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An original device for train bogie energy harvesting: a real application scenario

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Abstract. Today, as railways increase their capacity and speeds, it is more important than ever to be completely aware of the state of vehicles fleet's condition to ensure the highest quality and safety standards, as well as being able to maintain the costs as low as possible. Operation of a modern, dynamic and efficient railway demands a real time, accurate and reliable evaluation of the infrastructure assets, including signal networks and diagnostic systems able to acquire functional parameters. In the conventional system, measurement data are reliably collected using coaxial wires for communication between sensors and the repository. As sensors grow in size, the cost of the monitoring system can grow. Recently, auto-powered wireless sensor has been considered as an alternative tool for economical and accurate realization of structural health monitoring system, being provided by the following essential features: on-board micro-processor, sensing capability, wireless communication, auto-powered battery, and low cost. In this work, an original harvester device is designed to supply wireless sensor system battery using train bogie energy. Piezoelectric materials have in here considered due to their established ability to directly convert applied strain energy into usable electric energy and their relatively simple modelling into an integrated system. The mechanical and electrical properties of the system are studied according to the project specifications. The numerical formulation is implemented with in-house code using commercial software tool and then experimentally validated through a proof of concept setup using an excitation signal by a real application scenario.

Keywords: wireless technology; energy harvesting; piezoelectric sensor

1. Introduction

The development of wireless sensor and communication node networks has received a great deal of interest in research communities over the past few years. Applications envisioned from these node networks include building structural health monitoring and environmental control systems, smart homes and tracking devices on animals in the wild. However, as the networks

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increase in number and the devices decrease in size, the proliferation of these autonomous microsensors raises the problem of an effective power supply. The conventional solution is to use electrochemical batteries for power. However, batteries can not only increase the size and weight of microsensors but also suffer from the limitations of a brief service life and the need for constant replacement, which is not acceptable or even possible for many practical applications. On the other hand, simultaneous advances in low power electronic design and fabrication have reduced power requirements for individual nodes (Shul and Lien 2006). It has been predicted that power consumption could be reduced to tens to hundreds of microwatts depending on the application (Anton and Sodano 2007). This opens the possibility for self-powered sensor nodes, and the need to power remote systems or embedded devices independently has motivated many research efforts focused on harvesting electrical energy from various ambient sources. These include solar power, thermal gradients and vibration (Mitcheson *et al*. 2008). Among these energy scavenging sources, mechanical vibration is a potential power source that is abundant enough to be of use, is easily accessible. Vibration energy can be converted into electrical energy through piezoelectric, electromagnetic and capacitive transducers. Among them, piezoelectric vibration-to-electricity converters have received much attention, as they have high electromechanical coupling and no external voltage source requirement (Zhu *et al.* 2009, Liu *et al*. 2009).

In the previous literature, only the harvested energy was emphasized as a function of the rectified voltage or its corresponding DC load resistance. To be more general, it is shown (Wu *et al*. 2009) that both the harvesting energy and dissipated energy change with the rectified voltage; in addition, in addition, these two portions of energy also depend on the ratio between the rectifier voltage drop and the open circuit voltage. Three experiments are carried out with a synchronized switch harvesting on inductor device to measure its performances on energy harvesting, energy dissipation, and structural damping. The experimental results show good agreement with theoretical analysis. The functional relations among these branches of energy flow are found (Wu *et al*. 2009, Junrui and Wei-Hsin 2011). Experiments are carried out with a synchronized switch harvesting on inductor device to measure its performances on energy harvesting using multiple piezoelectric oscillators (Lien and Shu 2012) for parallel connection and (Lin *et al*. 2013) for series connection. The switch is triggered at the extremes of the overall equivalent voltage source in steady-state regime. The result demonstrates that the parallel-SSHI array system exhibits higher power output with moderate bandwidth improvement, while the series-SSHI system delivers a pronounced wideband at the cost of peak harvested power. The standard array system shows a mild ability in power harvesting between these two SSHI systems.

Roundy *et al.* (2004) performed a study to investigate amount of power generated through the vibration of a piezoelectric plate, as well as two methods of power storage. The plate was excited using an electromagnetic shaker with both resonant and random excitation signals. It was found that the piezoelectric could generate a maximum power of 2mW when excited at the resonant frequency of the clamped-free plate. In addition, the ability of the piezoelectric plate to store its power in both a capacitor circuit and a rechargeable battery were tested. This paper was the first to demonstrate that the power output of piezoelectric material was able to recharge a fully discharged battery without the use of external energy sources.

Since then, piezoelectric elements used for power harvesting in various forms of structure have been proposed to serve specific purposes. Ng and Liao (2005) have used the piezoelectric element simultaneously as a power generator and a sensor. They have evaluated the performance of the piezoelectric sensor to power wireless transmission and validated the feasibility of the self-powered sensor system. Erika *et al*. (2005) have analyzed and developed a piezoelectric generator based on a two-layer bending element and used it as a basis for generator design optimization. Similar works based on cantilever-based devices using piezoelectric materials to scavenge vibration energy. Membrane has modeled and designed piezoelectric plates (membranes) to harvest energy from pulsing pressure sources. Other harvesting schemes include the use of piezoelectric 'cymbal' transducers operated in the {3-3} mode. A vibration energy harvesting device using a modified rectangular cymbal transducer has been designed and fabricated.

