

# PERFORMANCES EVALUATION OF AN AUTONOMOUS SENSING NETWORK NODE FOR RAIL VEHICLES SUPPLIED BY A PIEZOELECTRIC ENERGY HARVESTER

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**Abstract:** This work describes the assembling and experimental characterization of a piezoelectric energy harvester for the supplying of the nodes of an autonomous sensors network for trains. The macrodimensional prototype developed is used to characterize the electro-mechanical outputs when some fundamental parameters vary. A semiempirical analytic formulation is introduced, which is able to predict the power generated for a specific excitation and harvester configuration. The efficiency and the duty cycle of one sensing node were finally validated on a scaled railway bogie that is able to simulate the real working conditions.

**Keywords:** piezoelectric generator, energy harvesting, reliability, safety, sensors network, train, MEMS

## INTRODUCTION

Structural monitoring techniques are commonly adopted to control the proper functioning of vehicles and to predict their malfunctioning or the failure of critical components. Other applications of sensors on vehicles are addressed to the measurement of static and dynamic parameters in normal working conditions, or to provide positioning data (navigation systems). The sensors for vehicular applications are usually supplied by wire by the central engine or battery; however the proliferation of measurement points may dramatically complicate the cabling architecture and cause reliability and maintenance problems. These reasons are pushing the research to develop self-powered sensing systems to convert the kinetic energy of vibrations to electric power [1-3]. Rail vehicles are the most promising candidates for the first industrial development of sensors networks supplied by energy harvesters: trains for goods transportation are not equipped by electric cabling and a very large amount of vibrations are associated to these vehicles.

Several strategies were investigated in the literature to convert vibrations to electric power; the most popular transduction principles are piezoelectric, magnetic-inductive and capacitive. Each strategy is characterized by specific benefits, but even by intrinsic limitations. For instance, piezoelectric harvesters have a limited mechanical reliability due to the repetitive bending; the inductive generators have a poor tunability and a small specific power per unit of volume; the electric pre-load required by capacitive harvesters strongly reduces their efficiency [4-6]. Open problems for the electro-mechanical design of energy harvesters for vehicular applications are the optimization of the efficiency and the introduction of tuning strategies. The piezoelectric generators have been considered in this work because of the large availability of the components, the ease assembling, the propensity to be tuned on the excitation frequency and the acceptable output current [7, 8].

The network node proposed in this work should

include a piezoelectric micro energy harvester, probably built by the MEMS technology [9]; however the approach adopted here is to use a macrodimensional prototype for the harvester to estimate the conversion efficiency and to define some semi-empirical equations to calculate the power generated. The experimental tests are focused on the characterization of the harvester at different working conditions and dynamic configurations; the final goal is to relate some crucial parameters (acceleration, frequency, proof mass, mechanical stiffness, electric load, etc.) to the harvested power. These relations are still valid at microscale and can be easily used to design the MEMS energy harvester for the definitive autonomous network node. The calculation of the duty cycle of the system is also provided, by simulating the real working conditions of the node on a scaled railway bogie running at 120km/h.

## THE NETWORK NODE

The distributed sensors network is responsible of the detection of some safety-critical parameters on the train, as the temperature increasing in the stressed components where a damage process is occurring. Many parts of the vehicle are subjected to alternate loads, which may cause a fatigue damaging process initiation; other components such as ball bearings are subjected to wear degradation. All these effects are accompanied by a considerable temperature increasing, which should be detected in order to prevent failures. The detection of acceleration on three axes is also useful to monitor the vibrations caused by the rail-wheels contact and to store the loads history. Anomalous peaks of vibrations caused by the presence of debris can be recognized as well as their eventual effects on critical components. The network node also needs a transmission system to send the measurements to the main host, where data are processed and analyzed. At this purpose, a RF device with specific communication protocol can be integrated into the node. The schematic of the network node is

represented in Fig. 1; the alternate electric power generated by the harvester is rectified by a simple electric circuit (diodes bridge and leveling capacitor) and then stored in a battery. The sensors and the RF transceiver are activated at fixed time intervals, which are compatible to the duty cycle of the system.



