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# Multiphysics design and optimization of a vibration-based energy harvester from pantograph-catenary interaction

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Abstract. In this paper, the design of a vibration-based energy harvester mounted on the railway pantograph is discussed. The system aims to feed the diagnostic system of the pantograph-catenary interaction by recovering energy from the vibrations of the pantograph head itself. The design of the system is developed through a multiphysics finite element model, parametrized by means of experimental tests. The performance of the optimized solution, in terms of generated power, highlights the affability of the proposed solution.

### **1. Introduction**

Energy harvesting technologies have undergone an increasing interest by researchers in the last years and are nowadays used in a wide range of applications, particularly the powering of sensor nodes to monitor objects or activities.

The usage of sensor nodes become more popular also in transports with monitoring systems both for the infrastructure and the vehicles. In the railway industry, such systems are widespread because they grant a high affability and security [1],[2]. However, they are usually powered through cables, losing the advantage of mobility obtained by wireless communication, and increasing the difficulty in maintenance and accessibility. For this reason, EH appears as a valid solution for the power feeding.

The proposed work focuses on the pantograph-catenary diagnostic system for high-speed train and aims at the design of an energy harvester (EH) to feed such system, recovering energy from the vibrations of the pantograph head. Analogous systems are nowadays powered through cables that must be accurately isolated and protected due to the hostile environment. Furthermore, being the overhead contact line at high voltage, a conversion system is necessary to obtain the low voltages that drive the monitoring devices, implying significant costs and encumbrance. Subsequently, the usage of an EH would resolve these issues and, at the same time, realize a zero-cost power supply [3].

Most of the EH applications in the railway field focuses on the energy recovered from brakes [4] or on track induced vibrations [5]. Looking at train-side, some application regarding the energy harvesting from train suspensions vibration can be found [6], [7]. However, at the best of our knowledge, no applications for the pantograph-catenary system were found, leading to an innovative application in this field.

Section 2 of this paper describes the pantograph-catenary system and the studies carried out to establish the vibrations of interest. Section 3 focuses on the EH concept, while Section 4 presents the experimental tests and the modelling steps. In Section 5 the multiphysics design is carried out and the last Section summarizes the results of the study.

### 2. Pantograph-catenary system: analysis of the vibration source

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An electric railway gathers the necessary power from an overhead wire system, called catenary, through a mechanical system mounted on the roof of the train, named pantograph.

The pantograph unfolds and extends along a vertical axis through an uplift mechanism, pushing the contact strips up against the underside of the contact wire to draw the electricity needed to run the train [8]. A good and continuous contact is then an important factor that directly affects the powertrain and is particularly difficult to guarantee at high speed; therefore, different solutions for both components have been developed [9]. Particularly, to guarantee a good contact, the contact wire must be as parallel to the ground as possible; for this reason, as schematized in Figure 1 (a), it is sustained through droppers, spaced of 6-8 m, by the messenger wire, which in turn is suspended by masts placed in intervals of around 65 m. So, the catenary stiffness is variable along the span and, due to the train travelling at a certain speed v, the pantograph head is subjected to forces and vibrations, linked to the masts and the droppers, that affect the contact quality [10].



Figure 1. Representation of the overhead contact line (a) and of the 3 DOFs pantograph model (b).

The usage of active pantographs is then becoming increasingly popular; they are characterized by a diagnostic system to monitor the interaction with the overhead contact line, sending a signal to the drive system to properly modify the force exerted, guaranteeing a continuous contact.

In order to perform a quantitative analysis, the pantograph Contact ATR95, currently mounted on top of high-speed trains in Italy, was chosen for this study remarking that all in the following can be extended and scaled for any pantograph.