The electrical properties under different frequencies, load resistances, and proof masses were studied systematically (Kim *et al.* 2004). With the increasing of the proof mass, the resonance frequency of the system decreases and the output from the device increases. Under the cyclic force of 0.55 N (17.0 g proof mass), the device can generate a peak voltage of 45.7 V and a maximum power of 14 mW at 500 Hz with a matching load resistance of 74 k (Kim *et al*. 2005).

In this work the authors focused on the design of an original power harvesting device, using piezoelectric elements to be applied in a train derailment detector system, supplying a wireless transmission unit (Amoroso *et al.* 2011).

The first part of the work is a presentation of the harvesting system motivations and requirements, related to the specific field of application. The excitation signal coming from the train bogie dynamic response has been at first characterized on the field, during a typical train route and the bogie geometry also studied for finalizing the system design in terms of maximum dimensions and easy access for installation and inspection. Then, assessed theoretical and numerical models used for the simulation of the piezoelectric energy transduction are applied and optimization for the electrical wiring for multiple piezoelectric elements is also presented. A preliminary experimental validation at subcomponent level is performed to check the functionality of a simpler system, finally the full scale energy harvester is tested by using a slip table simulating the same train acceleration and vibration amplitude in time domain.

2. Bogie harvesting system: motivations and requirements

Rail vehicles are subject to innumerable elements and activities that have a detrimental effect on their conditions and potentially on the safety of passengers.

Infrastructure condition monitoring is not only a legal mandatory requirement but is also the basis for cost-efficient maintenance and renewal planning.

An automatic system for real time detection of such defects, as a means for preventing accidents would allow for train predictive maintenance schedule offering an opportunity for cost-saving and time inspection speed-up. Such diagnostic system must be able to acquire functional parameters for commercial wireless technology (GSM and DCS), which has the advantage to allow connections between an unspecified number of users, the ability to allow connectivity as a function of the traffic; create a communication system without the need to lay cables or optical fibres in places where this would be no economic or impossible as the case of a train coaches.

The device herein presented is conceived to supply such a wireless diagnostic sensors network while harvesting energy from a train bogie during its route. The system must be installed on the bogie of a train (see Fig. 1) where the exiguous available space on one side, and the transversal stresses on the other are the main constraints affecting the architecture design. Moreover the system must be compliant with a robust and compact layout and conceived for a simple access for maintenance and inspections. The geometry and mechanical requirements of the system have been fixed according to the specific operative working conditions of the train. The freight train acceleration from Brindisi to Foggia are acquired and processed by using the LMS software.

The acquisition data lasted about 5h30' and during this interval the train stopped 6 times before reaching its final destination. Five travel phases are obtained as reported in Table 1.

The vertical accelerations, monitored during periods 3, 4 and 5 as fraction of gravity acceleration "*g*" are plotted in Fig. 2. The acceleration spectrogram is reported in Fig. 3. Harmonics are present in the band ranges of 40-50 Hz, 70-80 Hz and 95-105 Hz. The highest level of acceleration is present in the first range band with a mean amplitude of 0.6 g (see Fig. 4).

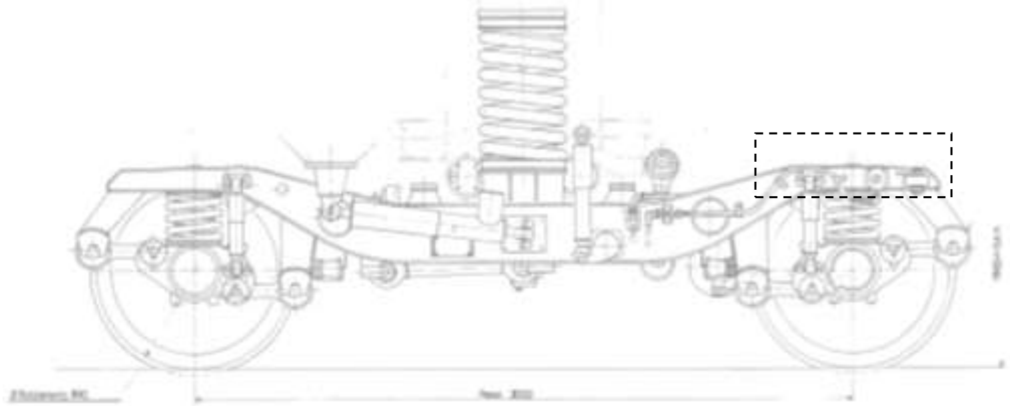

Fig. 1 Detail of a train bogie. The black rectangle identify a possible installation area

Table 1 Temporal phases during the route

Event	Start time	End time	Description (where available)
1	16:00 (2400s)	16:10 (3000s)	Transfer from the railway station to the station of Brindisi
2	16:42 (5200s)	16:57 (6250s)	Departure from the station of Brindisi and intermediate stop after 15 minutes
3	17:31 (8200s)	18:39 (12300s)	Not available
4	18:54 (13250s)	19:20 (14750s)	Not available
5	19:30 (15350s)	20:40 (19550s)	Arrival in Foggia station

