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ANALYTICAL AND FEA OF PIEZOELECTRIC VIBRATION ENERGY HARVESTERS FOR IOT-BASED RAILWAY TRACK MONITORING SYSTEM

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***Abstract* -** This study aimed to evaluate a cantilever beam-type piezoelectric energy harvester operating on train-induced vibrations for powering Wireless Sensor Networks (WSNs) used in railway track monitoring systems. The harvester's behaviours under different conditions are simulated in MATLAB using the analytical model. Natural frequency, maximum deflection, and stress were calculated with greater precision using eigen frequency and stationary analysis using COMSOL Multiphysics. At a base excitation of 2 g and a resonant frequency of 120.2 Hz, the simulated results showed that the developed energy harvester prototype could generate up to 14 V of AC output voltage and 495 mW of output power. These findings highlight the promising potential of the proposed energy harvester for transforming train mechanical energy into electrical power. This energy harvester's viability and dependability for real-world applications in monitoring railway tracks are supported by developed analytical and simulation models.

Keywords—COMSOL Multiphysics, Energy harvester, IoT, Train-induced vibration, railway track monitoring.

I. INTRODUCTION

In light of advancements in the Internet of Things (IoT), energy harvesting, and wireless sensor technology, autonomous systems are undergoing development and deployment across various applications. These include health monitoring of civil structures, fault identification in industrial machinery, automation of living and working areas, weather forecasting, aircraft tracking, and notably, bridge and railway track monitoring systems. The economy of densely populated nations heavily relies on an efficient transportation system, with railways serving as a pivotal component for the transportation of large volumes of goods and passengers. For an effective railway transmission system, railway tracks are crucial to the security of transportation. Therefore, a vast railway network is installed in different countries

Railway tracks play an indispensable role in the transportation industry by facilitating the dependable movement of people and goods. However, they are constantly subjected to wear and tear from factors such as the weight of passing trains, harsh weather conditions, and dynamic stresses. This deterioration significantly impairs maintenance efficiency, safety, and operational effectiveness. Even minor rail accidents incur substantial human and financial costs. Therefore, ensuring the integrity of railway tracks through proactive maintenance and monitoring is imperative for mitigating risks, enhancing safety, and sustaining the reliability of rail transportation networks. To prevent accidents and guarantee the safety of the transportation system, a monitoring system is a dire need that can keep an eye on the rails around the clock.

A modern solution to this issue is IoT based monitoring system for railway tracks. An IoT-based railway track monitoring system is shown in Fig. 1. There are multiple wireless sensor nodes (WSNs) positioned above the rail line that gather data from the rail line and send it to the gateway sensor node via wireless data transmission modules. The data is communicated to the user through the gateway sensor unit.

The primary concern at hand is supplying WSNs with power. As a power source, WSNs utilized for railway track monitoring typically employ batteries. Standard maintenance for WSNs consists of replacing or recharging the batteries, as their lifespan is quite short. However, because an enormous amount of WSNs are deployed across railway track networks, it is not possible to recharge or replace their batteries. The continuous operation of WSNs requires an alternative, long-lasting power source. Energy harvesters [1] can take the place of batteries in wireless sensor networks. The most promising aspect of these energy harvesters is that they will continually convert ambient accessible energies into usable electrical energy. These harvesters have the potential to give an alternate option for power supply sources. Motion-based [2-4], wearable-based [5-7], solar-based [8], RF-based [9-11], acoustic-based [12-15] or vibration based [16-37] energy harvesters have been successfully developed to power WSNs and wireless systems.

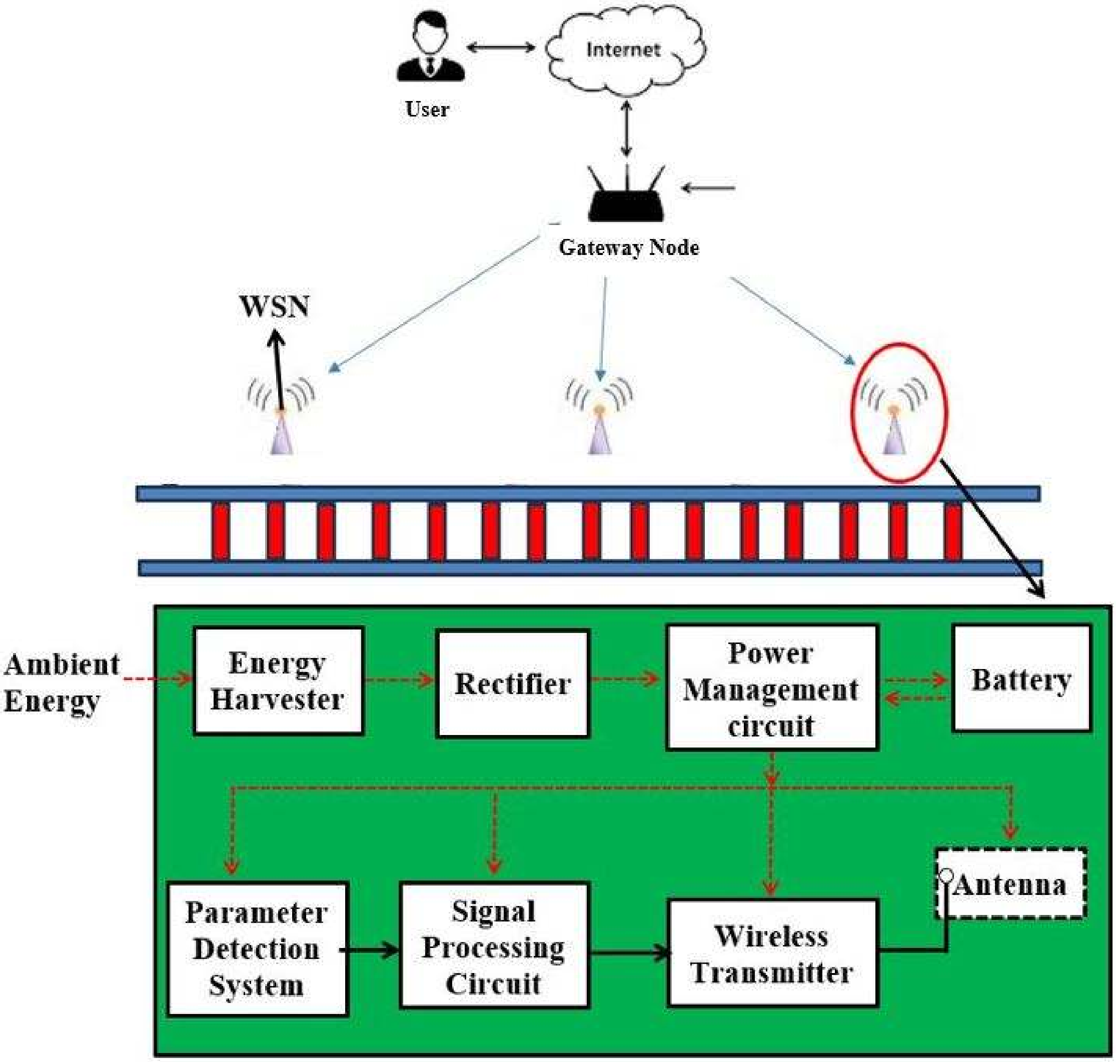

Fig. 1: IoT based Self powered Railway track monitoring system

Most of these energy sources have limitations. The efficiency of wind power plants varies widely depending on topography and climate. Sound and radio waves have a low output power density, making them unsuitable for use as a primary energy source on a large scale. Similarly, the density of solar energy is greatest in dry, cloudless regions and lowest in sunny ones. The vibrational energy of the railway, on the other hand, is a viable alternative. Using an electromagnetic or piezoelectric transduction mechanism, vibration energy in the railway track can be harnessed and used.

