |
| CASE 7 | 10 | 5.5 | 0.81983 | 0.49627 | 0.76612 | 1.0375 | 3.11972 |
| CASE 8 | 11 | 5.5 | 0.53921 | 0.50341 | 0.76041 | 0.48985 | - | 2.29288 |

The table above represents the various cases considered and the stress generated in each plate. This stress is simulated using ANSYS WORKBENCH. The results are thus obtained.

4.3. VOLTAGE CALCULATION
The theoretical AC voltage generated for each plate is calculated using the formula: \[ V = a \times g \times t \] [3]

\[ V_1 = 990V \quad V_3 = 926V \]

\[ V_2 = 600V \quad V_4 = 1254V \]

Half of the above voltages are taken as VRMS value for the power harvesting circuit and the value of the current for each plate is obtained through the circuit.

Fig-12. Power harvesting circuit \( V_{RMS} = 495 \)

Fig-13. Power harvesting circuit \( V_{RMS} = 300 \)

Fig-14. Power harvesting circuit \( V_{RMS} = 463 \)

Fig-15. Power harvesting circuit \( V_{RMS} = 627 \)
Table-5. DC Voltage and current obtained for CASE 7

| Input AC Voltage RMS (V) | 495 | 300 | 463 | 627 |
|-------------------------|-----|-----|-----|-----|
| Output DC Voltage (V)   | 320 | 212 | 312 | 348 |
| Current (mA)            | 601 | 387 | 574 | 651 |

Total current for 1 leaf spring = (601+387+574+651) mA = 2.213 A

An e-rickshaw has 2 leaf springs for its rear suspension and helical spring for the front wheel.

Therefore, the total current for 2 leaf springs = 4.426 A

The above current is used to calculate the time required for charging a lead-acid battery.

4.4. CALCULATION OF BATTERY CHARGING TIME FOR LEAD ACID BATTERY:

Lead-acid batteries used in e-rickshaws are low in cost and are employed in automotive. The charging time of the battery is calculated as the ratio of Battery Ah and charging current (Amperes).

Charging time of battery = \( \frac{\text{Battery Ah}}{\text{Charging Current}} \)

\[ T = \frac{\text{Ah}}{A} \]

Where T is time hrs, Ah is the Ampere hour rating of the battery, A is current in amperes. Battery Ah of lead Acid battery ranges from 90-105 Ah and weighs approximately 12-16kg.

4.4.1. IDEAL CASE: -

Charging current = 4.426 Ampere
Battery Ah of Lead Acid batteries = 90 Ampere
Charge Time of single battery = \( \frac{90}{4.426} \) = 20 hours

4.4.2. CONSIDERING LOSSES: -

Practically, 40% of losses are observed while charging a battery.

\[ 90 \times \left( \frac{40}{100} \right) = 40 \times (90\text{Ah} \times 40\% \text{ of losses}) \]

Therefore, Battery Ah = 90 + 40 = 130 ampere
Charging current = 4.426 A
Charge Time of single battery = \( \frac{130}{4.426} \) = 29 hours
4.5. CALCULATION OF BATTERY CHARGING TIME FOR AUXILIARY BATTERY:

An auxiliary battery will be installed to power the headlight of the e-rickshaw. A lead-acid battery (12v, 45Ah) can be used.

\[
\text{IDEAL Charging time} = \frac{45}{4.426} = 10 \text{ hrs}
\]

\[
\text{Charging time Considering losses} = \frac{45 \times (40 \div 100) + 45}{4.426} = 14 \text{ hrs}
\]

Fig 16. Variation of Stress with varying thickness and number of plates

5. CONCLUSION:

- The conventional leaf spring orientation is modified by including piezoelectric plates and modeled to analyze the voltage generated. As we vary the thickness and number of plates, the stress acting on the model varies to give maximum stress for case 7. Maximum stress was found in a leaf spring having 10 plates of 5.5mm thickness. This configuration of leaf spring resulted in a total current of 2.213A for each leaf spring.

- The piezoelectric plates will be able to fully charge the onboard lead battery with 29 hours of continuous operation. The operation time is practically not feasible for the e-rickshaw to run independently without any need for external charging.

- A lead-acid battery cannot be charged while in operation. Hence, an auxiliary battery is introduced to power the headlight. It requires 14hrs of continuous charging. Hence, with the e-rickshaw operating in the morning, the headlight could be powered in the evening and night without the need to charge the auxiliary battery. Hence, this battery is self-sustaining.
6. FEASIBILITY:
- In India, the piezoelectric material PVDF is available in form of thin sheets (thickness varying from 2-12mm), discs, and plates, the elasticity of material lies within a range of the conventional material, making it feasible to be used as leaf spring in the assembly.
- The technical requirements for the construction of the proposed system such as a capacitor, full-wave rectifier, and piezoelectric material of the desired range are practically available in the market making the proposed system experimentally feasible.
- In case of a Lead Battery which can be charged only when the vehicle is not in operation, we can install an additional battery for the headlight and other auxiliary devices. As this battery would not require much power for its operation, it could become self-sustaining and the need for an external charge will be eliminated. Various products are available in India will provide us with the auxiliary battery for approx. 2100 INR. Hence, there will not be a significant rise in the cost of production of e-rickshaw.