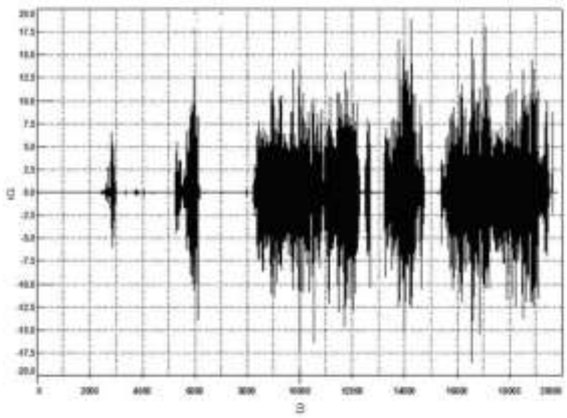

Fig. 2 Train bogie acceleration in the transversal direction – z axes

The acceleration spectrogram is reported in Fig. 3. Harmonics are present in the band ranges of 40-50 Hz, 70-80 Hz and 95-105 Hz. The highest level of acceleration is present in the first range band with a mean amplitude of 0.6 g (see Fig. 4).

The system is expected to supply a wireless sensor net from a random excitation providing an acceleration of 0.6 g within a resonance band of 40-50 Hz, as summarized in the Table 2.

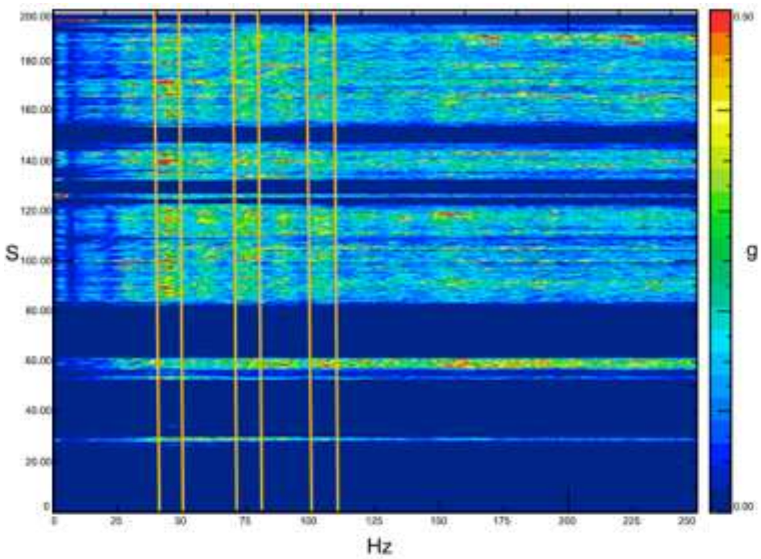

Fig. 3 Spectrogram of the accelerations: harmonics (highest g values, red color) in the band ranges of 40-50 Hz; 70-80 Hz; 95-105 Hz

Table 2 Harvesting system specifics

Transducer	Signal	Acceleration (g)	Frequency band (Hz)
PZT	random	0.6	40-50

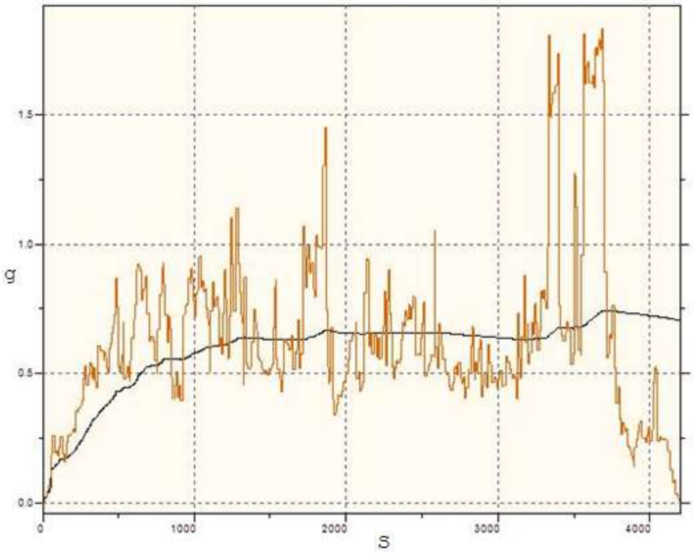

Fig. 4 Time evolution of the mean overall acceleration value (black curve)

A random signal generator (DAQPad-6052E, National Instruments) is adopted for experimental test. A band pass filter in the range of 40-50 Hz is applied to the signal and a running LEQ is then calculated. In the following figure the mean overall acceleration is plotted in function of time (time frame: 0-4200 s) (see Fig. 4).

The system is provided by a circular base that can be fixed by bolting to the train bogie.

The vertical acceleration induced by the train motion is then rigidly transmitted to each cantilever.

The pendulum arms are instrumented with co-located piezoelectric transducers.

In what follows, the analytical model for piezo-transducer is shortly resumed and the power generation from parallel piezo-electrical connection is formulated in terms of the optimal resistive load.

3. Mathematical model

A stack of cantilevers is realized. The central block is made of recessed modular elements and the cantilevers can be hosted within the recess and fixed in their middle point to the central block. Each arm of the stack represents a pendulum to be opportunely tuned to the resonance of interest by load masses. According to the signal acquisition, the harvesting system must be designed to have a first bending resonance in the range of 40-50 Hz. The value of such frequency has been fixed to 43.75 Hz.