To establish the vibration spectrum of interest, a lumped parameter model of the current collector has been developed. Although, in the literature, models with two, three or more DOFs can be found, for high speed applications the model with three DOFs has the minimum requirements to represent the system and its dynamic response with three peaks of resonance, as found in experimental tests done to physical prototype [11]. The three DOFs model of the pantograph is represented in Figure 1 (b) and the relative motion equations are presented below:

$$\begin{cases} m_{3}\ddot{y}_{3} + c_{3}(\dot{y}_{3} - \dot{y}_{2}) + k_{3}(y_{3} - y_{2}) = -m_{3}g - F_{c}(t) \\ m_{2}\ddot{y}_{2} + c_{3}(\dot{y}_{2} - \dot{y}_{3}) + c_{2}(\dot{y}_{2} - \dot{y}_{1}) + k_{3}(y_{2} - y_{3}) + k_{2}(y_{2} - y_{1}) = -m_{2}g \\ m_{1}\ddot{y}_{1} + c_{2}(\dot{y}_{1} - \dot{y}_{2}) + c_{1}\dot{y}_{1} + k_{2}(y_{1} - y_{2}) + k_{1}y_{1} = -m_{1}g + F_{up} \end{cases}$$
(1)

where  $y_1$ ,  $y_2$ , and  $y_3$  are the three DOFs. According to [11], for the pantograph under investigation the parameter set is summarized in table 1. As concerns the contact force applied on the pantograph head,  $F_c$ , which represents the interaction with the overhead contact line, it can be considered as the sum of two harmonics as in equation (2):

$$F_{c}(t) = F_{1} \cdot \cos\left(\frac{2\pi vt}{L_{s}}\right) + F_{2} \cdot \cos\left(\frac{2\pi vt}{L_{d}}\right)$$
(2)

where  $F_1$  is relative to the masts and has the lower frequency and  $F_2$  is relative to the droppers and has the higher frequency.

For the study the following operational condition has been considered: Train speed v = 300 km/h; Span between masts  $L_s = 60$  m; distance between droppers  $L_{d=} 8$  m; amplitude masts force  $F_1 = 150$  N and amplitude droppers force  $F_2 = 30$  N. The model has been implemented in MATLAB/Simulink as a set of differential equations and the pantograph head dynamics have been evaluated. Figure 2 shows the panhead acceleration frequency response and highlights that there are two main excitations due to the interaction with the catenary, one at 1.3 Hz and one at 10.4 Hz.

| Parameter             | Description                            | Value                     | Unit |
|-----------------------|--|---------------------------|------|
| $m_1, m_2, m_3$       | Masses                                 | 12.09, 19.41, 9.93        | kg   |
| $k_1, k_2, k_3$       | Stiffnesses                            | 9956.33, 19813.2, 19813.2 | N/m  |
| $c_{1}, c_{2}, c_{3}$ | First DOF Damping coefficients         | 425.92, 42.24, 73.76      | Ns/m |
| $F_{up}$              | Static force exerted by the pantograph | 70                        | Ν    |





Figure 2. FFT of the pantograph head acceleration.

# **3.** Energy harvesting system concept

Three different transducers can be used to harvest electric energy from vibrations: electromagnetic, electrostatic and piezoelectric. However, it must be considered that the railway power feeding system is characterized by high voltages both for normal and for high-speed trains (usually 3 kV/DC and 25 kV/AC respectively) [12], inducing a high electromagnetic field on the overhead contact line. Therefore, electromagnetic and electrostatic solutions could lead to severe problems. Moreover, piezoelectric transducer generally present an higher energy density [13], so it appears to be the best option.

Referring to the constitutive equations of piezoelectricity assuming a linear behaviour, normed by the IEEE Std 176 [14], the electrical energy converted by a piezoelectric system is proportional to the applied stress, so piezoelectric EH devices are designed to maximize it. For this reason, the most diffused configuration is the cantilever beam, that can be unimorph, with one piezoelectric layer, or bimorph with two piezoelectric layers. External vibrations are coupled to the cantilever through its base, causing the system to oscillate, so the piezoelectric layers undergo cycles of compression and tension generating a cyclic voltage signal across the cantilever electrodes.

A fundamental consideration in the architecture of the system is the matching between the external vibration frequency and the natural frequency of the cantilever, to maximize the deformations and thus the electrical generation. Since most vibrations can occur at low frequencies, additional proof masses are used to reduce the resonance frequency of the EH.

The concept for the implementation of the piezoelectric EH on the pantograph is presented in Figure 3, where the device is constrained between the contact strip and its housing. On this way, the excitation of the panhead is rigidly transmitted to the EH elements base.