Several researchers have worked to investigate the power obtained from the train-induced vibration, which can be later used to power WSNs used in the railway track monitoring system. Perez et al. [38] developed a tram-mounted electromagnetic vibration energy harvesting with two degrees of freedom. The VEH is merely a permanent magnet and coils. Numerical simulation and actual data suggest that the energy harvester can output 6.5 mW. The inductive voice coil system invented in [39] turns the vertical deflection of a track into electrical power. As the track deflected, a voltage was generated in the coil that was attached to the rail and traveled vertically through the stationary magnetic field. The average power with a 7.5 kΩ load resister was calculated to be 0.16 mW in the simulation. Many distinct designs of piezoelectric train-induced VEH systems have been created to accommodate a wide range of potential installation sites. Cantilever types, stacked types, bilateral fixed types, and circular types are the most common line-side structures for piezoelectric energy harvesters [40].

In a railway setting, piezoelectric VEHs based on a cantilever mechanism are the simplest method for harvesting vibration energy. To capture the vibrational energy from passing trains on a bridge, Cahill et al. [41] designed a piezoelectric energy harvester based on a cantilever beam. The estimated frequency of the bridge's energy harvesting is shown to be consistent with the tested natural frequency, and the maximum output voltage was found to be 99 mV. Gao et al. [42] aimed to create a prototype to supply electricity to outlying areas. A detailed modeling and simulation of a railway track-mounted electromagnetic energy harvester are presented. Li et al. [43] investigated the performance of piezoelectric VEHs based on cantilevers when subjected to varying resistors and frequencies. The power output performance of a piezoelectric harvester is at its best at its resonance point. Wang et al. [44] examined the efficiency of a piezoelectric stack device coupled to the train track as a means of energy gathering. Based on the findings, the proposed piezoelectric energy harvesting technology may be used to power wireless sensors in railway systems. Hou et al. [45] proposed installing a piezoelectric VEH based on a layered structure atop the rail transit bridge. Based on simulation results, we know that the max output voltage and current can be as high as 195.8 V and 5.6 mA, respectively, for a total of 1.09 W. The examined piezoelectric energy harvester has a power density of up to 0.048 mW/cm^3, which is double that of current low-frequency piezoelectric VEHs. Cantilever-structured piezoelectric VEHs for use on railway vehicles were proposed by Pasquale and colleagues [46].

The proposed energy harvester's performance was evaluated using a miniature train bogie. The results demonstrate that at its maximum capacity, the harvester can produce an output power of 4.12 mW. A piezoelectric VEH based on a cantilever construction was studied by Song et al. [47] and put on a superconducting Maglev train. Experiments showed that the harvester's output voltage rose with increasing vibration frequency, reaching a maximum of over 6 V.

In this work train induced vibration-based cantilever, beam-type piezoelectric energy harvester is modelled and simulated using MATLAB and COMSOL Multiphysics. The energy produced by the harvester can be used for powering WSNs installed at the railway track monitoring system. Most of the previously reported train-induced vibration energy harvesters were based on electromagnetic transduction mechanisms while for the developed piezoelectric energy harvester, there is no analytical modelling for optimization of different parameters, however, in this work an analytical model and simulation is presented for piezoelectric energy harvester to optimize the device working parameters. Stationery and Eigen frequency analysis is performed for the harvester for the estimation of maximum deflection and stress in the beam concerning device dimension and amplitude of applied vibration.

II. ANALYTICAL MODELLING OF PEHS

The architecture of the rail track-induced vibration is illustrated in Fig 2. PEH, the device is constructed utilizing a Unimorph cantilever piezoelectric beam. It is intended that the device be affixed securely to either the railway track or the rail car's structure. At the free end of the beam, a proof mass is affixed to reduce the natural frequency of the piezoelectric structure. Both the body and the track experience vibrations when the train is in motion. The disturbance of the rail car induces oscillation in the piezoelectric beam. Voltage is produced across the terminals of the beam when it vibrates under the influence of external sources, as dictated by the piezoelectric effect. By applying this voltage to the backup power battery, it is refueled for additional use. When a minor amplitude of applied vibration is present, the piezoelectric beam undergoes deflection, resulting in the generation of electrical energy by the piezoelectric principle. Fundamental piezoelectric equations [41]

$$D = e\epsilon + E\epsilon^T \qquad (1)$$

$$\sigma = C\epsilon + eE \qquad (2)$$

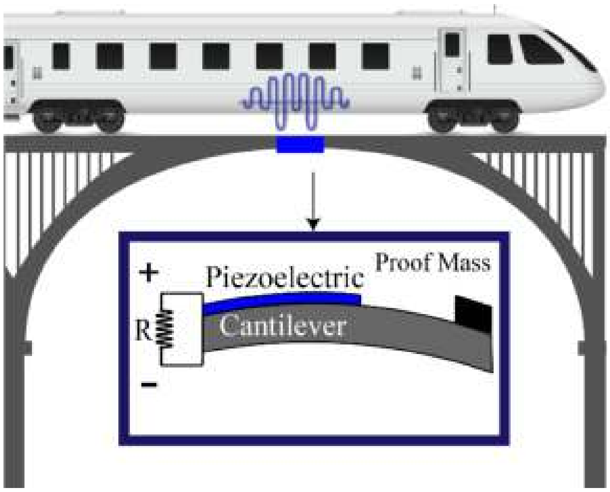

Fig 2: Architecture of train-induced vibration PEH

Where e is the strain, D is the electrical displacement, C is the stiffness, E is the Electrical field, σ is the stress, ϵ is the PZT stress constant, ϵ^T is the permittivity.

The stiffness of a cantilevered beam multilayered can be written as

$$K_{beam} = \frac{3b}{L^3}\left(\sum_{i=1}^{n_1} n_{i\,E_i h_i^3} + \sum_{j=1}^{n_2} n_{j\,E_j h_j^3}\right) \qquad (3)$$

Where b is the beam width, n_1 is the number of piezoelectric layers, n_2 is the number of electrode layers, Ei is the young modulus, hi is the height of each piezoelectric layer, Ei is the young modulus and hj is the height of each electrode layer. Multilayered cantilever beams that have a mass at their tip can have their effective mass calculated

$$m_{eff} = m_T + 0.23bL\left(\sum_{i=1}^{n_1} n_{i\,\rho_i h_i} + \sum_{j=1}^{n_2} n_{j\,\rho_j h_j}\right) \quad (4)$$

From equations (3 and 4) the corresponding natural frequency of the cantilevered beam can be derived

$$\omega_{beam} = \sqrt{\frac{K_{beam}}{m_{eff}}} \quad (5)$$

When a vibrating beam is subjected to a bending moment M(x), the average effective stress per unit length is

$$\sigma_{\mathrm{Beam}}\ \frac{1}{L}\int_0^L \frac{M(x)C}{I}\,dx \quad (6)$$

Cantilever beam length (L), maximum displacement (C), moment of inertia (I), and orientation (x) along the beam's length (x) are all inputs into the following equation.
The voltage generated is proportional to the average effective stress in the cantilevered beam because it is formed of piezoelectric material and electrode. The output voltage is given by

$$V = \frac{-d_{31} * t_p * \sigma_{beam}}{\varepsilon} \quad (7)$$

The output power of cantilever beam-based piezoelectric vibrational energy is given by

$$P = \frac{V^2 * R_L}{(R_S + R_L)^2} \quad (8)$$

III. COMSOL MODELING AND SIMULATION

Simulation and modelling of different kinds of engineering tasks can be done very well with COMSOL Multiphysics. This paper models and simulates a train-induced vibration-type piezoelectric energy generator with a cubical mass. COMSOL Multiphysics FEM is used to look at the greatest displacement that happened at the tip of the piezoelectric beam and the mode forms at natural frequencies that go through the beam because of the vibration. Fig. 3 shows the steps that were used to model and simulate a piezoelectric beam-type piezoelectric energy generator using COMSOL Multiphysics.