The system based on cantilever beam configuration installed as single slot. Each beam have a mass placed, on the free end has been preferred mostly for two reasons. First, the cantilever mounting results in the lowest stiffness for a given size; second, the cantilever configuration results in the highest average strain for a given force input. Because the converted power is closely related to the average strain in the bender, a cantilever mounting is preferred. The layer is made of spring steal because of its high yield strength which gives an excellent fatigue behaviour. A “comb configuration” has been adopted in order to reduce the mechanical phase shift between the slot (beams) and because of its compact shape that optimizes the space requirement.

The concept of the device is shown in Fig. 5.

A full description of the piezoelectric effect and the methods used in this paper, can be resumed from previous journal papers and conference proceedings of the authors (Ciminello *et al.* 2008). Nevertheless the fundamentals details can be also retrieved in (Crawley and de Luis 1987, Crawley and Anderson 1990, Hagood *et al*. 1990, Smits and Choi 1991, Smits *et al.* 1991, Near and Craig 1996, Inman and Cudney 2000, Niezrecki et al 2001,), as well as numerous books published on this topic (Clark *et al.* 1998, Srinivasan and McFarland 2001, Worden *et al*. 2003). For sake of completeness, a resume of the analytical model considered in this work, based on a 2D finite element formulation developed by the (Ciminello *et al.* 2010) is shortly presented.

The application of piezoelectric materials in power harvesting systems contains many variables which can be manipulated to obtain electrical energy from ambient vibration. There are some parameters to be taken into account for an optimal design, like the natural frequency of each beam and the beam thickness.

The next step of this research activity is focused on improving the efficiency of piezoelectric power harvesting device through the optimization of these parameters. Let us assume the classical working condition:

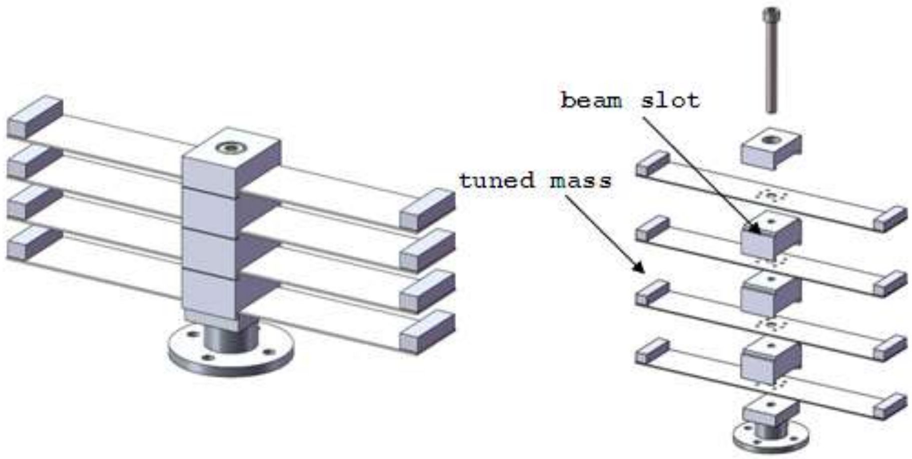

Fig. 5 Full assembled system (right); system subcomponents exploited view (left)

- the piezoelectric and the hosting structure are perfectly bonded and in linear elasticity condition;
- the electrodes completely cover the surfaces whose thickness is negligible;
- the excitation frequency is far from the piezoelectric resonance so static parameters can be adopted for the piezo.

Moreover:

The piezo is transversally isotropic

$$\begin{aligned} d_{31} &= d_{32} \\ d_{24} &= d_{15} \\ \epsilon_{11} &= \epsilon_{22} \end{aligned} \tag{1}$$

The thickness is negligible with respect to the in plane dimensions

$$\begin{aligned} \sigma_{xx}(z) &= \sigma_{xx,0} \\ \sigma_{yy}(z) &= \sigma_{yy,0} \\ \sigma_{zz} &= 0 \end{aligned} \tag{2}$$

Polarization axis is along z and the electric field component can be assumed uniform along the thickness

$$\begin{aligned} E_x &= E_y = 0 \\ E_z(x,y) &= E_{z,0} = -\frac{V_{z,0}}{t_p} \end{aligned} \tag{3}$$

In what follows, without losing generality, the pedix "0" will be removed. The 2D constitutive law of a piezoelectric material, homogeneous, isotropic, linearly elastic and poled along the z direction, is given by (Ciminello *et al*. 2010)

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \\ E_z \end{Bmatrix} = \frac{Y_p}{\left[\epsilon_{33}(\nu-1)+2Y_p d_{31}^2\right]} \begin{bmatrix} \frac{-\epsilon_{33}+d_{31}^2 Y_p}{(1+\nu)} & -\frac{\nu\epsilon_{33}+d_{31}^2 Y_p}{(1+\nu)} & 0 & d_{31} \\ -\frac{\nu\epsilon_{33}+d_{31}^2 Y_p}{(1+\nu)} & \frac{-\epsilon_{33}+d_{31}^2 Y_p}{(1+\nu)} & 0 & d_{31} \\ 0 & 0 & \frac{\epsilon_{33}(\nu-1)+2d_{31}^2 Y_p}{2(1+\nu)} & 0 \\ d_{31} & d_{31} & 0 & \frac{(\nu-1)}{Y_p} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ D_z \end{Bmatrix} \tag{4}$$

