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Investigation of non-linear orthogonal spiral piezoelectric energy harvester for Heavy Haul through simulated data

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Abstract

Brazilian freight railways are characterized by operating high-capacity rail vehicles, the growth of production occurs parallel to the development of continuous monitoring technics, data acquisition, and learning tools. This direction may be unfeasible by the characteristics of ore freight trains in Brazil, where most of the wagons do not have any electrical energy source along with the composition to power sensors. To solve this problem, this paper investigates the viability of piezoelectric vibration energy harvesters, the orthogonal spiral structure associated with permanent magnets, working in Heavy Haul environment. This study uses the acceleration profile of a multibody dynamic simulation of a GDE wagon with two three-piece ride control bogies running through a track with FRA 5 irregularities. The OSs presented a promising future in the railway environment during this investigation, with its compact configuration for ultralow frequencies. And the magnet force introduction has increased the energy production of a OSs by 81.83%, reaching a value of 54.5 mJ.

Keywords: Energy Harvesting, Autonomous sensor, Vibration, magnetic coupling.

1 Introduction

Brazilian freight railways are characterized by operating high-capacity rail vehicles, developed for medium and long-distance transportation. It has been developed over the decades in the search of increasing productivity and reducing operating costs [1]. The growth of compositions, which nowadays can contain over 330 wagons [2], the increase of load, and the increase of speed were and keep being the main challenge to reach such objectives.

However, changes in these directions can worsen working conditions and lessen safety yet ensuring safety during the journey is a priority for this evolution process. Monitoring systems have been used to avoid and/or reduce those risks. Traditionally, preventive, and predictive maintenance techniques are employed, which entail the removal of selected wagons or a whole set of the composition in service to pass through the workshops periodically. This cycle of maintenance is associated with an excessive and inefficient cost due to the transport interruption, sometimes useless because many components could work further without being repaired or replaced.

Modern maintenance techniques, such as Condition Based Maintenance (CBM), are based on the use of continuous monitoring strategies and learning tools. In this way, railroad maintenance staff can define an optimal date for a specific segment to undergo maintenance [3]. Nevertheless, this solution somehow collides with characteristics of ore freight trains in Brazil, where most of the wagons use pneumatic braking control valves and do not have any electrical energy source along with the composition [2] to power sensors, and related systems.

To solve this issue, piezoelectric vibration energy harvesters (pVEH) can be applied. pVEH are devices capable of converting the kinetic energy always present on machines with moving parts [4] into electrical energy through the piezoelectric phenomenon. Energy Harvesters based on piezoelectric materials have been widely used in many fields [5–10] and had a boost in the last decades [11]. These devices are characterized by their high-power density, compact size, and high energy conversion efficiency [12].

One design that stands out among pVEH is the orthogonal spiral structure (OSs), a multi-beam harvester proposed by Santos et al. [13], defined by its simple conception, modelling [13] and compactness, being adequate for low-frequency excitations [14], as found in ore wagons.

This study aims to evaluate the non-linear effect of adding magnets in the OSs energy harvester to increase power production, enabling the construction of compact energy-autonomous sensing systems, capable of working in Heavy Haul environment.

2 Methods

The OSs consists of a sequence of orthogonally connected unimorph cantilever beams, Figure 1a, which can have masses on its inner tip and/or corners to reduce the resonance frequency or modify its modal shape.