Fig. 1: Schematic of the self-powered network node for applications in rail vehicles.

Table 1: Piezoelectric harvester properties.

Description	Value	Unit
Beam length	51 - 53 - 55 - 57 - 59 - 61	mm
Beam width	35	mm
Beam thickness	0.5	mm
Beam mass	3.5	g
Young's modulus	23.3	GPa
Capacitance	90 - 150	nF
Operating temperature	-20 ÷ 180	°C
PVC layer thickness	0.19	mm
PVC Young's modulus	0.1 - 0.25	Gpa
Proof mass	12.05 - 19.08 - 25.48 - 30.70 - 36.62	g

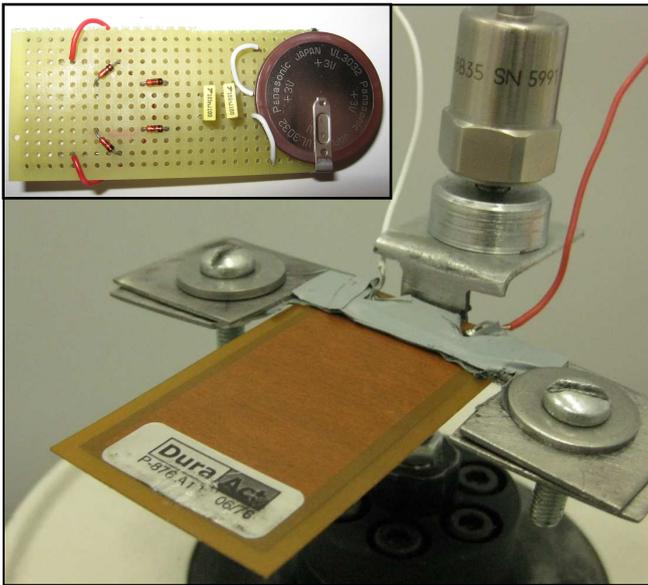


Fig. 2: Piezoelectric harvester prototype mounted on the shaker and rectification circuit.

## THE HARVESTER PROTOTYPE

The macrodimensional prototype of the energy harvester was built according to the cantilever shape with proof mass on the tip, commonly used in the literature [3]. The beam consists of a commercial PIC255 piezoceramic layer (200 $\mu$ m thickness, 90nF capacity) and an insulating polymeric package (P-876.A12 Dura Act); the electrical properties and geometrical dimensions of the beam are listed in Table 1. The dynamic response of the cantilever was changed by introducing a variable proof mass on the tip and by increasing its structural stiffness with additional

adhesive layers of PVC, attached to the upper and lower surfaces. Also, the length of the beam was modified to tune the resonance frequency. The proof masses used and the properties of PVC layers are listed in Tab. 1. A four diodes bridge and two leveling capacitors were used to rectify the voltage and current generated by the piezoelectric beam. The power storage is represented by a Panasonic VL3032 lithium-vanadium rechargeable battery, which was assembled in the electric circuit; the characteristics of the battery are: 30mm diameter, 3.2mm thickness, 100mAh capacity, -20 to 60°C temperature range. The piezoelectric cantilever and the rectification circuit are reported in Fig. 2.

## DYNAMIC BEHAVIOR

An electro-mechanical shaker was used to apply the alternate force on the constrained side of the piezoelectric beam, to simulate the environment vibration. The acceleration imposed by the shaker was controlled in open-loop with an accelerometer and the dynamic response of the generator was detected by measuring its output voltage.