From the last row of Eq. (4), the direct piezoelectric effect can be derived at open circuit condition, that is to say when $Dz=0$. The voltage is retrieved according the definition $Ez=Voc/t_p$ and the following equation can be written

$$V_{oc} = \frac{t_p Y_p d_{31}}{\epsilon_{33}(\nu-1)+2Y_p d_{31}^2}(\varepsilon_x+\varepsilon_y) = \frac{(1-\nu)}{[(\nu-1)+2k_{31}^2]} t_p Y_p g_{31}\varepsilon_x \tag{5}$$

When a resistor R is added to the circuit, the expression of the voltage becomes

$$V_R = V_{oc} - \frac{q}{C} \tag{6}$$

Passing to the first derivative and then to the Laplace domain (recalling the definition of current intensity *i=dq/dt* and substituting *dV/dt=jωV* at each occurrence), Eq. (6) turns into:

$$V_R = \frac{j\omega RC}{(j\omega RC + 1)} V_{oc} \tag{7}$$

An estimation of the optimal thickness ratio between piezo and beam can be evaluated in a static or quasi static regime. For co-located patches the energy transmission efficiency can be defined as follows; results are plotted in Fig. 6

$$\eta_{\_2pzt} = \frac{U_{2pzt}}{E_p V_p \frac{\Lambda^2}{2}} = \frac{24\frac{E_s t_s}{E_p t_p}}{\left(6 + \frac{E_s t_s}{E_p t_p}\right)^2} \tag{8}$$

According to Eq. (8), the optimal beam thickness is 0.6 mm when a pzt of 0.4 mm is actually used.

A parallel electrical connection for piezoelectric is the optimal configuration in terms of energy generation, as also demonstrated in the following.

If a resistive load is added in the loop and a simple sine excitation corresponding to an angular frequency ω is applied, piezo generators can be sketched as the equivalent Norton scheme (see Fig. 7) and, the voltage over the load can be then expressed by using the classical partition rule.

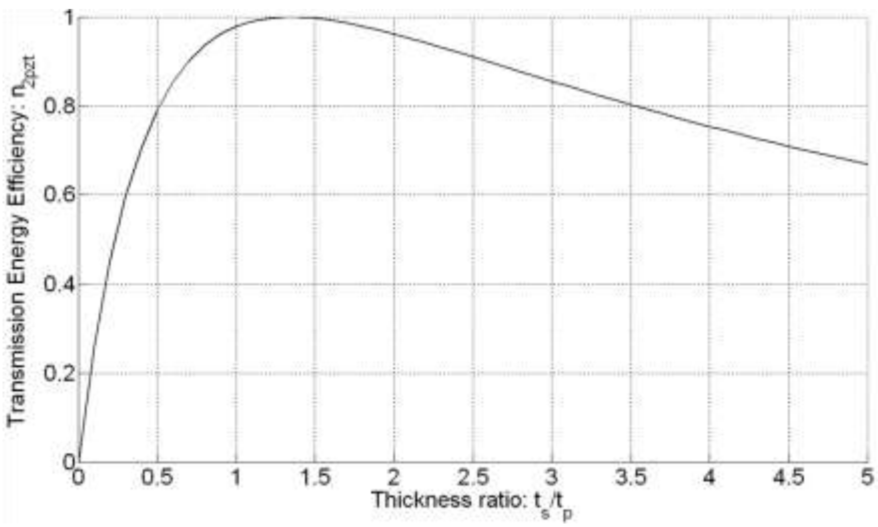

Fig. 6 Theoretical estimation of the optimal transmission energy in function of the thickness ratio

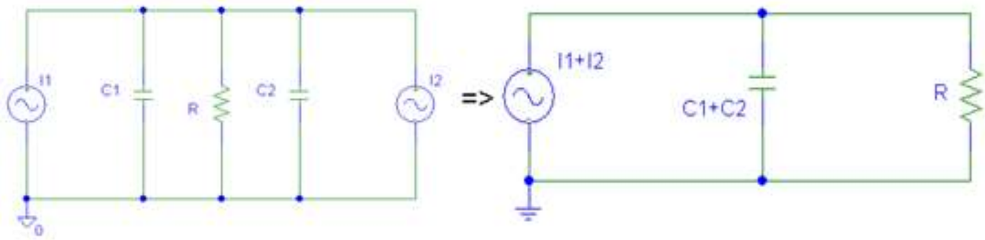

Fig. 7 Two piezo patches wired in parallel: Norton scheme

With reference to a parallel connection of n piezo devices having the same capacitor nominalvalue, the voltage on the resistive load can be finally defined as follows

$$V_{R\_n|} = \frac{j\omega RnC}{1 + j\omega RnC} V_{oc} \tag{9}$$

The ratio Kp between the voltage generated on the resistive load using a parallel of piezoelectric elements respect to the one generated with a single device has been calculated (see Fig. 8).

