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A Compact Non-Linear Energy Harvester to an Indirect Wagon Safety Monitoring

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Abstract

This article addresses safety concerns in heavy-haul trains, focusing on the evaluation of derailment propensity without the need for instrumented wheelsets. Based on an innovative approach, which utilises strategically positioned sensors along freight wagons to indirectly measure derailment propensity, thus circumventing the complexities and costs associated with instrumented wheelsets. However, implementing these sensor systems poses challenges, particularly regarding power autonomy. The article emphasizes the potential of vibrational energy harvesting, specifically the OSo-mag structure, as a sustainable power source for these sensors.

Keywords: energy harvester, autonomous sensor, safety, vibration, heavy-haul train, piezoelectric.

1 Introduction

Heavy-haul trains have long been a primary mode of transportation, particularly for commodities and ores over extended distances. Cost reduction in this transportation sector has consistently been a key focus for industry investment decisions. Increasing cargo capacity and velocity are direct strategies aimed at minimizing transportation expenses. However, these actions also heighten risks, especially since heavy-haul trains often operate in remote regions where derailments can be particularly severe and costly.

The principal method utilized to evaluate derailment safety in the railway industry is the Nadal index. The instrumented railway wheelset is the most used device for measuring contact forces. Nonetheless, the adoption of instrumented wheelsets encounters notable limitations. The equipment is costly and complex, requiring the establishment of an entire data collection and recording system, and relying on specialized personnel for installation and operation.

Recognizing the challenges associated with implementing and the potential applications of instrumented wagons, Silva [1] proposed an indirect measurement of the Nadal index in freight wagons, enabling the calculation of derailment propensity without the need for instrumented wheelsets. She identified the ideal type and positions of sensors for this purpose.

This set of sensors is arranged along the wagon in various positions, which can lead to excessive assembly complexity due to power and data transmission cables and increased difficulty in the operation and maintenance of the wagon. One way to facilitate the implementation and dissemination of this instrumented wagon solution is by using sensors with energy autonomy.

To address this issue, power sources need to be available. Transporting batteries alongside freight wagons presents several disadvantages i.e. periodic replacement, risk of robbery or damage, and the necessary wiring adds to maintenance challenges. Furthermore, there are concerns regarding the environmental impact of indiscriminate battery use, especially regarding disposal.

With advancements in low-power integrated circuits and high-efficiency energy storage systems, a new generation of autonomous sensors with their power supply is being developed, capable of employing energy harvesting (EH) technology. Constructing such autonomous and compact systems would benefit the control and monitoring of various environments, even those with electrical power sources, as these devices eliminate the need for cables, thus reducing the mass and fragility of monitoring systems.

Various energy sources have been explored so far [2], [3], [4], [5]. For sustainable development, the environmental impact of energy sources has gained increased importance. Vibrational energy extraction offers significant advantages, as it preserves the original state of the environment, is clean and low-cost, and systems developed using them typically require minimal maintenance.

Vibration energy harvesting (VEH) is used to generate energy using the vibration generated by mechanical systems, usually composed of piezoelectric materials that generate an electric charge under mechanical stress. These are small-scale kinetic-electric energy transducers [6], [7], making them suitable candidates for use in wagon and railway composition instrumentation.

Among numerous energy harvester designs, the OSo (Orthogonal Spiral Structure) was selected for its compact design [8], with low-frequency resonance [9]. Its compact and adaptable structure, coupled with ease of assembly, makes it an optimal choice for ensuring sustained energy harvesting performance [10], [11], [12].

In developing new structures, modifications like tuners[13], limiters [14] and others [15] allow for enhancements in harvester behaviour, such as resonance displacement, band of actuation expansion and increment in production. These solutions have been explored and can be applied across different structures. Among the mechanisms, one of the most used strategies is including magnets [16], aiming at the extension of the actuation band of the device.

Thus, the present study aims to evaluate the use of vibrational energy harvesters to power the sensors of the instrumented wagon. As the collector structure to be studied, the orthogonal spiral enhanced by magnets was chosen, dubbed OSo-mag, as shown in Figure 1, with the main components highlighted.