In the realm of energy harvesting, optimized geometry plays a crucial role. It's important to remember that the harvester's high-power density is only available at the low natural frequency. The proposed device geometry is shown in Fig. 4. It consists of a piezoelectric layer and a rectangular substrate layer. The precise geometrical specifications of the proposed device are displayed in Table I. PZT-5A is employed for the piezoelectric component, whereas brass is used for both the substrate layer and the proof mass. All of the device's areas are set free, except for the fixed end of the beam. The fixed end must be securely connected to the rail line. The option for linear elastic properties such as Young modulus, density, and Poisson ratio is set to receive their values from the material library

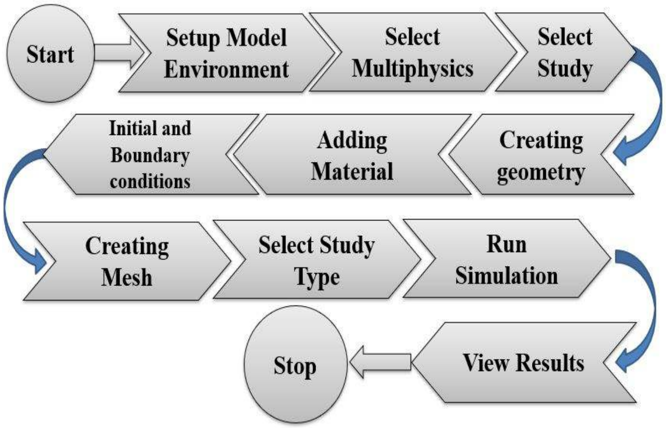

Fig 3: Steps in COMSOL Multiphysics modeling and simulation

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TABLE 1: MATERIAL AND VARIABLE DESCRIPTION

Description	Variable	Values	Unit
Elastic layer Length	L_e	20	mm
PZT layer Length	L_p	20	mm
Elastic layer Width	We	10	mm
PZT layer Width	Wp	10	mm
Thickness of the PZT layer	h_p	0.23	mm
Thickness of the elastic layer	H_e	0.22	mm
The volume of proof mass	V	4x10x3	mm^3
Density of proof mass	ρ_m	8,587	Kg/m^3
Elastic layer elasticity	Y_e	97	Gpa
PZT layer elasticity	Y_p	66	Gpa
Elastic layer density	P_e	8785	Kg/m^3
PZT layer density	ρ_p	7800	Kg/m^3
Piezoelectric Charge	d31	1.75x10^{-9}	C/N

Fig. 5 illustrates mesh geometry. COMSOL Multiphysics has numerous meshing defaults. This simulation uses tetrahedral mesh. The domain is small; hence an exceptionally normal element size is used. Meshing yielded 18672 boundary elements, 43967 domain elements, and 844 edge elements.

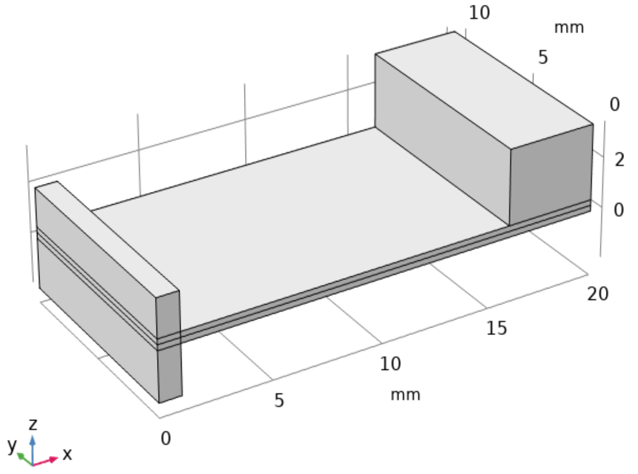


Fig 4: 3D model geometry of the flow-based piezoelectric energy harvester

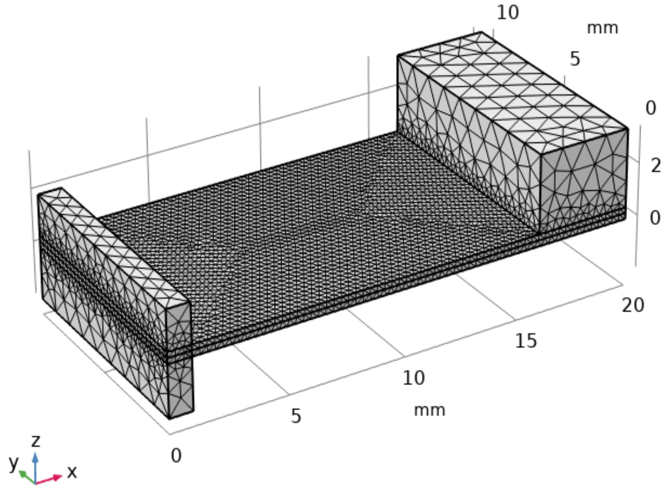


Fig 5: Mesh result

IV. SIMULATION RESULTS AND DISCUSSION

When vibration is applied at the fixed support of the beam, deflection is produced in the beam as shown in Fig. 6. The deflection is maximum at the free end and minimum at the fixed end of the beam. Piezoelectric beams bend and twist, causing tensions within the plates themselves. Vibration given to the device causes a corresponding fluctuation in stress. Fig. 7 displays the simulation results showing that at 2 g acceleration, the greatest stress created is 4.47 MPa at the fixed side of the beam and the minimum stress developed is 0.001360 MPa at the free end of the beam.