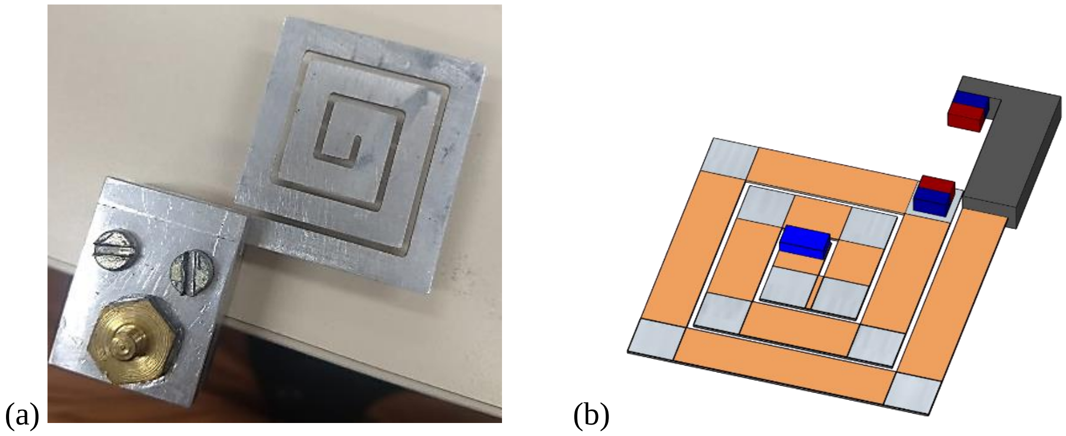

Figure 1 – Orthogonal Spiral Structure example:
(a) Substrate only (b) 3D Model with magnet

In the literature, several studies indicate the benefits of using non-linear mechanisms on pVEH. These mechanisms are responsible for extending the bandwidth and incrementing power production [14]. Among the non-linear mechanisms, magnets stand out for their easy-to-build configuration. In such designs, the inter-potential-well vibration [15], which arises on the harvester due to the interaction of the magnetic force and elasticity of the structure, is responsible for the features.

In OSs, the outer corner was selected as the position for the addition of a permanent magnet, Figure 1b, aiming to enhance an already existing Oss. Besides, the selected position presents a relevant amplitude of movement during work.

To establish a prediction model for the magnetic OSs, the model of Lopes et al. [16], that uses the Euler-Bernoulli equation to estimate the modal form, natural frequencies, and equivalent mass-damping-stiffness parameters, was submitted to the generalized Hamiltonian variational principle,

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

which relates kinetic, T, and internal potential energy, W, with the work of external forces, W_{nc}, and magnetic potential energy, U_m. Once defined the origin of these terms, the expressions are straightforward to define. A procedure similar to the one employed here can be seen in [17].

The model was built on MATLAB/Simulink®, its outputs are the electric voltage, power output, and tip displacement, which was used to evaluate the life in work as proposed by Lopes et al. [18].

Roos et al. [19] demonstrated the importance of real-world signals on EHs evaluation. Still, validated models can be used instead. In this study, the acceleration profile was estimated through a multibody dynamic simulation of a 62-degree of freedom GDE wagon modelled in SIMPACK® with two three-piece ride control bogies, in consist of 172 cars, running through a track with FRA 5 irregularities.

Some positions on the wagon were considered to place the EH; the acceleration on those was measured during the simulation; and the winning position was defined by the maximum peak of acceleration in the frequency domain shown in Figure 2, 0.145 m/s²/Hz @ 1.31 Hz.