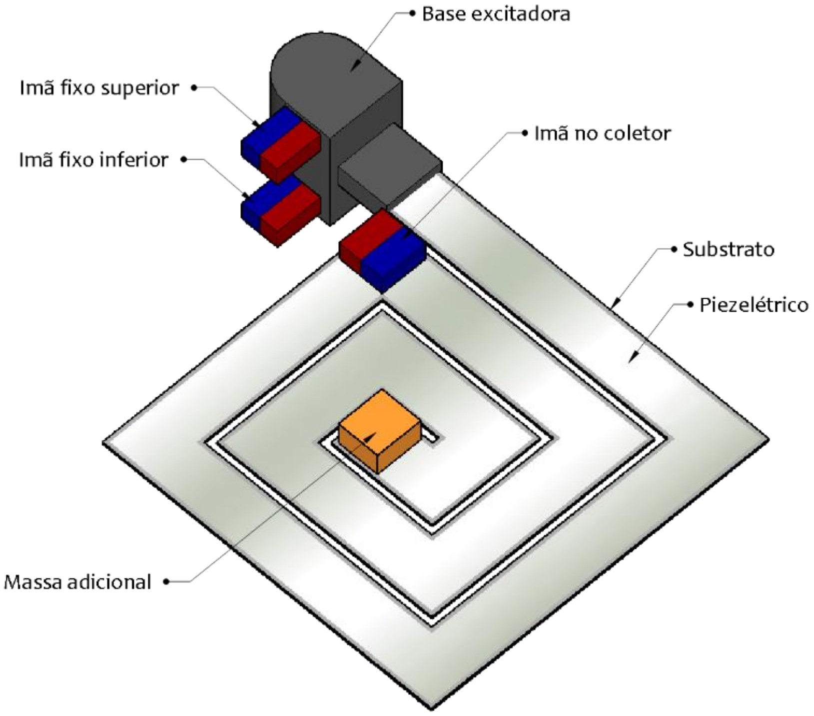

Figure 1: Typical Orthogonal Spiral harvester modified by magnets, OSo-mag

2 Methods

In this section, we delve into the innovative design of the OSo-mag energy harvester, a promising solution for efficient environmental energy capture. We will outline its design and introduce the predictive model. Furthermore, we will present the source of excitation and the evaluation of the magnetic arrangement modification.

2.1 OSo-mag Design

The OSo-mag structure can be designed based on some main characteristics, such as the number of beams, masses, lengths, and spacing. Some of these are shown in Figure 2.

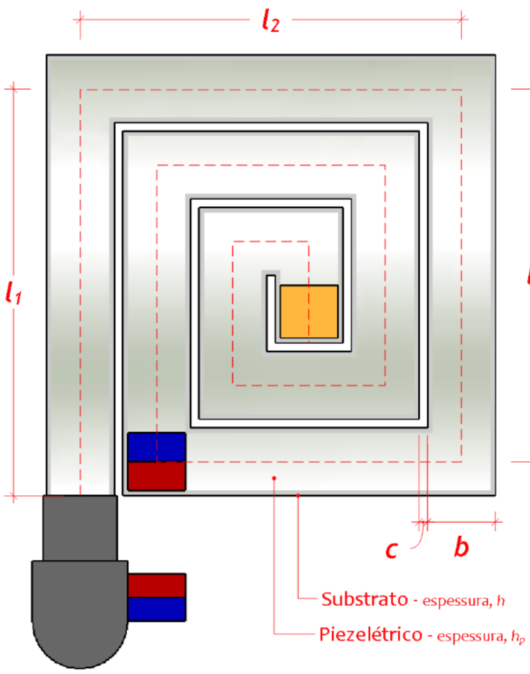

Figure 2: Main geometric dimensions of an OSo-mag.

The influence of the magnets is defined by the mass of the magnet on the collector, m_{mag}^{on}, located at the end of the fourth beam, and the fixed magnets on the exciter base, m_{mag}^{out}, positioned a $d_{imã}^{h}$ horizontally, and d_{mag}^{sup} above and d_{mag}^{inf} below the central line of the magnet fixed to the harvester (Figure 3).