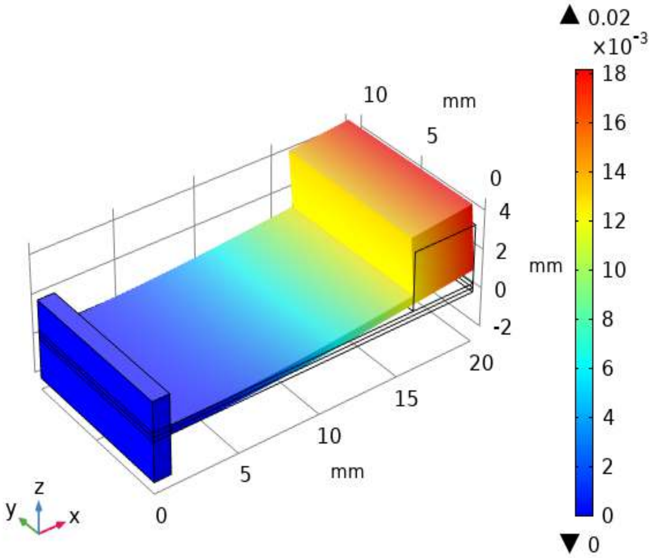


Fig 6: Maximum deflection observed in the device

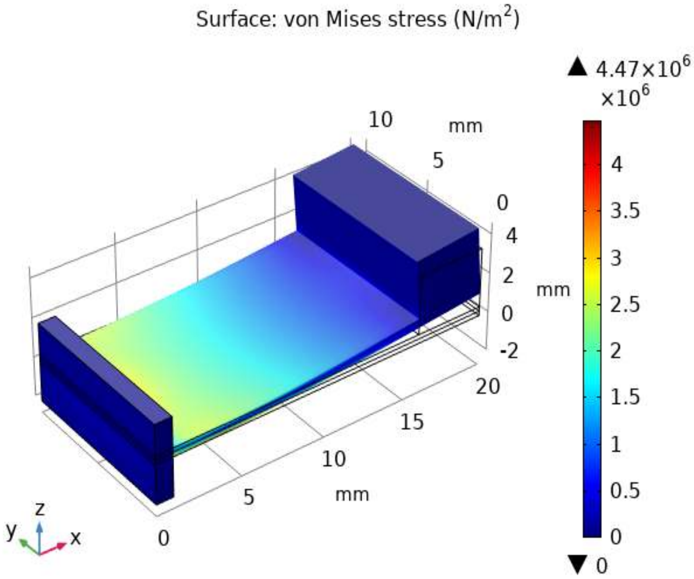
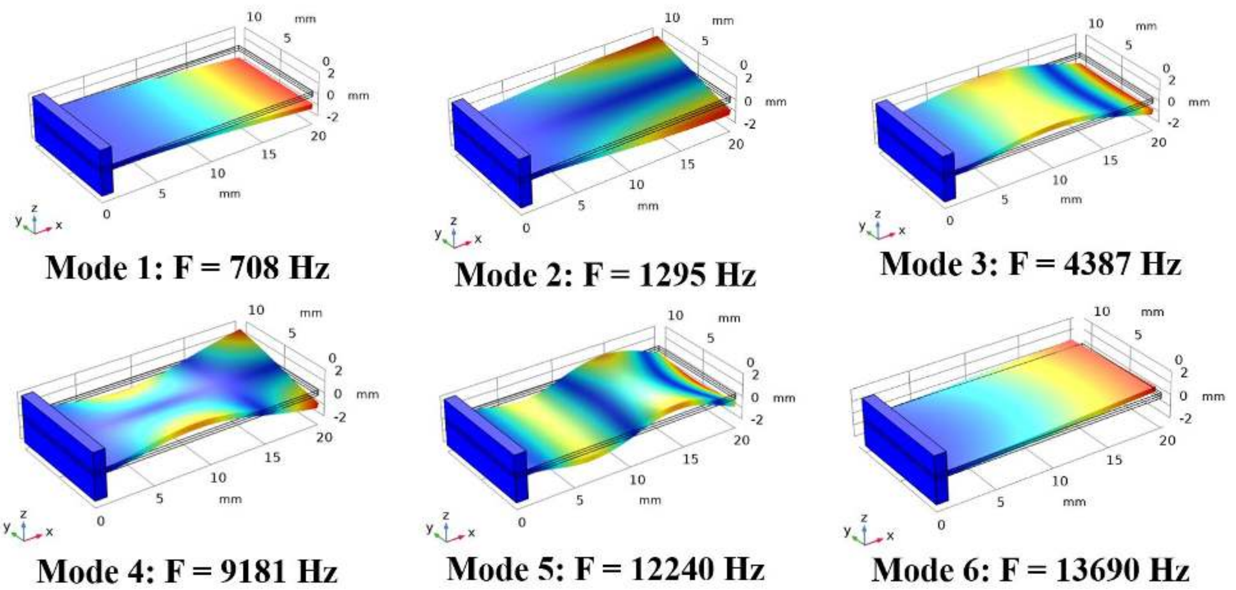


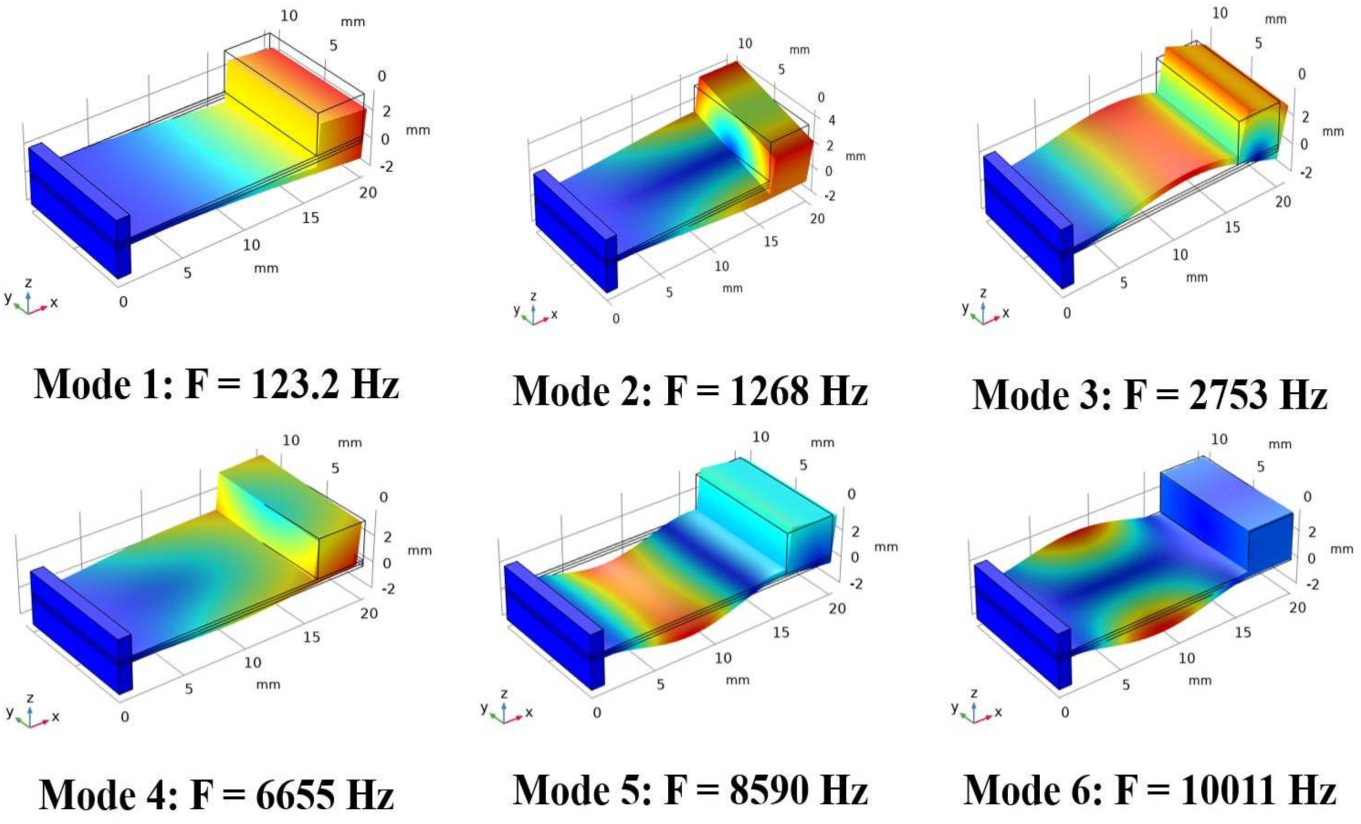
Fig 7: Maximum stress produced in the device

The eigenfrequencies and mode shapes are the outputs of an eigenfrequency analysis. Fig. 8 shows the first six eigenfrequencies and the corresponding mode shape of the device without proof of mass. As can be seen from Fig. 9, adding proof mass at the tip of the beam can reduce the eigenfrequency of the beam from 708 Hz to 120 Hz.