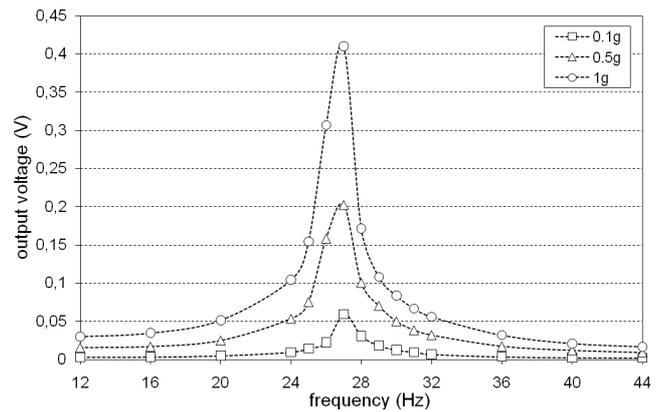


Fig. 3: Output voltage curve at different accelerations.

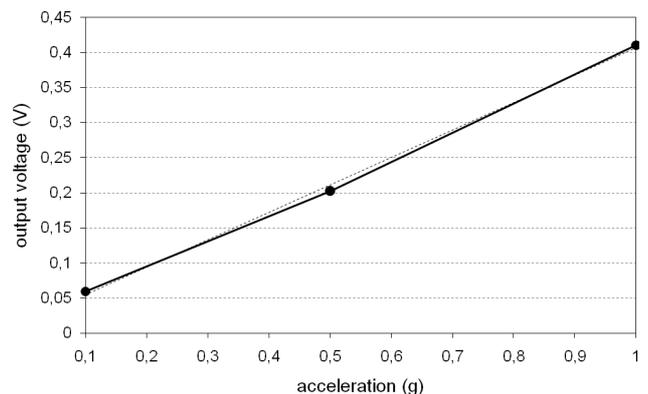


Fig. 4: Relation between acceleration and output voltage at resonance conditions.

## Preliminary Characterization

In this section, the electro-mechanical properties of the piezoelectric harvester are investigated. Figure 3 reports the dynamic response of the piezo beam (without proof mass or additional stiffening layers) in terms of output voltage for three levels of acceleration.

The relationship between the acceleration and the output voltage at resonance condition is approximately linear for the range of frequencies considered, as shown in Fig. 4.

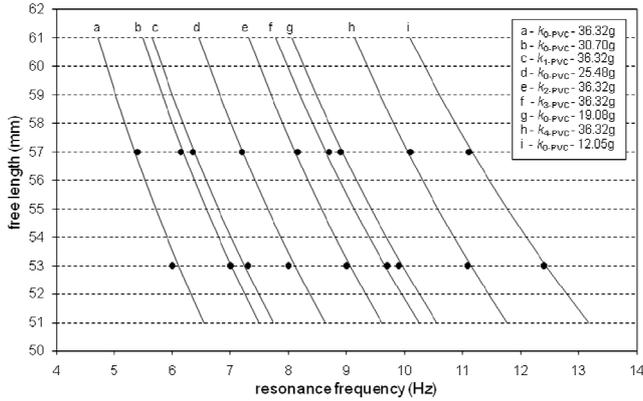


Fig. 5: FEM simulations and experimental measurements (black dots) of resonance frequency at different configurations of mass and stiffness.