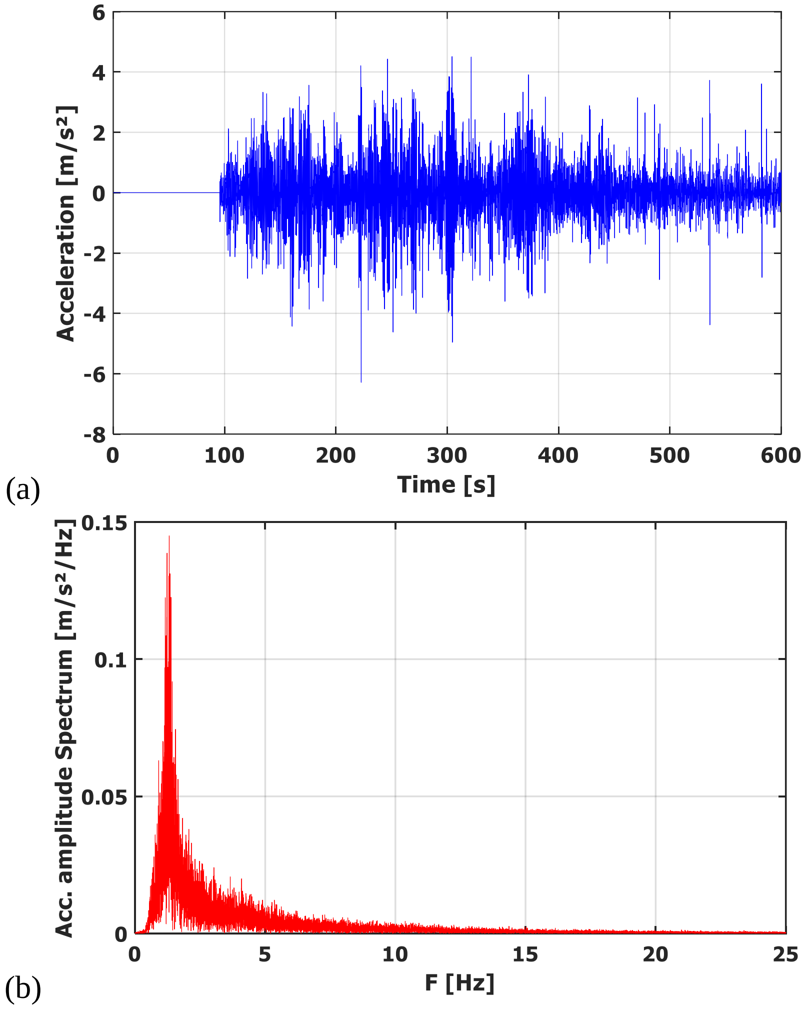

Figure 2 – Acceleration of the point of interest
(a) Time-domain; (b) Frequency domain

3 Results

From the dynamic model, standard OSs was defined, which are shown in Table 1.

Number of elements	18	Elements' width	10 mm
Substrate Material	Aluminum 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	10 g

Table 1 - OSs design parameters

The response of the EH during the simulation was recorded by the energy produced. The effectiveness of the magnetic force was evaluated by varying the horizontal distance between the magnets from 10 to 60 mm, and the result is plotted in Figure 3a, associated with the respective Safety factor, Figure 3b, as a reference about the feasibility of the configuration.

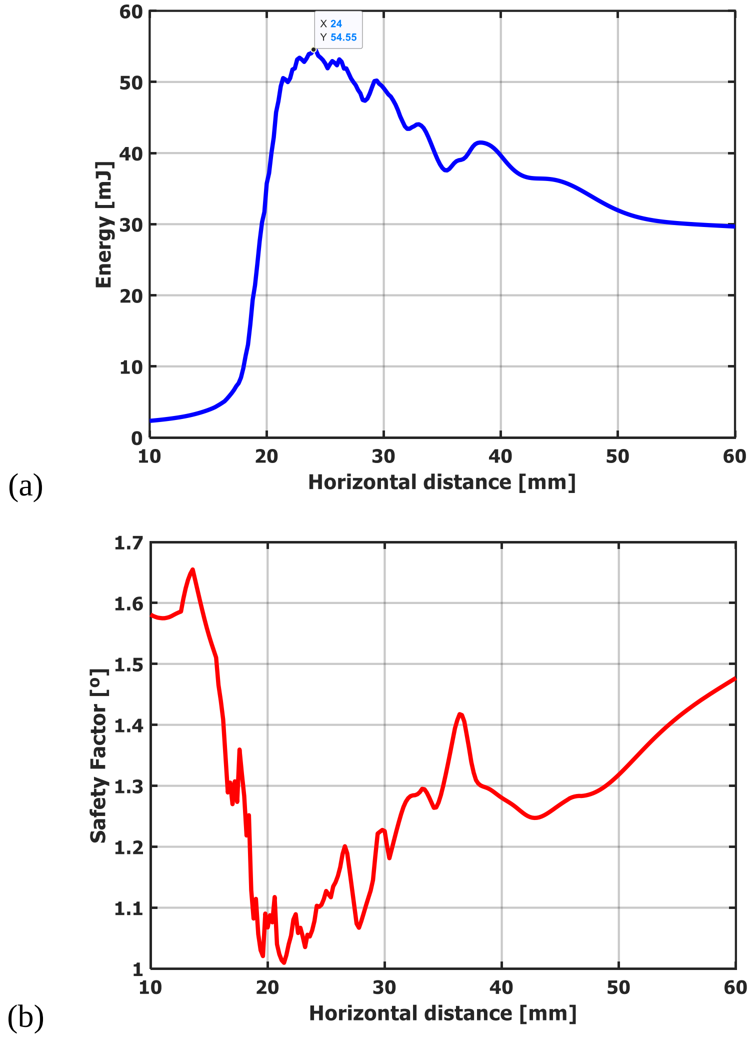

Figure 3 – Performance of the OSs with magnet for different distances *(a)* Accumulated Energy *(b)* Safety Factor

It is well-known that the non-linear forces produce a greater effect when associated with bigger excitations. As can be seen in Figure 3a, a clear increment occurs to the EH production in some distances. Analysing the response, as the distance between magnets is reduced a softening effect act, which increases the energy production, while reaching a maximum of 54.55 mJ when the distance is equal to 24 mm. The time response of the given configuration is presented in Figure 4. In our results, for numerical reasons, the response before 50 s weren't considered to evaluate the performance.