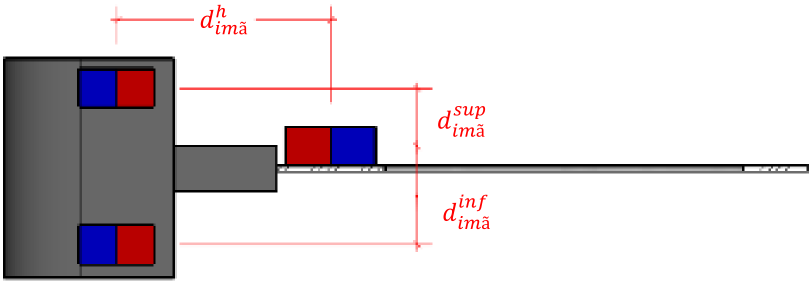

Figure 3: Main dimensions of the magnet arrangement of an OSo-mag

2.2 OSo-mag prediction Model

To develop a predictive model for OSo-mag, the Lopes et al. [10] model, which employs the Euler-Bernoulli equation to predict modal shapes, natural frequencies, and equivalent mass-damping-stiffness parameters, underwent refinement through the generalized Hamiltonian variational principle.

$$\int_{t_1}^{t_2}[\delta(T - W) + \delta W_{nc} + \delta U_m]dt = 0, \quad (1)$$

The relationship between kinetic energy, T, internal potential energy, W, external forces' work, W_{nc}, and magnetic potential energy, U_m, is established through the generalized Hamiltonian variational principle. Once the derivation of these terms is understood, their expressions become straightforward to define. A similar procedure to the one employed here can be observed in [17].

The model was built on MATLAB/Simulink® and its outputs are the electric voltage, power output and safety factor (*Nf*), as proposed by Lopes et al. [9].

2.3 Excitation Source

To define the excitation to be used, acceleration profiles resulting from dynamic simulations of vehicles were employed. The input data were based on values obtained for a dynamic model [18] of a pair of wagons in a railway composition. The wagons are of the GDE Ride Control, 110 tons gross, in a train with two GE-DASH9 locomotives and 170 wagons (85 pairs). The simulations were conducted using the multi-body dynamics software SIMPACK®.

The velocity profile was determined for each wagon in the composition using a longitudinal dynamics model [19]. The initial velocity of the first pair of wagons was 30 km/h, accelerated to 53.8 km/h, and then decelerated to 36.9 km/h. The connection between the wagons is made with a Draft Gear.

The track used in the simulation (metric gauge) contains two curves, one left and one right, each with a radius of 371.6 m, a length of 195.6 m, and a superelevation of 57.2 mm, with 150 m tangent sections before the curves. This path can be observed in Figure 4.

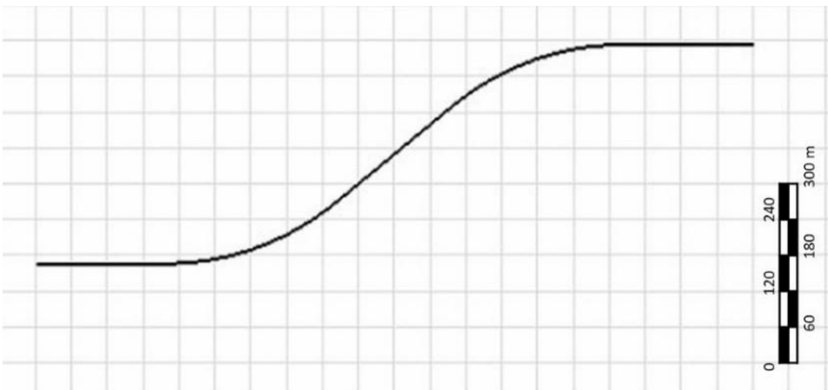

Figure 4: Track used in the simulation of the composition

Throughout the studied pair of wagons, sensors are positioned to measure acceleration at certain points. The sensor locations are presented in Figure 5.