From this graph an evaluation of the maximum number of piezo connections can be derived before the saturation incoming. The transferred power to the load using a parallel configuration is given by Eq. (10).

$$P = \frac{\sqrt{n^2\omega^2 R^2 C^2}}{\sqrt{1 + n^2\omega^2 R^2 C^2}} |V_{oc}| \tag{10}$$

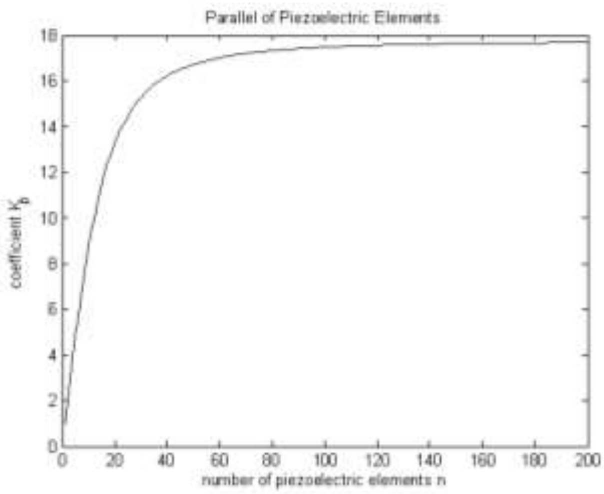

Fig. 8 Coefficient Kp in function of the number of piezo elements

and the optimal resistor is classically obtained by differentiating Eq. (10)

$$R_{opt} = \frac{1}{\omega \cdot nC} \tag{11}$$

The optimal resistor value decreases with the number of piezoelectric elements, as demonstrated in Fig. 9 which shows the power-resistance behaviour obtained changing the pzt number.

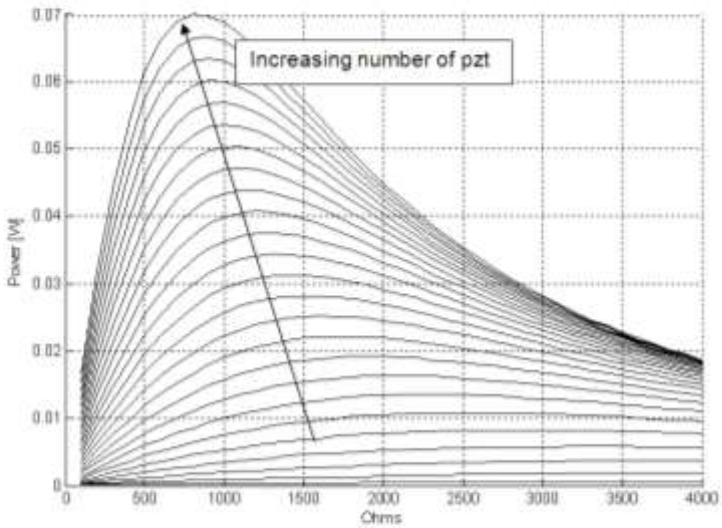

Fig. 9 Power-Resistance qualitative curves increasing the number of piezoelectric elements

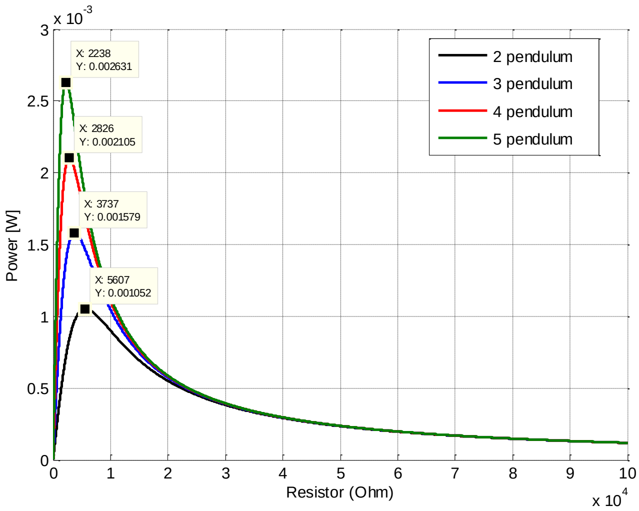

Fig. 10 Numerical prediction of the power generation for multiple beams electrically connected in parallel

In what follows, a preliminary experimental validation at subcomponent level is performed to check the functionality of a simpler system, finally the full scale energy harvester is tested by using a slip table simulating the same train acceleration and vibration amplitude in time domain. A standard circuit for output signal processing is here preferred in comparison to other solutions (Lin *et al.* 2013), due to the high frequency (pink noise) nature of the input signal which would lead, to a more complex signal treatment (Ciminello *et al*. 2010).

4. Preliminary experimental validation on subcomponent

The numerical simulations have been performed with an in-house Matlab code implementing the equations retrieved from analytical description of the previous paragraph. The reference test signal is modelled as a Nastran excitation function. A preliminary validation has been provided when using a representative sub-component, that is a single slot of the full scale system, described in Fig. (5). List of parameters used for simulations are reported in Table 3:

4.1 Sine excitation

In order to perform a preliminary validation, a simple sine signal by using a shaker with an increasing vibration amplitude is chosen to excite the structure in open circuit condition. The Eq. (5) is then verified (Fig. 11) using strain values measured at the clamped edge.

The Eq. (4), describing the closed circuit voltage using 1 KΩ resistor load, is also verified with a constant amplitude sweep signal using a shaker. Output voltage are measured at the resistor edges and results are plotted in Fig. 12.

The validation of piezoelectric elements wiring for both series and parallel configurations gave different voltage level as stated in the previous paragraph. For a sinusoidal excitation voltage level are 0.01 V for the series and 0.024 V for the parallel.

