



PIEZOELECTRIC ENERGY HARVESTERS FOR RAILWAY TRACK VIBRATIONS: A REVIEW OF STRUCTURAL DESIGNS AND PERFORMANCE ENHANCEMENT STRATEGIES

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Abstract – Wireless sensors deployed along railway infrastructure are commonly powered by batteries, whose replacement can be costly, particularly on remote sections. Track vibrations induced by passing trains represent a local source of mechanical energy that can be converted into electrical energy using piezoelectric harvesters. This paper reviews structural configurations for railway track applications, including cantilever beams, piezoelectric stacks, and arched and ring-shaped structures. Methods for improving performance, including resonance tuning, broadband operation, frequency up-conversion, mechanical amplification, and overload protection, are examined. Representative designs are compared in terms of mounting location, excitation conditions, and output power.

Keywords – railway track, piezoelectric energy harvesting, vibration, structural design, performance enhancement.

1. INTRODUCTION

Railway transport is playing an important role in both passenger and freight transportation, while the total length of the global railway network reached approximately 1.15 million kilometres by 2023. [1]. As traffic volumes increase, the need for continuous monitoring of railway infrastructure condition also becomes more pronounced. Traditional manual inspections are labour-intensive and make it difficult to obtain continuous and reproducible data over long distances [2]. Consequently, sensor-based monitoring systems are being widely deployed along railway infrastructure to assess the condition of the track and its components [1].

One of the challenges associated with the broader deployment of such systems is ensuring a reliable power supply. Batteries require periodic replacement and maintenance, whereas wired power supply may be technically complex and economically unjustified on remote railway sections [2, 3]. As an alternative, local energy harvesting from the surrounding environment has been investigated. Passing trains induce periodic deformations and vibrations in rails and other track components, making the resulting mechanical energy a potential source for powering sensor systems [3]. Piezoelectric energy harvesters enable the conversion of mechanical energy from railway track vibrations

into electrical energy. Their compact dimensions, relatively simple design, and suitability for integration within the limited space available along railway tracks make them attractive for railway applications [1, 2].

However, the efficient utilization of railway track vibrations presents a significant design challenge. The excitation characteristics depend on train speed and axle load, axle arrangement, wheel-rail condition, and the mechanical properties of the track. These variations make the selection and design of the harvester important for effective energy conversion. [1-3]. The aim of this paper is to review the structural designs of piezoelectric harvesters proposed for railway track and the methods used to increase their output, and to compare representative solutions by mounting position, excitation and output power.

2. RAILWAY TRACK VIBRATIONS AND PIEZOELECTRIC ENERGY CONVERSION

At frequencies below approximately 30 Hz, vertical track vibration is dominated by the quasi-static response to moving axle loads, while dynamic effects associated with wheel-rail irregularities become more significant at higher frequencies [4]. The periodic arrangement of axles produces characteristic trainload frequencies, whose amplitudes

depend on train geometry, particularly axle and wheel spacing, as well as track properties [4]. Railway vibrations therefore cover a broad frequency range, with significant components reported from approximately 15 to 650 Hz, depending on the train and track conditions [1, 2].

Harvesters exploit the direct piezoelectric effect, where a material becomes polarized and produces electrical energy under mechanical stress [3]. Their operating mode is commonly described by the coefficient d_{ij} , where i and j indicate the directions of the resulting electric field and applied strain, respectively, with 3 denoting the polarization axis [2]. The d_{31} mode, commonly used in bending configurations, enables relatively large deformation under low-amplitude excitation. In the d_{33} mode, the applied force acts along the polarization direction and is commonly employed in multilayer piezoelectric stacks subjected to compression [2]. Lead zirconate titanate (PZT) ceramics are widely used because of their favorable piezoelectric properties and energy output, although their limited tolerance to large strains must be considered in harvester design [1, 2].

3. STRUCTURAL DESIGNS OF PIEZOELECTRIC ENERGY HARVESTERS

Piezoelectric energy harvesters for railway applications have been developed in different structural configurations to adapt the mechanical excitation of the track to the operating characteristics of the piezoelectric element. The representative configurations considered in this review are grouped into cantilever harvesters, piezoelectric stack harvesters, and arched and ring-shaped harvesters, as illustrated in Fig. 1.