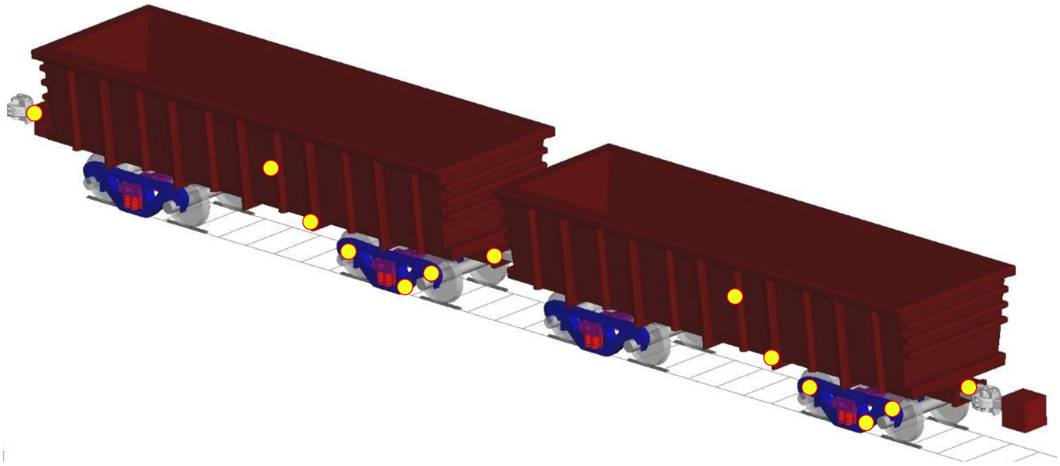

Figure 5: Position of the measured sensors in the pair of wagons

The position for measuring the frequencies needed to excite the energy harvester could be any, ideally as close as possible to the measurement position where the measuring sensor should be installed. As the proposal is to create harvesters to power autonomous sensors in the future, with miniaturised sets, it is ideal for them to be exactly in the same position. For this thesis, the positions of the sensors used are based on the arrangement of sensors proposed by [1].

With the acceleration profiles from multiple points of cargo wagons, aiming to evaluate the availability of energy to be extracted, a transformation to the frequency domain of each of the signals was performed to select the highest peak present in the set or other characteristic values found.

Among the measured positions, the pedestals for the cargo wagon stand out. These showed the highest value of the Power Spectral Density (PSD) among all measured positions (3.51 $(m/s^2)^2/Hz$ at 24.6 Hz), which represents the maximum value in the survey of the spectral distribution of each of the measured.

2.4 Evaluation of Magnetic enhanced

Based on the previous definition, EH and excitation, an OSo-mag (characteristics defined in Table 1) without magnetic force influence is used as a benchmark to evaluate the benefits of the magnetic modification.

Number of elements	18	Elements' width	10 mm
Substrate Material	Aluminium T6061	Last element length	40 mm
Substrate's thickness	0.6 mm	Gap	1 mm
Piezoelectric Material	PZT 5A4E	Tip mass	20 g
Piezoelectric film's thickness	300 μm	Magnet mass	1 g

Table 1: OSo-mag design parameters

During the simulation, the EH's response was monitored through the energy it generated. The efficiency of the magnetic force was assessed by adjusting the horizontal and vertical gaps between the magnets as defined in Table 2.

	min	max	Value
d_{mag}^{h}	10 mm	80 mm	
d_{mag}^{sup}	0 mm	10 mm	
d_{mag}^{inf}	0 mm	10 mm	
m_{mag}^{out}	-	-	1 g

Table 2: Magnets arrangement parameters

By employing these variations, we aim to discern their direct impact on energy generation efficiency. This methodical exploration allows us to discern the relationship between magnetic configurations and energy output within the OSo-mag. The outcomes are depicted in Figure 6. Through this analysis, we seek to enhance our understanding of optimal energy harvesting configurations and provide valuable insights for future implementations in diverse environmental settings.

3 Results

Based on the methodology stated before, the results are shown in this section. The predicted energy production of the OSo-mag, and its corresponding safety factor are shown in Figure 6. The increment in production due to magnetic enhancement is related to a greater deflection, which represents higher stress on the structure of the EH, as can be seen in Figure 6 (bottom), which limits the feasibility of that solution. Based on that, Figure 6 also contains the maximum production with *Nf* greater than 1.50, representing a feasible design.