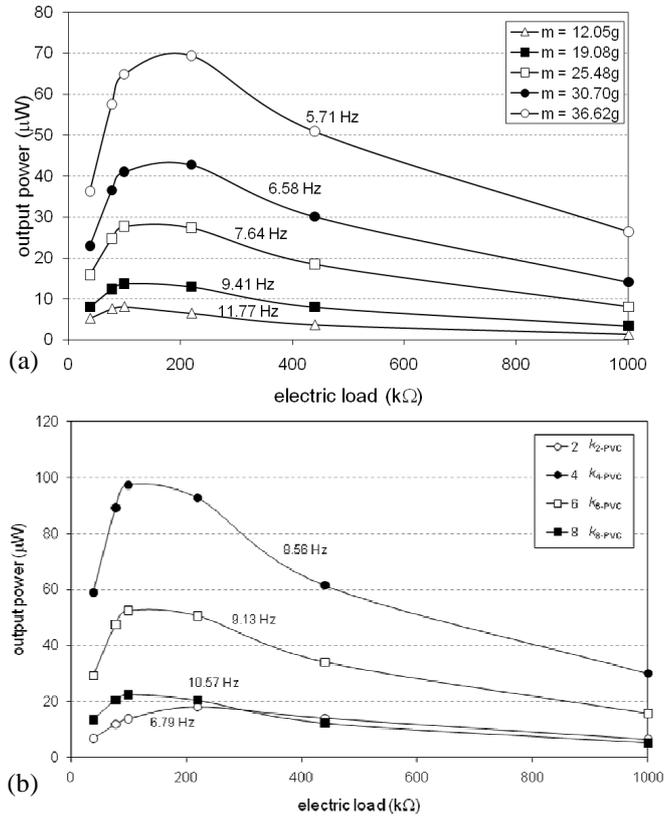


Fig. 6: Output power at variable proof masses (a) and beam stiffness (b) measured at different electric loads.

### Resonance Tuning

To tune the resonance frequency of the harvester on the driving frequency of the external force is a key feature of the design. The development of low-power tuning strategies is determinant to increase the global efficiency of the device for vehicular applications, where the vibration spectrums are pretty wide.

A structural FEM model of the piezo beam was used to calculate its resonance frequency in presence of variable proof masses and adhesive PVC layers.

Additionally, the effect of the deflection length was included. The results predicted by the simulations were validated by experiments for some configurations of mass, stiffness and free length. Figure 5 reports the results obtained for two lengths of deflection, respectively 53 and 57mm; the stiffness of the beam is indicated as  $k_{i-PVC}$ , where  $i$  corresponds to the number of PVC layers attached to the surfaces. The beam stiffness without additional PVC layers is indicated as  $k_{0-PVC}$ .

### Electric Dimensioning

The output power of the piezoelectric beam having stiffness  $k_{0-PVC}$  and variable proof masses is reported in Fig. 6a; it was calculated as  $P=RI^2$ , where  $I$  is the current measured at the output. The maximum power corresponds to an optimum electric load. The characterization was performed with the shaker at resonance and 0.2g acceleration; the resonance frequencies are in the range 5.71-11.77Hz depending to the proof mass considered and are reported near each curve. Figure 6b reports the same measurements when the proof mass  $m=36.62g$  and variable stiffness are introduced; in this case, the resonance frequencies are in the range 6.8-10.6Hz depending to the stiffness of the beam.

### ANALITIC MODEL OF OUTPUT POWER

The analytic model introduced in this section is based on empirical coefficients derived from the experimental characterization activity. The most important parameters affecting the electro-mechanical properties of the harvester and its output power were analyzed at variable accelerations. The following compact formulation for the output power was obtained:

$$P = e^{\frac{\alpha + \beta}{R} + \gamma \ln(R)} \frac{aC(0.027m - 0.025)}{18} f(k), \quad (1)$$

where  $P$  [ $\mu W$ ] is the output power,  $R$  [ $\Omega$ ] is the electric load,  $a$  [g] is the acceleration,  $C$  [nF] is the piezo beam capacitance and  $m$  [g] is the proof mass. The empirical coefficients are

$$\alpha = 11.63m^{1.0059/m} \quad (2)$$

$$\beta = 23.81m^2 - 1057.09m - 80352.73 \quad (2)$$

$$\gamma = 0.013m - 1.12$$

and the stiffness function  $f(k)$  is

$$f(k) = 1 \quad (n = 0) \quad (3)$$

$$f(k) = \frac{1}{0.27n^2 - 2.48n + 6.05} \quad (n > 0) \quad (4)$$

where  $n$  is the total number of PVC adhesive layers applied to the beam.

### EXPERIMENTS ON A RAILWAY BOGIE

The piezoelectric harvester was mounted on a 1:4 scaled model of railway bogie [10] to characterize the performances of a sensing node in real working conditions (Fig. 7). The resonance of the harvester was tuned to the bogie excitation frequency (5.71Hz) by

adding the proof mass  $m=36.62\text{g}$ ; no additive PVC layers were used. The acceleration measured at resonance was  $a=1.53\text{g}$ . The measured output power is reported in Fig. 8 (black dots); the output power of a higher capacitance (150nF) piezo beam is also reported (white dots). The analytic predictions given by the semiempirical model of Eq. (1) are plotted as well.