Mode 1: F = 708 Hz
Mode 2: F = 1295 Hz
Mode 3: F = 4387 Hz
Mode 4: F = 9181 Hz
Mode 5: F = 12240 Hz
Mode 6: F = 13690 Hz

Fig 8: Eigenfrequencies and modes shapes of device without proof of mass



Mode 1: F = 123.2 Hz
Mode 2: F = 1268 Hz
Mode 3: F = 2753 Hz
Mode 4: F = 6655 Hz
Mode 5: F = 8590 Hz
Mode 6: F = 10011 Hz

Fig 9: Eigenfrequencies and modes shapes of the device without proof mass

MATLAB simulation is used to analyze the different factors based on the analytical model developed in the previous section. There is a strong correlation between the length, width, and thickness of a cantilever beam and its stiffness, as shown in Fig 10. Stiffness values decline noticeably from 5600 N/m to 80 N/m as the length of the cantilever beam grows from 10 mm to 30 mm. This finding is consistent with the general rule that beams with a greater length are less rigid because they bend more easily under the same strain. In contrast, beams that are shorter by definition are stronger and less likely to deform under load.

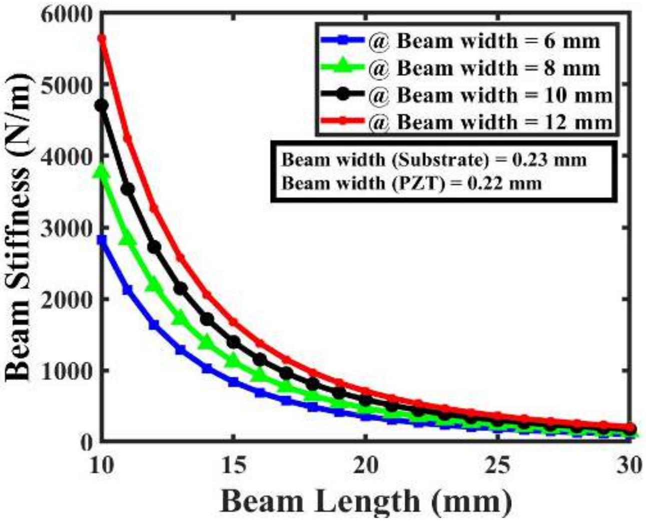


Fig. 10. Beam stiffness with Vs. Length of the beam

The dependency of the beam's natural frequency on beam dimension is depicted in Fig. 11. The dynamic behaviour of a cantilever beam is best understood by displaying the relationship between the length of the beam and its natural frequency at constant beam width and thickness. A significant drop in natural frequency is shown as beam length is increased from 10 mm to 30 mm, with values going from 350 Hz to 60 Hz. This trend can be attributed to the fundamental principle that longer beams exhibit lower natural frequencies, indicating greater flexibility and a longer period for oscillation. However, shorter beams indicate stiffer materials with faster oscillation cycles due to their higher inherent frequencies Certainly, the width and thickness of each layer affect the natural frequency of a cantilever beam in addition to its length.

Fig. 12 depicts the relationship between the cantilever beam's tip mass and natural frequency. By adding a proof mass at the free end of the beam, the natural frequency is drastically reduced. As the proof mass varies between 10 g to 30 g, the frequency decreases from 200 Hz to 10 Hz. This decrease in natural frequency is directly attributable to the additional mass, which effectively modifies the beam's inertia and stiffness, resulting in a decreased oscillation rate. In numerous applications, such as vibration isolation, energy harvesting, and precision sensing, modulating the natural frequency to meet specific requirements is essential for optimal performance.

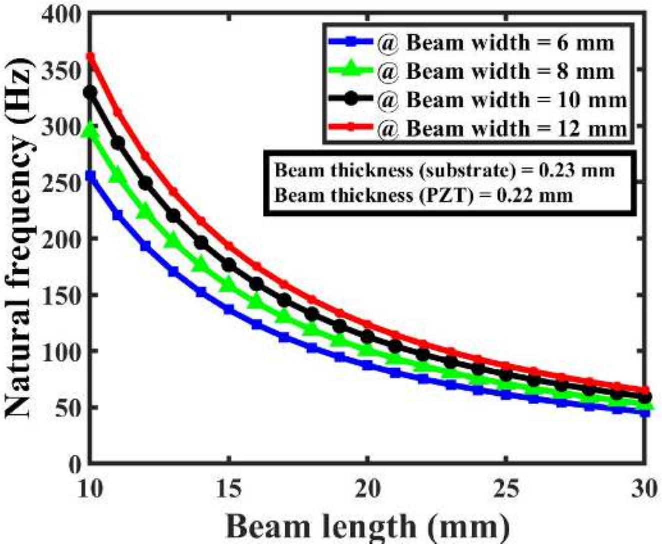


Fig 11: Beam natural frequency Vs. Length of the beam

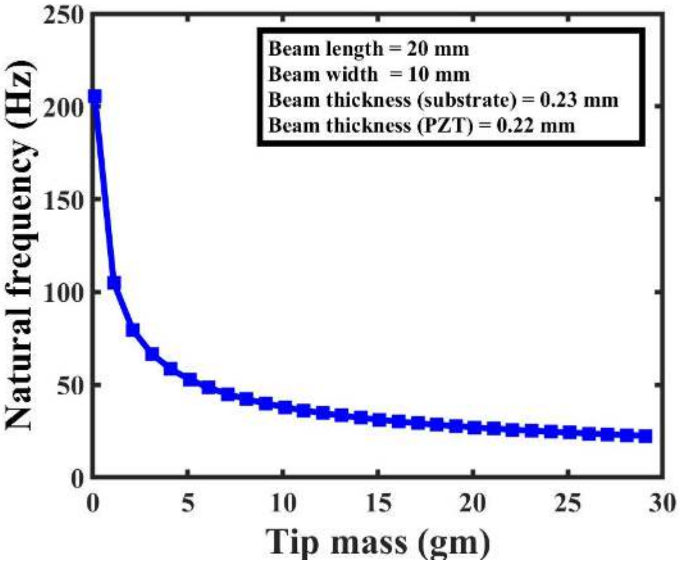


Fig 12: Natural frequency vs. tip mass

The stress generated within the beam is highly dependent on its dimensions (length, width, and layer thickness) as depicted in Fig. 13. Maximum stress increases with beam length because longer beams bend and deform more under an applied excitation. In contrast, the maximum stress decreases as beam width increases because broader beams provide greater resistance to bending, hence reducing the stress concentration. Increasing the beam's length from 10 mm to 30 mm results in a corresponding increase in maximum stress from 0.5 MPa to 1.8 MPa.