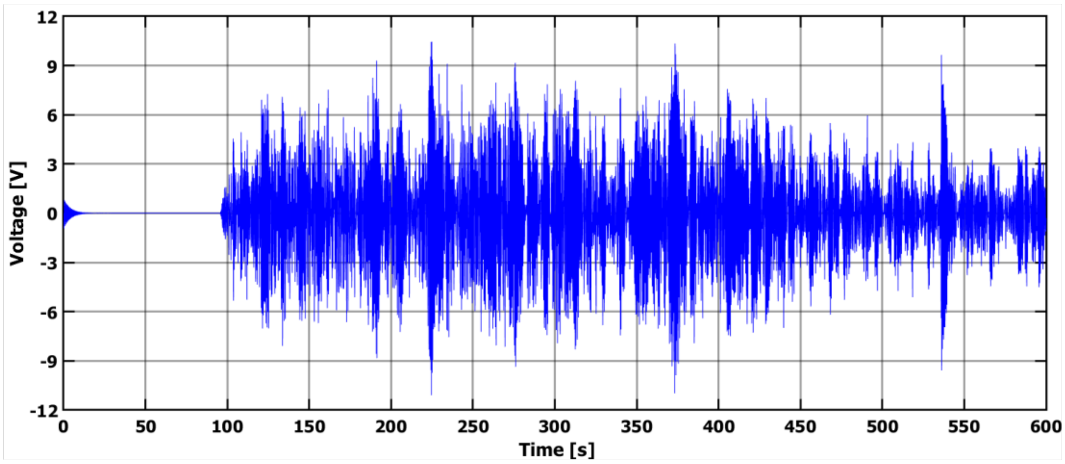

Figure 4 – Performance of the OSs with the best magnet position (24 mm)

The improvement in production can be justified due to the existence of two stable equilibrium points with a small potential barrier between them. These multiple equilibrium points are the main reason for the application of non-linear forces on vibrational EH in the literature.

However, when the distance between the magnets is less than 20 mm, the excessive proximity of the magnets produces a higher potential barrier, restricting the movement of the structure, reducing abruptly the energy extracted.

4 Conclusions and Contributions

Modern maintenance and monitoring strategies require a trustworthy real-time database to be effective, and this can be only obtained through in-situ measurement of the assets. In wagons where there is no electric energy available, the combination of sensors with energy harvesters has been the best solution. Such autonomous measurement systems for wagons can be used, provided their characteristics are set to the application and they have enough bandwidth to adapt to the changings on the vibrations in the place where they are installed. The railway environment provides ultralow frequencies, as low as 1.3 Hz, with an amplitude of 0.15 m/s²/Hz, which is much lower than usual mechanical system (10~100 Hz [21]).

To study the problem and develop an adequate design for the required Oss to power autonomous sensors in wagons, a 62-DoF wagon model was developed, which confirms the low frequencies in all parts of the vehicle.

In this study the Oss design improved with the nonlinearities generated by magnets has shown a good performance, producing up to 54.5 mJ, a growth of 81.83% in power production over the original design, without magnets. That energy could be used to power some systems under a designed duty cycle, such as accelerometers (5 mW per axis [22]), pressure manometers (45 mW [22]), ultrasonic sensors (210 μW [23],) or even derailment detectors (440 μW [24]).

The OSs has shown a promising future in the railway environment due to its compact configuration for ultralow frequencies. The soft/hardening effect of the magnet introduction on the OSs must be more widely explored, aiming to increase the power output and the frequency bandwidth.

The next steps of this research will be to develop an OSs parametric optimization for ultralow frequencies of the railway and evaluate other magnets arrangements to obtain more distant equilibrium points with a minimum barrier, that is, a more flattened potential energy profile permitting a huge amplitude of movement with small excitations. The aim is to obtain an optimized, as well as viable, and feasible autonomous sensor designed for the railway environment based on a piezoelectric Vibrational Energy Harvester.

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