Figure 3. EH system implementation on the pantograph head

### 4. Multiphysics modelling

#### 4.1. Finite element model

The piezoelectric EH behaviour has been simulated in COMSOL Multiphysics 5.4, applying the Finite Element Method. The physics that rule the phenomenon of interest are selected. Particularly, COMSOL presents a Piezoelectric Devices setup that includes the Piezoelectric Effect, Solid Mechanics and Electrostatics physics. Moreover, an external electrical circuit can be introduced and connected to the piezoelectric EH, with the aim to estimate the actual harvestable power. Of course, this power is maximal for a specific value of load impedance, which depends on the generator electromechanical characteristics and the base excitation frequency [15].

Different studies [16], [17] have demonstrated that the usage of a DC-DC converter, interleaved between a rectifier and a storage cell, solve this optimization problem: the optimal power point can be tracked by controlling the converter so that its input average current is proportional to its input voltage, with an average voltage/current ratio equal to the matching load impedance. So, a purely resistive load equal to the optimal value is connected to the PEH model, obtaining the maximum harvestable power.

### 4.2. Experimental model parametrization

To obtain the parameters necessary to develop a realistic finite element model, an experimental test campaign on a mock-up has been carried out. The prototype consists of eight cantilevers in unimorph configuration, composed of a steel sublayer on which is attached, with a bicomponent glue, a PZT layer. The aim is to identify the piezoelectric and the mechanical properties and parameters of the layers around the resonance to build a predictive multiphysics model.

The cantilevers are inserted between two plates and fixed on a shaker as showed in Figure 4 (a).

Figure 4 (b) depicts the experimental set-up which is composed by the EH (1); a signal generator (2) connected to an amplifier (3) that drives the shaker (4). The motions at the base of the cantilevers are measured by an accelerometer (5), while the free-end displacement of the cantilevers is measured by a laser vibrometer (6) and visualized by means an oscilloscope (8). The generated voltage is acquired by a data acquisition board connected to a voltage divider (7). A personal computer to analyse the data (9) completes the measurement chain.



Figure 4. (a) Piezoelectric energy harvester, (b) Measurement chain scheme

The geometric and electric values of the device under test are reported in Table 2.

| Parameter          | Description                               | Value | Unit |
|--------------------|---|-------|------|
| 1 <sub>p</sub>     | Piezo length                              | 70    | mm   |
| t <sub>p</sub>     | Piezo thickness                           | 0.3   | mm   |
| $l_i$              | Sublayer length                           | 95    | mm   |
| ti                 | Sublayer thickness                        | 0.2   | mm   |
| m <sub>p</sub>     | Tip mass                                  | 34    | g    |
| W <sub>plate</sub> | Energy harvester width                    | 13    | mm   |
| $R_1$              | Voltage divider resistance R <sub>1</sub> | 1     | MΩ   |
| $R_2$              | Voltage divider resistance R <sub>2</sub> | 100   | kΩ   |

| <b>Table 2.</b> Prototype's geometric and electric value | les |
|--|-----|
|--|-----|

The acceleration exerted through the shaker was sinusoidal with both amplitude and frequency (3-8 Hz) variable; so the ratio between the free end and fixed end displacement is considered. A finite element model is then developed with the same geometry and electric parameters of the experimental mock-up. Two studies are performed:

- *Eigenfrequency Analysis*: in order to evaluate the resonance frequencies of the piezoelectric energy harvester. This study highlights a natural frequency of the model around 5.9 Hz, i.e. in the prototype range.
- *Time Dependent*: to identify the electric power and voltage output of the harvester for a time dependent base excitation. The acquired results are compared with the experimental ones at resonance and the parameters of the numerical model were tuned until the results in terms of normalized-root-mean-square-error (NRMSE) were satisfying, both for mechanical and piezoelectrical behaviour.

Figure 5 and 6 show the comparison between experimental and simulation results at 5.9 Hz (resonance condition) for the cantilevers free-end displacements and generated voltage respectively. A very good matching between experimental and numerical results is achieved having a NRMSEs equal to 0.0061 for the displacements and 0.0098 for the generated voltage. The FEM model parameters identified at the end of the parametrization phase are summarized in table 3.

Lastly, to establish the reliability of the model, the response to varying the input acceleration frequency is evaluated and the frequency response of the generated voltage is reported in Figure 7 where the piezoelectric linear behaviour is highlighted.