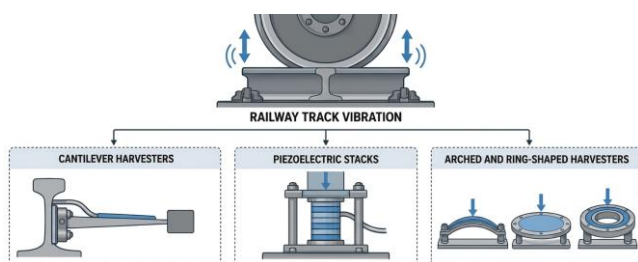


Fig. 1. Piezoelectric energy harvesting from railway track vibration: representative structural configurations

3.1. Cantilever Harvesters

Cantilever harvesters convert track vibration into bending deformation of a piezoelectric beam, typically operating in the d_{31} mode. Since the bending stress is highest near the clamped end and decreases towards the free end, different beam geometries and

proof-mass arrangements have been investigated to improve strain distribution and tune the resonant response [2]. Gao et al. [5] developed a rail-mounted PZT cantilever with a tip mass for low-frequency vibration harvesting, achieving 4.9mW at 7 Hz. To improve the response over a wider frequency range, Yang et al. [6] optimized a bimorph cantilever for the dominant track vibration frequencies, while Dong et al. [7] introduced a dual-mass configuration that allows the first two natural frequencies to be tuned to different components of the track excitation. These studies show the development from simple single-resonance cantilevers towards broadband and multimodal configurations.

3.2. Piezoelectric Stack Harvesters

Piezoelectric stacks consist of multiple piezoelectric layers and generally operate in compression using the d_{33} mode. Their high stiffness allows them to withstand substantial compressive loads, but also makes efficient mechanical excitation and force transfer important. Stack-based harvesters therefore often incorporate mechanisms for frequency up-conversion or force amplification. Shan and Zhu [8] separated the inertial mass and piezoelectric stack into two interacting systems, using impact to excite the stack close to its resonant frequency even when the track excitation occurs at a much lower frequency. The prototype generated a maximum power of 495.74mW and an average power of 43.58mW at 18Hz. A later design [9] combined frequency up-conversion with a mechanical transformer that amplifies the force applied to the stack, producing a maximum power of 568mW under measured railway vibration.

3.3. Arched and Ring-Shaped Harvesters

Arched and ring-shaped structures use their geometry to transfer track loads to piezoelectric elements while reducing direct impact and improving mechanical load distribution. Min et al. [10] proposed an arch-beam piezoelectric stack harvester for low-frequency railway vibration, achieving 193mW. The concept was further developed into a double-arch structure [11], in which the frame cushions the impact and protects the brittle piezoelectric stacks; the complete harvester produced 1.05mW under a 3Hz, 8kN excitation. A different geometric approach was adopted in the doughnut-shaped harvester [12], which uses stacked ring-shaped units and produced 7.23mW under a 3kN, 7Hz laboratory load and 207.67mW under railway track vibration conditions.

4. PERFORMANCE ENHANCEMENT METHODS

Several methods have been developed to broaden the operating frequency range, improve mechanical energy transfer, and protect piezoelectric harvesters from excessive loads.

4.1. Resonance Tuning and Broadband Operation

Resonance tuning can be achieved by modifying the structural parameters of the harvester, particularly the proof masses in cantilever configurations. Dong et al. [7] introduced a dual-mass cantilever in which the tip mass primarily affects the first natural frequency, while the middle mass has a stronger influence on the second. Optimization of the middle mass and its position increased the voltage response at the second dominant track frequency by 32% [7]. Yang et al. [6] addressed the broadband nature of railway vibration through the design of a bimorph harvester adapted to the measured rail response. Other approaches, including multistable structures and arrays of harvesters tuned to different frequencies, can further extend the effective operating bandwidth [2, 3].

4.2. Frequency Up-Conversion and Mechanical Amplification

The relatively low dominant frequencies of railway track vibration can be substantially lower than the resonant frequency of a piezoelectric stack transducer. Frequency up-conversion addresses this mismatch by using low-frequency motion to generate an impact that excites the piezoelectric transducer at its higher natural frequency [8]. In the design of Shan and Zhu [9], an inertial mass system impacts a separate piezoelectric stack system, after which the stack

vibrates freely at its resonant frequency.

Mechanical amplification can additionally increase the force transmitted to the piezoelectric stack. Shan et al. [9] used a mechanical transformer with inclined beams, for which the force amplification factor is determined by the beam angle. The transformer increases the force applied to the stack, while its dimensions must be selected so that mechanical stresses remain within acceptable limits. Arched structures [10, 11] provide another means of transferring and redistributing mechanical loads while protecting the piezoelectric elements.