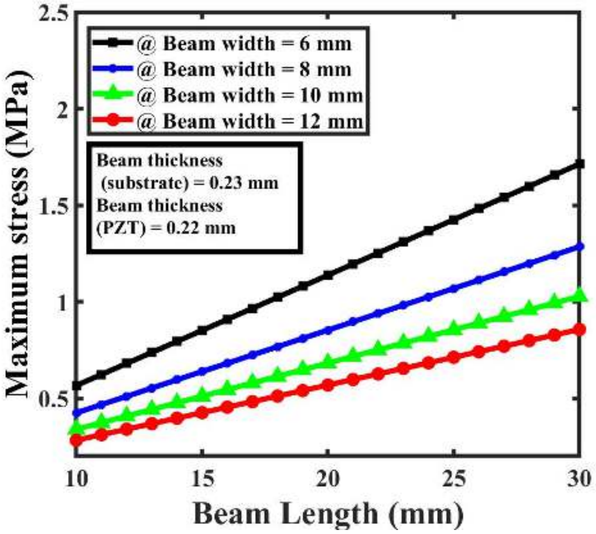


Fig 13: Maximum Stress Vs Beam Length

Fig. 14 depicts the relationship between the output voltage generated by the piezoelectric energy harvester and the variation in input base acceleration. Depending on the magnitude of the applied base acceleration, the harvester's output voltage might vary widely. When the input acceleration is increased from 1 g to 2 g, the harvester's output voltage varies dramatically, going from 0.5 V to 15 V at the beam length is 20 mm and the beam width of 10 mm

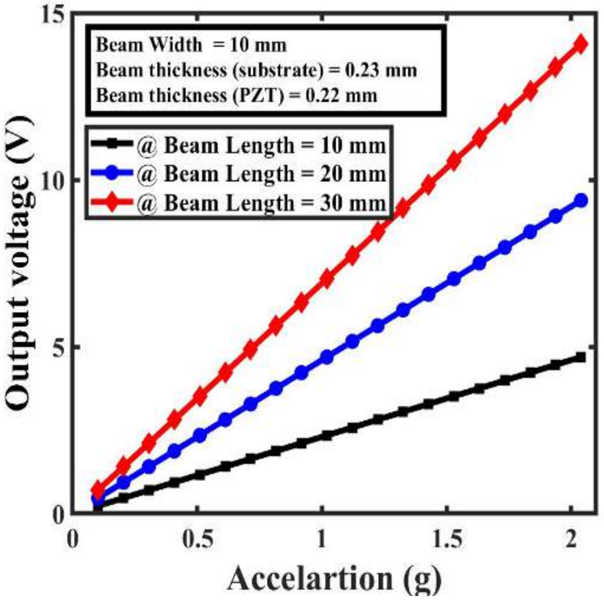


Fig 14: Output voltage Vs. input base acceleration

Power output by the piezoelectric beam-type energy harvester as a function of input base acceleration is shown in Fig 15. The input base acceleration has a considerable effect on the output power. As the input base acceleration is doubled from 1 g to 2 g, the harvester's output power changes from 100 µW to 495 mW, demonstrating a significant boost in its ability to generate electricity. The highest output power of the harvester is 495 mW, and it is achieved under specified conditions with a beam length of 20 mm, width of 10 mm, thickness of 0.45 mm, and an input acceleration of 2 g.

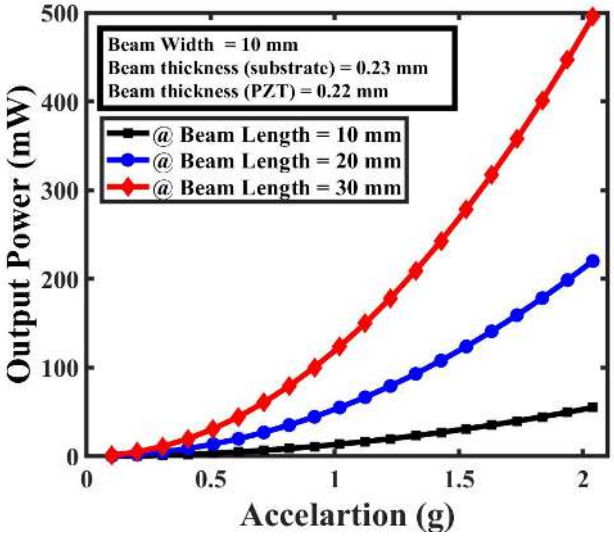


Fig 15: Output power Vs. input base acceleration

V. COMPARISON AND DISCUSSION

The performance of the train-induced vibration energy harvester prototypes that have been produced is compared with the performance of train-induced vibration type harvesters that had been developed in the past. Table 2 shows all the train-induced vibration energy harvester types that have been recorded. These comparisons are carried out concerning the place where the installation was carried out, the internal resistance, the frequency, the output-input base acceleration, the output voltage, and the output power. When compared to piezoelectric harvesters, the Electromagnetically developed harvesters have a comparatively lower Internal Impedance. Piezoelectric energy harvesters, on the other hand, have a high impedance.

The voltage production of the developed prototypes is quite better than the developed energy harvester that has ever been reported. However, when evaluated based on power output, the prototypes generated in this work are capable of generating higher output power than all of the reported energy harvesters combined. It is evident from this comparison that the energy harvester that was produced in this work is capable of producing higher voltage and output power than the majority of the reported harvesters that have been developed in the past.

Type	Installation position	Frequency (Hz)	Input acceleration (g)	Load resistance (Ω)	Voltage (V)	Power (mW)	Ref.
Electromagnetic	Line side	6	-	44.6	2.23	119	[42]
	Onboard	8	-	-	2.5	100	[48]
	Line side	7-500	2	-	-	45.5	[49]
	Line side	27	-	-	1.7	10	[50]
	Onboard	28	0.8	-	-	6.5	[38]
	Onboard	-	-	300	7.07	28.4	[51]
	Line side	4	-	50	-	196	[52]
	Onboard	-	-	-	-	263	[53]
Piezoelectric	Line side	-	0.2	44	1.8	-	[54]
	Line side	50	0.21	15000	-	1.843	[55]
	Onboard	26	-	11000	-	3	[56]
	Line side	-	-	55024	-	1.03	[57]
	Onboard	-	1	-		0.3	[58]
	Line side	16.6	-	-	0.144	-	[41]
	Line side	1.8		-		1.09	[45]
	Line side	3-6	-	40000	-	40	[59]
This prototype	Line side	120	2	100	14	495	This work

Table 2: Comparison of the developed train-induced vibration energy harvester

VI. CONCLUSION

This study aimed to evaluate the cantilever beam-type energy harvester that operates on train-induced vibrations and the developed prototypes may be used to supply power for Wireless Sensor Networks (WSN) employed in the condition monitoring of railway networks. The study covered a detailed discussion of the architecture, working mechanism, modeling, and simulation of the proposed energy harvester. An analytical model was built to estimate a number of factors such as maximal stress, stiffness, natural frequency, output voltage, and output power. Different factors were examined employing MATLAB simulations based on the analytical model, yielding important insights into the harvester's performance under changing conditions. COMSOL Multiphysics modelling and simulation of the proposed energy harvester device was carried out to validate the analytical modelling and acquire more accurate findings. The device's natural frequency, maximum deflection, and stress were calculated using eigen frequency and stationary analysis. Simulated data showed that the designed energy harvester prototype could generate up to 14 V of AC output voltage and 495 mW of output power at a base excitation of 2 g and a resonant frequency of 120 Hz. These findings show that the suggested energy harvester has great potential as a means of mechanical energy from trains into electrical power. The analytical models developed were and validated and showed that the suggested energy harvester is practical and reliable for use in monitoring IoT-based railway tracks in the real world.