**Figure 5.** Comparison between the free end displacement of the EH prototype with the one obtained from COMSOL



**Figure 6.** Comparison between the voltage generated by the EH prototype with the one obtained from COMSOL

|                                | *                      | •         |                   |
|--------------------------------|------------------------|-----------|-------------------|
| Parameter                      | Description            | Value     | Unit              |
| ρ                              | Density                | 7.8E+3    | kg/m <sup>3</sup> |
| d <sub>13</sub>                | Piezoelectric Constant | -1.74E-10 | m/V               |
| $\epsilon_{11}^{T}$            | Dielectric Constant    | 1.46E-8   | F/m               |
| $\epsilon_{13}^{\overline{T}}$ | Dielectric Constant    | 1.56E-8   | F/m               |
| $E_{11}^{piezo}$               | Young's Modulus Piezo  | 1.590e-11 | $m^2/N$           |
| $E_{33}^{piezo}$               | Young's Modulus Piezo  | 2.097e-11 | $m^2/N$           |
| Y <sub>sublayer</sub>          | Young's Modulus Steel  | 206       | GPa               |
| ζpiezo                         | Damping Ratio Piezo    | 0.01      | -                 |
| $\zeta_{\text{sublayer}}$      | Damping Ratio Steel    | 0.04      | -                 |

Table 3. Results of the experimental parametrization



Figure 7. Comparison of the voltage generated at the vary of frequency

# 5. Multiphysics design

The developed FEM model has been validated so that, according to its parameters, the most suitable solution for the application of interest can be built. Considering the FFT of the pantograph head acceleration (Figure 2), the harmonic at 10 Hz is easier to match, requiring a less heavy tip mass and has a higher energy content compared to the one at 1 Hz. So, the device must have a natural frequency around 10 Hz to exploit this excitation and to work at resonance. It should be noted that, although the harvested power should be maximized, the structure can't be too heavy or bulky. Variations in the geometry and mass of the cantilever beam have then been analysed trying to satisfy design constraints and the frequency match with the excitation.

Several simulations have been performed in order find the best device layout that can guarantee the maximization of the power generation observing the design constraints, leading to a final layout consists of a bimorph structure that grants an increase in the harvested power due to the double piezoelectric layer. Adopting a geometry of 95x13x0.2 mm for the substrate and one of 70x10x0.2 mm for the piezoelectric layers, a tip mass of 16 g guarantees the match between the natural frequency of the harvester and the excitation at 10 Hz. Figure 8 represents the open-circuit voltage generated by a single piezoelectric layer, calculated as a function of the input frequency, per unitary acceleration amplitude.

Lastly, applying the pantograph head acceleration, calculated with the MATLAB model as described in Section 2, as the input excitation, the optimal load and, consequently, the maximum harvestable power has been evaluated for a parallel connection of the two piezoelectric layers (Figure 9).

About 0.3 mW can be generated from a single EH piezoelectric cantilever. Thus, considering the average length of the contact strip and the width of the proposed device, about 35 energy harvesters

can be mounted for each contact strip, leading to a total power generated of 21 mW and a total added mass of approximately 1 kg.



**Figure 8.** Open-circuit voltage generated by the bimorph PEH vs. frequency



**Figure 9.** Power generated by the bimorph PEH vs. resistance load

# 6. Conclusions

The aim of this paper is the design of a piezoelectric energy harvester, mounted on the head of a railway pantograph, to recover the energy from vibrations and feed a diagnostic system, substituting the usage of electrical converters and power cables. The pantograph dynamics have been simulated through a MATLAB/Simulink model to define the forcing excitation. Then, an experimental activity has been carried out to obtain the parameters necessary to realize a consistent energy harvester finite element model in COMSOL multiphysics environment. The simulation results show an excellent match with the experimental data around the resonance. So, from these results, a modified geometry has been designed and analysed to maximize the transferable electrical power. The proposed solution appears feasible for the application of interest, yet a few considerations should be deeper examined. For example, a detailed study of the influence of the device's mass on the pantograph's dynamics should be performed to verify the mechanical interaction between the systems. Moreover, since this work was a first approach to the matter, some simplifications have been made. Particularly the interaction between the pantograph and the overhead contact line has been modelled only through the contact force, which consists of two harmonics. Yet the contact is much more complex, so it should be further investigated.