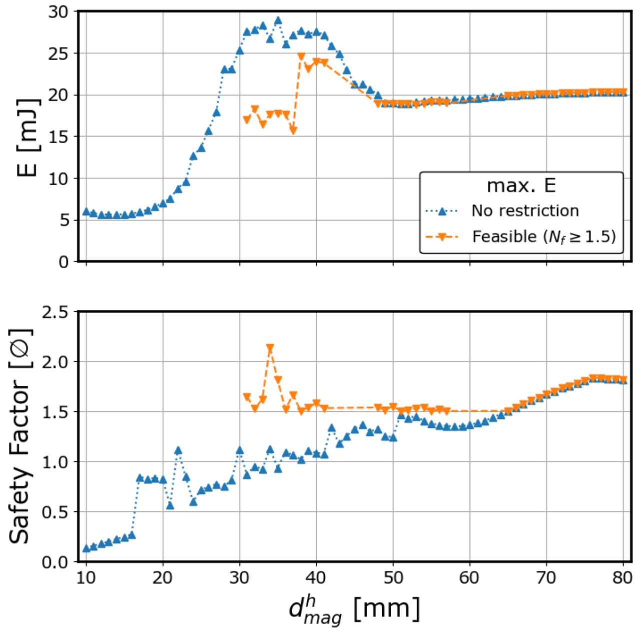

Figure 6: OSo-mag production (top) and safety factor (bottom) varying magnets horizontal distance

As depicted in Figure 6, noticeable enhancements in EH production occur at certain distances. Upon analyzing the response, a softening effect becomes evident as the distance between magnets decreases, leading to increased energy production. This culminates in a peak of 28.98 mJ when the distance equals 35 mm.

The enhancement in production can be attributed to the varying stiffness and the presence of two stable equilibrium points separated by a small potential barrier. These are the main reasons behind the utilization of non-linear forces in vibrational EH systems as documented in the literature. However, when the distance between the magnets drops below 20 mm, the magnets' excessive proximity results in a heightened potential barrier. This constrains the movement of the structure and causes a sharp decline in the extracted energy.

The most productive feasible configuration is at 38 mm, with a production of 24.56 mJ, which represents a gain of 19.81%. Its performance is presented in Figure 7.

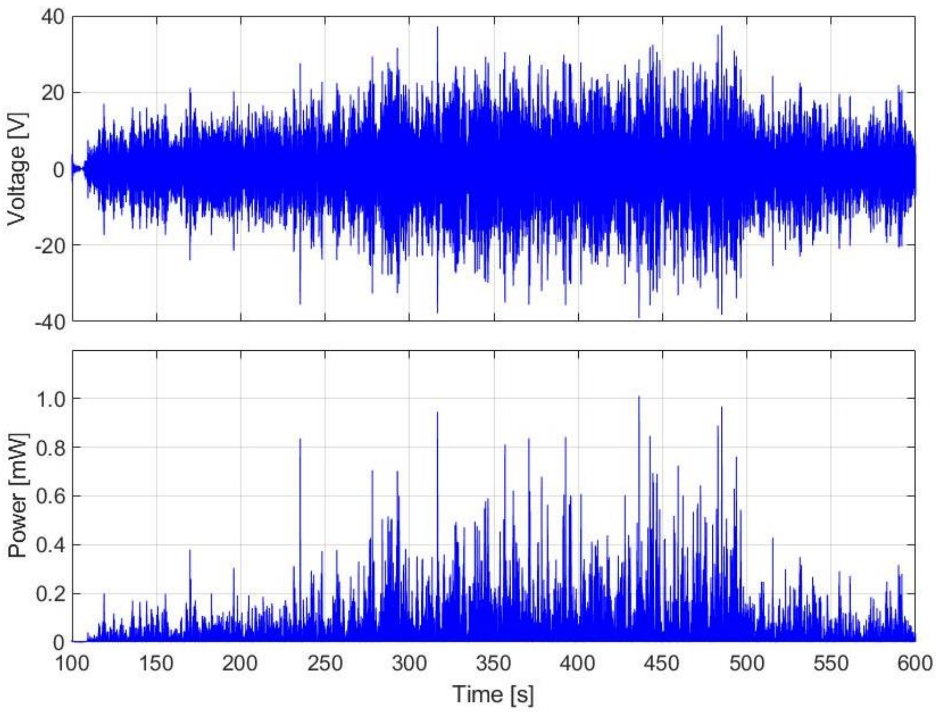

Figure 7: OSo-mag production with 38 mm of horizontal distance

To observe the effects of vertical displacement, the production at d_{mag}^{h}=38 mm is presented in Figure 8.