REFERENCES

[1] S. J. Roundy, “Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion,” 2000.

[2] Iqbal, M., Khan, F. U., Mehdi, M., Cheok, Q., Abas, P. E., & Nauman, M. M. (2020). Power harvesting footwear based on piezo-electromagnetic hybrid generator for sustainable wearable microelectronics. Journal of King Saud University: Engineering Sciences. https://doi.org/10.1016/j.jksues.2020.11.003

[3] Iqbal, M., Nauman, M. M., Khan, F. U., Abas, P. E., Cheok, Q., & Aïssa, B. (2021). Nonlinear multi-mode electromagnetic insole energy harvester for humanpowered body monitoring sensors: Design, modeling, and characterization. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 235(22), 6415–6426. https://doi.org/10.1177/0954406221991178

[4] Iqbal, M., Nauman, M. M., Khan, F. U., Abas, P. E., Cheok, Q., Iqbal, A., & Aïssa, B. (2020). Multimodal

Hybrid Piezoelectric-Electromagnetic Insole Energy Harvester Using PVDF Generators. Electronics, 9(4), 635. https://doi.org/10.3390/electronics9040635

[5] Khan, A. S., & Khan, F. U. (2021). Experimentation of a Wearable Self-Powered Jacket Harvesting Body Heat for Wearable Device Applications. Journal of Sensors, 2021, 1–22. https://doi.org/10.1155/2021/9976089

[6] A. S. Khan and F. Khan, "A survey of wearable energy harvesting systems", Int. J. Energy Res., vol. 46, no. 3, pp. 1-53, 2021. https://doi.org/10.1002/er.7394

[7] Khan, A. S., & Khan, F. U. (2022). A Wearable Solar Energy Harvesting Based Jacket With Maximum Power Point Tracking for Vital Health Monitoring Systems. IEEE Access, 10, 119475–119495. https://doi.org/10.1109/access.2022.3220900

[8] Shakoor, W., & Khan, F. U. (2021). Solar Based Human Embedded Energy Harvester. In 2021 International Bhurban Conference on Applied Sciences and Technologies (IBCAST). https://doi.org/10.1109/ibcast51254.2021.9393290

[9] Khan, N. A., & Khan, F. U. (2019). RF Energy Harvesting for Portable Biomedical Devices. https://doi.org/10.1109/inmic48123.2019.9022759

[10] Farid Ullah Khan, "Energy Harvesting from the Stray Electromagnetic Field around the Electrical Power Cable for Smart Grid Applications", The Scientific World Journal, vol. 2016, Article ID 3934289, 20 pages, 2016. https://doi.org/10.1155/2016/3934289

[11] Khan, N.U., Khan, F.U., Farina, M. et al. RF energy harvesters for wireless sensors, state of the art, future prospects and challenges: a review. Phys Eng Sci Med (2024). https://doi.org/10.1007/s13246-024-01382-4

[12] Izhar and Khan, F.U. (2018), "Electromagnetic based acoustic energy harvester for low power wireless autonomous sensor applications", Sensor Review, Vol. 38 No. 3, pp. 298-310. https://doi.org/10.1108/SR-04-2017-0062

[13] F. U. Khan and Izhar, "Electromagnetic-based acoustic energy harvester," INMIC, Lahore, Pakistan, 2013, pp. 125-130. doi: 10.1109/INMIC.2013.6731337.

[14] Khan, F. U., & Izhar. (2015). State of the art in acoustic energy harvesting. Journal of Micromechanics and Microengineering, 25(2), 023001.https://doi.org/10.1088/0960-1317/25/2/023001

[15] Izhar, & Khan, F. U. (2016). An improved design of Helmholtz resonator for acoustic energy harvesting devices. International Conference on Intelligent Systems Engineering (ICISE). https://doi.org/10.1109/intelse.2016.7475135

[16] F. U. Khan and T. Ali, "A piezoelectric based energy harvester for simultaneous energy generation and vibration isolation", Int. J. Energy Res., vol. 43, no. 11, pp. 5922-5931, Sep. 2019. https://doi.org/10.1002/er.4700

[17] Farid Ullah Khan, Shahzad Ahmad, Flow type electromagnetic based energy harvester for pipeline health monitoring system, Energy Conversion and Management, Volume 200, 2019, 112089, ISSN 0196-8904. https://doi.org/10.1016/j.enconman.2019.112089.

[18] Khan, F., Stoeber, B. & Sassani, F. Modeling of linear micro electromagnetic energy harvesters with nonuniform magnetic field for sinusoidal vibrations. Microsyst Technol 21, 683–692 (2015). https://doi.org/10.1007/s00542-014-2359-5

[19] F. U. Khan, “A vibration-based electromagnetic and piezoelectric hybrid energy harvester,” International Journal of Energy Research, vol. 44, no. 8, pp. 6894–6916, 2020. https://doi.org/10.1002/er.5442

[20] Farid Ullah Khan, "Energy Harvesting from the Stray Electromagnetic Field around the Electrical Power Cable for Smart Grid Applications", The Scientific WorldJournal, vol. 2016, Article ID 3934289, 20 pages, 2016. https://doi.org/10.1155/2016/3934289

[21] F. U. Khan and M. Iqbal, "Electromagnetic-based bridge energy harvester using traffic-induced bridge's vibrations and ambient wind," 2016 International Conference on Intelligent Systems Engineering (ICISE), Islamabad, Pakistan, 2016, pp. 380-385. doi: 10.1109/INTELSE.2016.7475152.

[22] Ali, T., & Khan, F. U. (2021). A silicone based piezoelectric and electromagnetic hybrid vibration energy harvester. Journal of Micromechanics and Microengineering, 31(5), 055003. https://doi.org/10.1088/1361-6439/abda90

[23] Khan, F. U. (2020). A vibration based electromagnetic and piezoelectric hybrid energy harvester. International Journal of Energy Research, 44(8), 6894–6916. https://doi.org/10.1002/er.5442

[24] Multi-mode vibration based electromagnetic type micro power generator for structural health monitoring of bridges. Sensors and Actuators A-physical, 275, 154–161. https://doi.org/10.1016/j.sna.2018.04.005

[25] Ahmad, M., Khan, N. A., & Khan, F. U. (2022). Multidegrees of freedom energy harvesting for broad-band vibration frequency range: A review. Sensors and Actuators A-physical, 344, 113690. https://doi.org/10.1016/j.sna.2022.113690

[26] Khan, S. F. U. (2011). Vibration-based Electromagnetic Energy Harvesters for MEMS Applications. Doctoral dissertation, The University of British Columbia Vancouver, Canada. https://dx.doi.org/10.14288/1.0071751