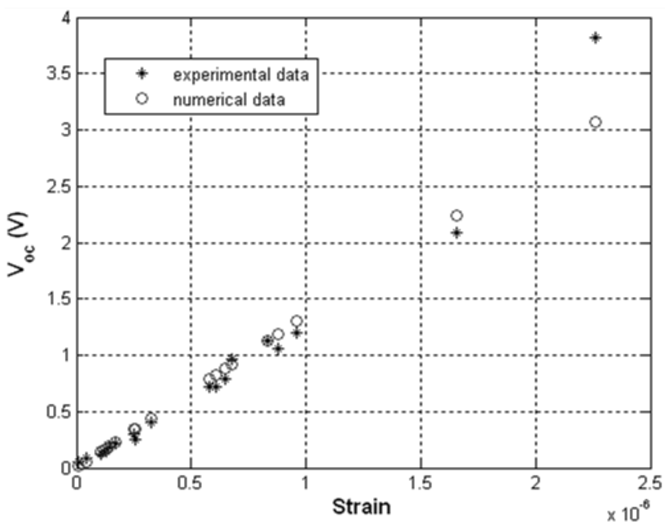

Fig. 11 PZT open circuit voltage in function of the strain

Table 3 main parameters for numerical simulations

tp[m]	0.4e-3
ts[m]	0.6e-3
Ep[Pa]	76e9
e0[F/m]	8.854e-12
g31[V]	14e-3

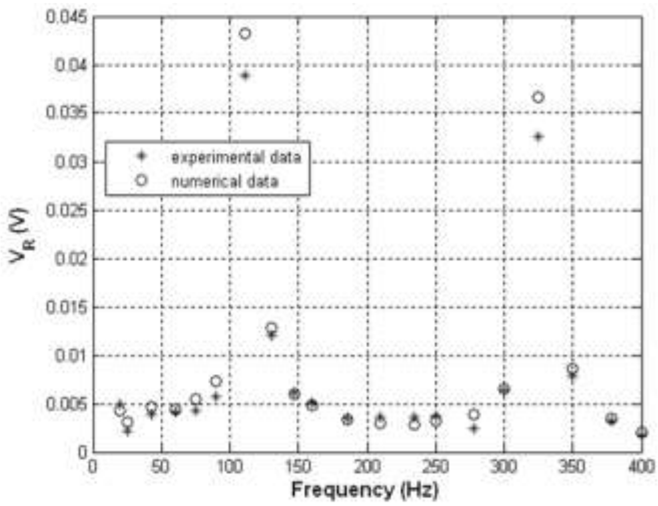

Fig. 12 Closed circuit voltage at different frequencies

4.2 Train bogie excitation

The experimental test campaign has been performed by using a shaker simulating the acceleration and vibration amplitude of the train in time domain. A structural model of the device has been developed in Patran pre-processing environment. Through the modal analysis the natural frequency has been evaluated considering a load mass configuration. The load mass is used to tune the natural frequency of the beam which is 43.75 Hz which is compliant with the frequency band stated in Table 2. In Figs. 13 and 14, the voltage and generated power for the system as it is (“basic configuration”) and the optimized one are plotted. The optimized configuration is indeed obtained using a tuned mass (8.4 gr) for the resonance frequency condition and an optimal load resistance (34800 Ohm).

Fig. 14 shows the voltage and generated power when using the optimized configuration.

The optimal configuration in terms of load resistor and tuning mass as well as the output voltage and generated power are summarized in Table 4 and Table 5 respectively.