7. PRACTICAL APPLICATIONS:
- The power generated can provide an agreeable alternative to the conventional power resources that are used to charge various components within an E-rickshaw including battery, spotlight, actuators, and sensors.
- The lost energy is captured adjoining the system by the means of piezoelectric placed in the suspension system for the consumption of the electrical system resulting in cost optimization in the distant future.
- Wired devices such as sensors and actuators can be directly run by the piezoelectric leaf spring. This will reduce the cost and weight of the vehicle.
- Energy optimization and harvesting systems are expected to increase the lifecycle of the system and might further eliminate the usage of additional batteries (renewal of the depleted batteries is mostly improbable) that implicate the restrictions on the sustainability of the system.
- In the case of a Lithium Battery, it can be simultaneously charged while in operation. Hence, it will reduce the charging time and the costs related to it without the need for an additional battery. Furthermore, it requires lesser charging time and longer life as compared to a Lead acid battery.

8. FUTURE WORK
- The project can further be extended, and experimental analysis can be concluded comparing the results with software values.
- This paper focuses on static analysis, further evaluation could be done for dynamic loading conditions.
- Cost analysis can be conducted to determine the true cost of the system and its optimization w.r.t the time to promote cost-saving opportunities.

REFERENCES
[1] Jaffe, B. (2012). Piezoelectric ceramics (Vol. 3). Elsevier.
[2] Porcelli, E. B. (2016). Induction of Forces Performed by Piezoelectric Materials. arXiv preprint arXiv:1612.04201.
[3] Jamadar, M. E. H., & Manjunath, B. S. (2016). Power Generation from Leaf Springs Using Piezoelectric Materials.
[4] Xie, X. D., & Wang, Q. (2015). Energy harvesting from a vehicle suspension system. Energy, 86, 385-392.
[5] Elahi, H., Israr, A., Swati, R. F., Khan, H. M., & Tamoor, A. (2017, November). Stability of piezoelectric material for suspension applications. In 2017 Fifth International Conference on Aerospace Science & Engineering (ICASE) (pp. 1-5). IEEE.
[6] Prasannabalaji, V., Rakesh, R., Sairam, S., & Mahesh, S. (2013). Staircase Power Generation
Using Piezo-Electric Transducers. Advance in Electronic and Electrical Engineering Vol. 3 Number, 6, 747-754.

[7] Anton, S. R., & Sodano, H. A. (2007). A review of power harvesting using piezoelectric materials (2003–2006). Smart Materials and Structures, 16(3), R1.

[8] Lee, H., Jang, H., Park, J., Jeong, S., Park, T., & Choi, S. (2013). Design of a piezoelectric energy-harvesting shock absorber system for a vehicle. Integrated Ferroelectrics, 141(1), 32-44.

[9] Ajitsaria, J., Choe, S. Y., Shen, D., & Kim, D. J. (2007). Modeling and analysis of a bimorph piezoelectric cantilever beam for voltage generation. Smart Materials and Structures, 16(2), 447.

[10] Erturk, A., & Inman, D. J. (2011). Piezoelectric energy harvesting. John Wiley & Sons.

[11] Gautschi, G. (2002). Piezoelectric sensors. In Piezoelectric Sensorics (pp. 73-91). Springer, Berlin, Heidelberg.

[12] Najini, Hiba, and Senthil Arumugam Muthukumaraswamy. "Piezoelectric energy generation from vehicle traffic with technoeconomic analysis." Journal of Renewable Energy 2017 (2017).

[13] Raghu Chandra Garimella, V.R. Sastry, and Mohammed Shoeb Mohiuddin. "Piezo-Gen - An Approach to Generate Electricity from Vibrations" Procedia Earth and Planetary Science, vol. 11, 2015. doi:10.1016/j.proeps.2015.06.044

[14] Srivastava, Ratnesh, et al. "POWER GENERATION USING PIEZOELECTRIC MATERIAL."

[15] Kim, Kyu-Han, et al. "Wave power generation by piezoelectric sensor attached to a coastal structure." Journal of Sensors 2018 (2018).

[16] Dayou, J., Man-Sang, C., Dalimin, M. N. & Wang, S. (2009). “Generating electricity using piezoelectric material.” Borneo Science

[17] Savarimuthu, K., Sankarajan K., & Murugesan, S., (2017). “Design and implementation of piezoelectric energy harvesting circuit.” Circuit World, Volume 43 Issue2