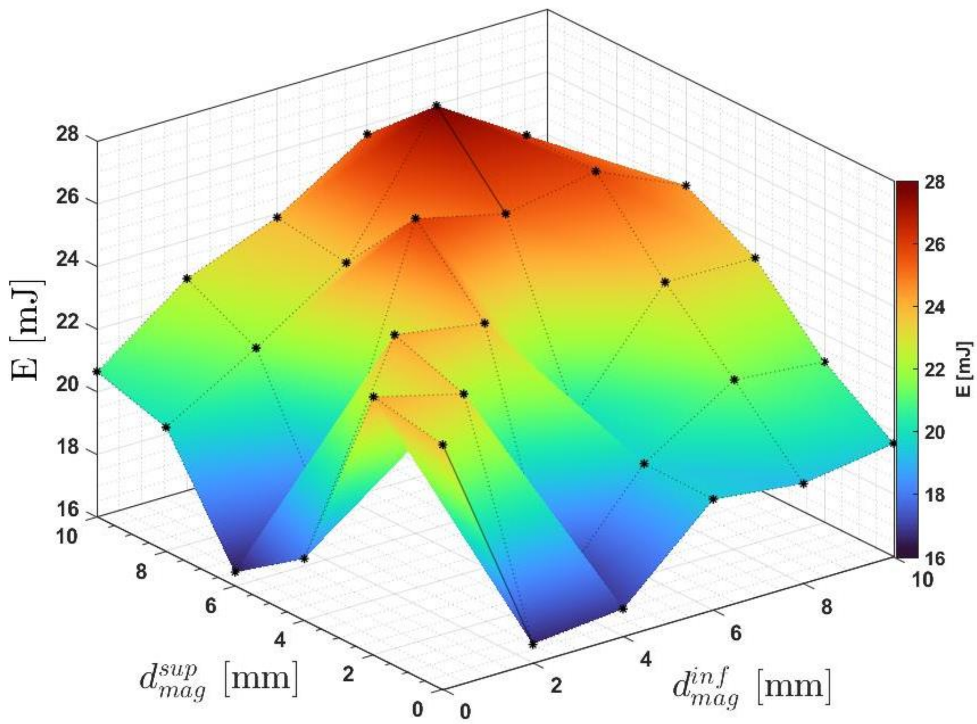

Figure 8: OSo-mag production with 38 mm of horizontal distance

In Figure 8, it becomes evident that subtle alterations in the vertical alignment of magnets wield a significant influence on system productivity. The configuration featuring a vertical offset, where $d_{mag}^{\text{sup}} = d_{mag}^{\text{inf}} + 2\ mm$, remarkably outperformed its symmetric counterpart. However, it can be seen configurations with worse performance than the linear configuration $\left(d_{mag}^{\text{sup}} = 0\ mm, d_{mag}^{\text{inf}} = 2\ mm\right)$.

These observations underscore the nuanced interplay between magnet positioning and *EH* efficiency. Thorough design, like asymmetrical magnet arrangements, can significantly boost system performance. This underscores the importance of thoughtful arrangement design.

4 Conclusions and Contributions

This study focuses on evaluating the application of nonlinear energy harvesters in the Brazilian railway environment to enhance safety and provide input for Condition-Based Maintenance systems. Utilizing orthogonal piezoelectric structures, the study aims to enhance energy harvesting from available vibrations. The behaviour of a nonlinear vibrational energy harvester, OSo-mag, was examined to assess the impact of electromagnetic forces.

The integration of magnets enhances the harvester's ability to manage a range of frequencies, resulting in a more flexible response. Up to 24.56 mJ of energy can be harvested in railway environments, a value 19.81% greater than the linear counterpart.

Crucially, the strategic integration of magnets within the vibrational piezoelectric harvester OSo has been demonstrated to engender multiple advantages. Notably, it has facilitated a marked improvement in energy conversion efficiency, widened the operational bandwidth of the device, and streamlined its integration into existing infrastructure and devices. Such findings herald a new era of innovation in energy harvesting technologies, promising substantial enhancements in both safety and operational efficiency within the realm of railway systems.

The findings suggest that meticulous design considerations, such as asymmetrical magnet arrangements, can yield substantial enhancements in system performance. Such insights underscore the imperative for thoughtful optimization strategies, wherein even minor adjustments hold the potential to yield substantial gains in productivity and operational efficacy.

Future studies should focus on developing an optimized nonlinear structure for vibration energy harvesters. This endeavour aims to facilitate sensor power supply and enable the construction of autonomous, compact, and straightforward systems for the railway environment, addressing diverse instrumentation requirements.

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