# 7. References

- [1] C. Roberts and R. M. Goodall, "Strategies and techniques for safety and performance monitoring on railways," *IFAC Proc. Vol.*, vol. 42, no. 8, pp. 746–755, 2009, doi: 10.3182/20090630-4-es-2003.00123.
- [2] "Modern techniques for condition monitoring of railway vehicle dynamics," doi: 10.1088/1742-6596/364/1/012016.
- [3] A. Michael Kolbe and D.-I. Wilhelm Baldauf, "Compact contact force measurement systemonline diagnosis of the overhead line system with regular trains."
- [4] K. Chalkhure, S. Jijankar, A. Dhore, A. Sanganwar, V. R. Parihar, and A. Professor, "UGC Approved Journal Regenerative Braking System for Energy Harvesting from Railways and Vehicles: A Review and an Approach," *Int. J. Innov. Res. Electr. Electron. Instrum. Control Eng. ISO*, vol. 3297, pp. 2321–5526, 2007, doi: 10.17148/IJIREEICE.2017.51004.
- [5] Y. Tianchen, Y. Jian, S. Ruigang, and L. Xiaowei, "Vibration energy harvesting system for railroad safety based on running vehicles," *Smart Mater. Struct.*, vol. 23, no. 12, p. 125046, Nov. 2014, doi: 10.1088/0964-1726/23/12/125046.
- [6] A. Genovese, S. Strano, and M. Terzo, "Design and multi-physics optimization of an energy harvesting system integrated in a pneumatic suspension," *Mechatronics*, vol. 69, p. 102395, 2020, doi: 10.1016/j.mechatronics.2020.102395.
- [7] A. Genovese, S. Strano, and M. Terzo, "Study of a Vibration-Based Piezoelectric Energy

Harvester Embedded in an Air Spring," in 5th International Forum on Research and Technologies for Society and Industry: Innovation to Shape the Future, RTSI 2019 - Proceedings, 2019, pp. 314–319, doi: 10.1109/RTSI.2019.8895557.

- [8] T. X. Wu and M. J. Brennan, "Basic analytical study of pantograph-catenary system dynamics," *Veh. Syst. Dyn.*, 1998, doi: 10.1080/00423119808969460.
- [9] G. Poetsch *et al.*, "Pantograph/catenary dynamics and control," *Veh. Syst. Dyn.*, 1997, doi: 10.1080/00423119708969353.
- [10] T. Wu X and M. J. Brennan, "Active vibration control of a railway pantograph," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 211, no. 2, pp. 117–130, 1997, doi: 10.1243/0954409971530969.
- [11] R. M. G. A. Vieira, "High Speed Train Pantograph Models Identification Multibody Dynamics Overview," no. December, pp. 1–10, 2016.
- [12] R. T. Today, "Railway Electric Power Feeding Systems," *Transport*, vol. 8, no. 10, pp. 81–83, 1998.
- [13] F. Yildiz, "Potential Ambient Energy-Harvesting Sources and Techniques," *J. Technol. Stud.*, vol. 35, no. 1, Sep. 2009, doi: 10.21061/jots.v35i1.a.6.
- [14] A. American and N. Standard, "IEEE Standard on Piezoelectricity: An American National Standard," *ANSI/IEEE Std 176-1987*, pp. 8–10, 1988, doi: 10.1109/IEEESTD.1988.79638.
- [15] A. Koszewnik, P. Grześ, and W. Walendziuk, "Mechanical and electrical impedance matching in a piezoelectric beam for Energy Harvesting," *Eur. Phys. J. Spec. Top.*, vol. 224, no. 14–15, pp. 2719–2731, 2015, doi: 10.1140/epjst/e2015-02585-5.
- [16] E. Lefeuvre, D. Audigier, C. Richard, and D. Guyomar, "Buck-boost converter for sensorless power optimization of piezoelectric energy harvester," *IEEE Trans. Power Electron.*, 2007, doi: 10.1109/TPEL.2007.904230.
- [17] N. Kong, D. S. Ha, A. Erturk, and D. J. Inman, "Resistive impedance matching circuit for piezoelectric energy harvesting," in *Journal of Intelligent Material Systems and Structures*, 2010, doi: 10.1177/1045389X09357971.