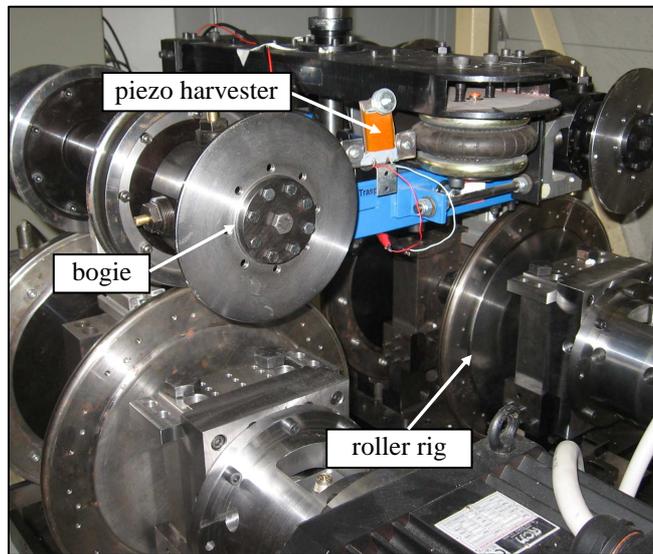


Fig. 7: Scaled bogie for the node characterization.

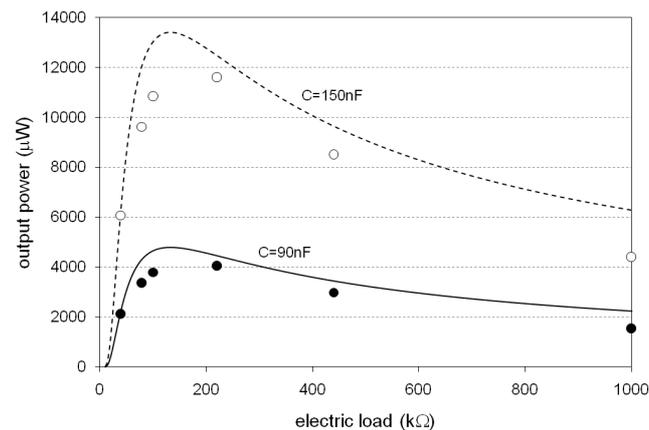


Fig. 8: Comparison between measurements and analytic predictions of the output power at 1.53g acceleration on the railway bogie.

Table 2: Efficiency of the self-powered node.

Devices supplied	Residual charge after 1s	Harvesting time to restore the initial charge	
		C = 90nF	C = 150nF
2-axes accelerometer	99.8%	0.3s	-
2-axes accelerometer 3-axes accelerometer	97.6%	2s	1s
2-axes accelerometer RF transceiver	78.6%	16s	6s
2-axes accelerometer 3-axes accelerometer RF transceiver	77.4%	17s	7s

The duty cycle of the network node was calculated, by considering the presence of a 2-axes linear accelerometer (LIS2L02AS4 ST Microelectronics:  $\pm 3\text{g}/\pm 6\text{g}$ ), a 3-axes linear

accelerometer (LIS3L02AS4 ST Microelectronics:  $\pm 3\text{g}/\pm 6\text{g}$ ) and a RF transceiver (CC2520 Texas Instruments: 2.4GHz, ZigBee protocol). After 1s of supplying, the time required by the harvester to restore the full battery charge is reported in Table 2.

## CONCLUSIONS

The design and characterization of a piezoelectric energy harvester for sensors network on trains was introduced. The model proposed is suitable to design small harvesters at the microscale; further efforts are needed to build a proper package for the node and to define algorithms for converting the measured parameters to thresholds of alarm for the failures prevention.

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