4.3. Overload Protection

Railway vibration amplitudes can vary considerably with operating conditions, making overload protection important for long-term operation. Shan et al. [13] developed two protection strategies based on mechanical stoppers and impact protection components. Type I restricts inertial-mass displacement and is designed for operation within a 5g ($g=9.81\text{m/s}^2$) acceleration threshold, while Type II dissipates excess energy and enables operation at accelerations up to 15g [13]. These mechanisms reduce the risk of mechanical damage under high vibration levels.

5. COMPARATIVE ANALYSIS

Table 1 reveals substantial differences in the operating principles, excitation conditions, and reported performance of the reviewed harvesters. Cantilever harvesters [5–7] exploit rail vibration through bending and provide relatively simple means of resonance tuning. While the conventional tip-mass configuration [5] is suitable for low-frequency excitation, the broadband [6] and dual-mass [7] designs extend the operating frequency range or

Tab. 1. Comparison of representative piezoelectric energy harvesters for railway track applications

Harvester type (Ref.)	Mounting position	Excitation conditions	Output power	Main advantage
Cantilever with tip mass [5]	Rail web	5–7 Hz, 5g, 100 k Ω	4.9 mW peak	Simple design for low-frequency vibration
Bimorph cantilever, broadband design [6]	Rail web	Random broadband rail vibration	1036.9 $\mu\text{W/Hz}$ and 8.01 $\mu\text{W/Hz}$	Broadband response
Dual-mass cantilever [7]	Rail web	Dominant frequencies: 64 Hz and 721 Hz	65.5 mW and 1.4 mW at the two dominant frequencies	Two tunable natural frequencies
Piezo stack with freq. up-conversion [8]	Rail	18Hz, 0.7g RMS, 150 Ω	495.74 mW peak / 43.58 mW average	Frequency up-conversion (18 to 161 Hz)
Piezo stack with mech. transformer [9]	Rail	21 Hz, 0.7g RMS; measured track vibration signal	511mW peak/24.5mW avg. 568mW peak/7.3mW avg.	Frequency up-conversion and force amplification
Arch beam piezo stack [10]	Under the rail	3Hz, 21kN, 1kN pre-stress	193 mW (211.8 $\mu\text{W/g}$)	Load transfer through arch structure
Double-arch piezo stack [11]	Under the rail	3Hz, 8kN, 340k Ω	1.05 mW total	Impact cushioning and stack protection
Doughnut-shaped harvester [12]	Under the rail	3kN at 7 Hz, 230 k Ω ; track vibration conditions	7.23 mW; 207.67mW under track vibration	Compact stacked-ring structure
Piezo stack with protection [13]	Sleeper	5g (Type I) 15g (Type II)	718mW peak/4.6mW avg. 1365mW peak/11 mW avg.	Overload protection

enable tuning to multiple dominant track frequencies. Their main limitation is the dependence of the output on the relationship between the excitation spectrum and the natural frequencies of the harvester.

Stack-based configurations use different approaches to improve energy conversion. Frequency up-conversion [8] enables low-frequency track motion to excite the piezoelectric stack near its higher natural frequency, while the mechanical transformer [9] additionally amplifies the transmitted force. Both approaches achieved peak powers of approximately 0.5 W, although the corresponding average powers were substantially lower.

Arched and ring-shaped designs [10–12] focus on load transfer and protection of brittle piezoelectric elements. Reported outputs range from 1.05 mW for the double-arch configuration [11] to 207.67 mW for the doughnut-shaped harvester under track vibration [12]. At higher vibration levels, the stopper and impact-protection concepts in [13] provide additional mechanical protection at acceleration levels of 5g and 15g.

Direct performance ranking is difficult because the prototypes were tested under different excitation, electrical load, and mounting conditions. The comparison therefore indicates that railway piezoelectric harvester design involves a trade-off between electrical output, frequency adaptability, mechanical load transfer, and protection. More standardized testing under representative track vibration would enable more reliable comparison of future designs.

6. CONCLUSION

Piezoelectric energy harvesting offers a potential solution for powering low-power railway monitoring systems. The reviewed studies show a development from conventional cantilever harvesters towards broadband, frequency up-conversion, mechanically amplified, and protected stack-based configurations. While these approaches can improve energy conversion under railway vibration, differences in experimental conditions make direct performance comparison difficult. Further long-term testing under representative railway traffic is needed to evaluate practical reliability and energy supply capability.

ACKNOWLEDGEMENT

This research was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-34/2026-03/200109).

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