[27] Ahmad, M., & Khan, F. U. (2021). Dual Resonator-Type Electromagnetic Energy Harvester for Structural Health Monitoring of Bridges. Journal of Bridge Engineering, 26(5). https://doi.org/10.1061/(asce)be.1943-5592.0001702

[28] Ahmad, M., & Khan, F. U. (2021). Review of vibration based electromagnetic–piezoelectric hybrid energy harvesters. International Journal of Energy Research, 45(4), 5058–5097. https://doi.org/10.1002/er.6253

[29] Ahmad, M., Khan, N. A., & Khan, F. U. (2021). Review of frequency up conversion vibration energy harvesters using impact and plucking mechanism. International Journal of Energy Research, 45(11), 15609–15645. https://doi.org/10.1002/er.6832

[30] Ahmad, M., & Khan, F. U. (2021). Two degree of freedom vibration based electromagnetic energy harvester for bridge health monitoring system. Journal of Intelligent Material Systems and Structures, 32(5), 516–536. https://doi.org/10.1177/1045389x20959459

[31] Izhar, Iqbal, M., & Khan, F. U. (2023). Hybrid acoustic, vibration, and wind energy harvester using piezoelectric transduction for self-powered wireless sensor node applications. Energy Conversion and Management, 277, 116635. https://doi.org/10.1016/j.enconman.2022.116635

[32] Khan, F. U., & Iqbal, M. (2016). Electromagnetic-based bridge energy harvester using traffic-induced bridge's vibrations and ambient wind. https://doi.org/10.1109/intelse.2016.7475152

[33] Bakhtiar, S., and Khan, F. U. (2019). Analytical Modeling and Simulation of an Electromagnetic Energy Harvester for Pulsating Fluid Flow in Pipeline. The Scientific World Journal, 2019, 1–9. https://doi.org/10.1155/2019/5682517

[34] Khan, F. U., Sassani, F., & Stoeber, B. (2010). Copper foil-type vibration-based electromagnetic energy harvester. Journal of Micromechanics and Microengineering, 20(12), 125006. https://doi.org/10.1088/0960-1317/20/12/125006

[35] Khan, F. U. (2016). Review of non-resonant vibration based energy harvesters for wireless sensor nodes. Journal of Renewable and Sustainable Energy, 8(4), 044702. https://doi.org/10.1063/1.4961370

[36] Khan, F. U., Stoeber, B., & Sassani, F. (2014). Modeling and Simulation of Linear and Nonlinear MEMS Scale Electromagnetic Energy Harvesters for Random Vibration Environments. The Scientific World Journal, 2014, 1–15. https://doi.org/10.1155/2014/742580

[37] Farid Ullah Khan and Muhammad Usman Qadir, State-of-the-art in vibration-based electrostatic energy harvesting, Journal of Micromechanics and Microengineering, Vol. 26, issue10. 10.1088/0960-1317/26/10/103001

[38] Perez, Matthias, et al. 'A two-degree-of-freedom electromagnetic vibration energy harvester for the railway infrastructure monitoring.' Smart materials, adaptive structures and intelligent systems (2018).

[39] Ghasemi-Nejhad, M. N., Pourghodrat, A., Nelson, C. A., Phillips, K. J., & Fateh, M. (2011). Improving an energy harvesting device for railroad safety applications. In Active and Passive Smart Structures and Integrated Systems 2011. International Society f."

[40] P. Wang, Y. F. Wang, M. Y. Gao, and Y. Wang, "Energy harvesting of track-borne transducers by train-induced wind," *J. Vibroengineering*, vol. 19, no. 3, pp. 1624–1640, 2017, doi: 10.21595/jve.2017.17592.

[41] Cahill, Paul, et al. 'Data of piezoelectric vibration energy harvesting of a bridge undergoing vibration testing and train passage.' Data in brief 17 (2018): 261-266.

[42] Gao, M. Y., et al. 'A rail-borne piezoelectric transducer for energy harvesting of railway vibration.' Journal of vibroengineering 18.7 (2016): 4647-4663.

[43] J. Li, S. Jang, and J. Tang, "Design of a Bimorph Piezoelectric Energy Harvester for Railway Monitoring," *J. Korean Soc. Nondestruct. Test.*, vol. 32, no. 6, pp. 661–668, 2012, doi: 10.7779/jksnt.2012.32.6.661.

[44] Wang, Jianjun, et al. 'Modeling on energy harvesting from a railway system using piezoelectric transducers.' Smart Materials and Structures 24.10 (2015): 105017.

[45] Hou, Wenqi, et al. 'Piezoelectric vibration energy harvesting for rail transit bridge with steel-spring floating slab track system.' Journal of Cleaner Production 291 (2021): 125283.

[46] De Pasquale, G., Soma`, A., and Fraccarollo, F. (2012a). Piezoelectric energy harvesting for autonomous sensors network on safety-improved railway vehicles. Proc. Inst. Mech. Eng. C: J. Mech. Eng. Sci. 226, 1107–1117. https://doi.org/10.1177/095440621141.

[47] Song, D., Jang, H., Kim, S.B., and Sung, T.H. (2013). Piezoelectric energy harvesting system for the vertical

vibration of superconducting Maglev train. J. Electroceram. 31, 35–41. https://doi.org/ 10.1007/s10832-013-9817-9.

[48] De Pasquale, Giorgio, Aurelio Somà, and Federico Fraccarollo. 'Piezoelectric energy harvesting for autonomous sensors network on safety-improved railway vehicles.' Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engin.

[49] Gao, Mingyuan, et al. 'Condition monitoring of urban rail transit by local energy harvesting.' International Journal of Distributed Sensor Networks 14.11 (2018): 1550147718814469.

[50] Hosseinkhani, A., et al. 'Sound and vibration energy harvesting for railway applications: A review on linear and nonlinear techniques.' Energy Reports 7 (2021): 852-874.

[51] Lin, Teng, John J. Wang, and Lei Zuo. 'Efficient electromagnetic energy harvester for railroad transportation.' Mechatronics 53 (2018): 277-286.

[52] Pan, Yu, et al. 'Modeling and field-test of a compact electromagnetic energy harvester for railroad transportation.' Applied Energy 247 (2019): 309-321.

[53] Wang, Yifeng, et al. 'An electromagnetic vibration energy harvester using a magnet-array-based vibration-to-rotation conversion mechanism.' Energy Conversion and Management 253 (2022): 115146.

[54] Song, Yooseob. 'Finite-element implementation of piezoelectric energy harvesting system from vibrations of railway bridge.' Journal of Energy Engineering 145.2 (2019): 04018076.

[55] Hou, Wenqi, et al. 'Railway vehicle induced vibration energy harvesting and saving of rail transit segmental prefabricated and assembling bridges.' Journal of Cleaner Production 182 (2018): 946-959.

[56] Mouapi, Alex. 'Design, modeling and simulation of piezoelectric microgenerator for application in underground vehicles.' 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Eur."

[57] Li, Shoutai, et al. 'Investigation on a broadband magnetic levitation energy harvester for railway scenarios.' Journal of intelligent material systems and structures 33.5 (2022): 653-668.

[58] Wischke, M., et al. 'Vibration harvesting in traffic tunnels to power wireless sensor nodes.' Smart Materials and Structures 20.8 (2011): 085014."

[59] Costanzo, Luigi, et al. 'Stochastic Thermodynamics of an Electromagnetic Energy Harvester.' Entropy 24.9 (2022): 1222.

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