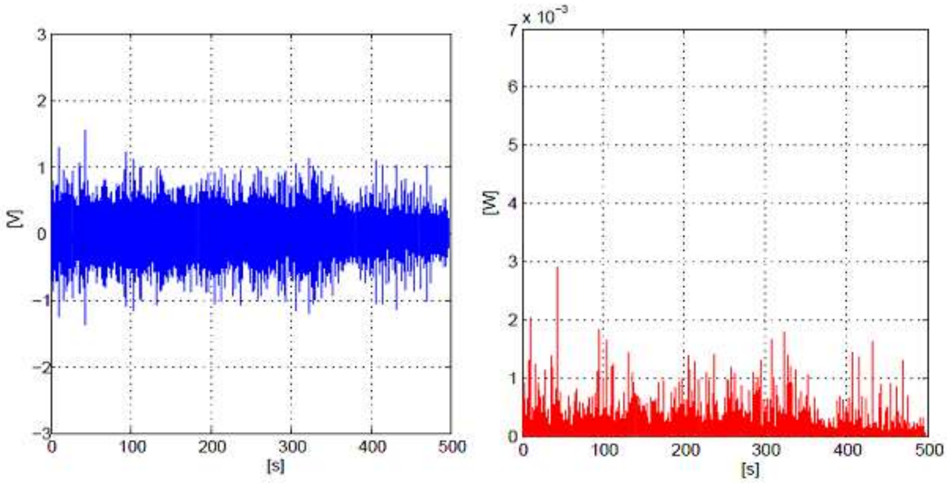

Fig. 13 Voltage and power with a baseline system configuration

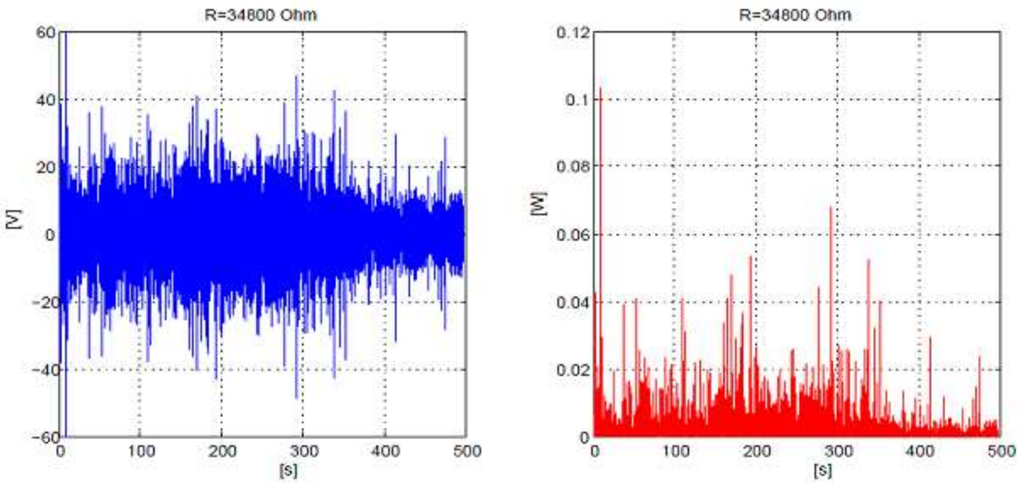

Fig. 14 Voltage and power with optimal load resistor and tuned mass

Table 4 Optimal configuration with a single beam slot

Optimal thickness (mm)	Natural frequency (Hz)	Optimal resistive load (Ohm)
0.6	43.75	34800

Table 5 Voltage and power output comparison

	Voltage [V]	Power [W]
Basic system configuration	2	1e-3
Optimal system configuration	40	0.02

5. Experimental validation of the full scale system

When multiple piezoelectric materials are attached to the same circuit in an attempt to produce more electric energy, the energy loss will be very high.

The reason for this is that the energy generated by one piezoelectric transducer causes the converse piezoelectric effect to occur at the other transducers, resulting in consumption of a part or all of the generated energy. Also, further losses occur due to the destructive electric signal interference produced from each piezoelectric device.

According to the previous considerations the piezoelectric energy harvesting system should include individual diode bridge circuits rectifying the signals. This allows for the use of a battery or super capacitor storing the energy produced. It has been possible developing a program in LabVIEW and the signal passes through an amplifier and is input to the shaker on which is mounted the prototype. The voltage generated across the piezoelectric elements is then recorded with a data recorder or with an oscilloscope (see Fig. 15).

The optimal configurations and the corresponding power generated when using different number of beam slot, are shown in Table 6. The experimental data and numerical prediction plotted in Fig. (10) are here compared.

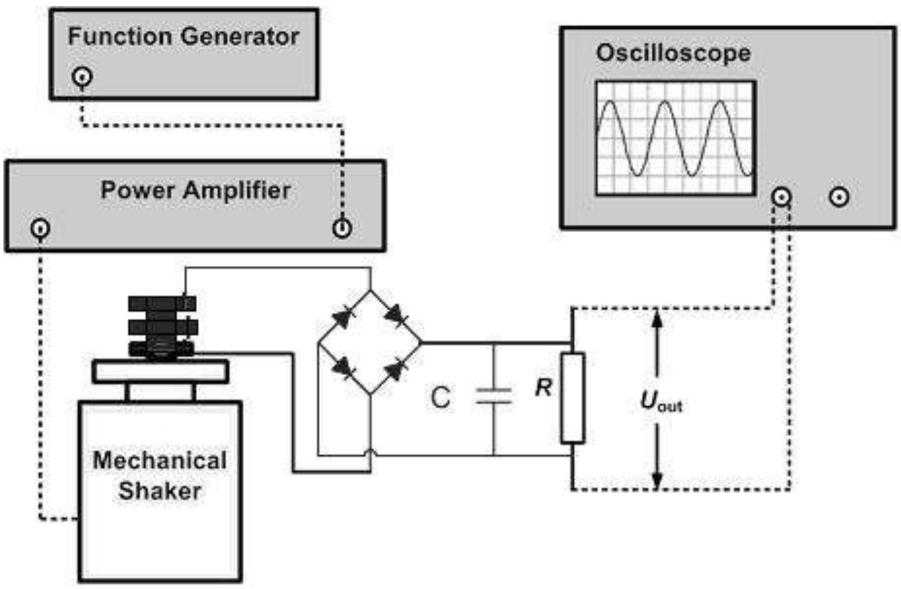

Fig. 15 Experimental setup

Table 6 Main characteristics of the flexible sensor and comparison with the rigid one

Number of slot	Optimal resistive Load (Ohm)	Exp. Power (mW)	Num. Power (mW)
2	5600	12.6	10.52
3	-	-	15.79
4	3100	20.0	21.05
5	2000	26.6	26.31

According to the data reported in Table 6, it is possible to confirm that the optimal resistive load decreases with the number of piezoelectric elements placed in parallel. Moreover the harvested energy do not increase linearly with respect to the number of used slot. Indeed, the deviations of parameters in each beam may result in the shifting of resonances of each beam slightly, causing the charge cancellation.

Some discrepancies arose with respect to the experimental trends, but substantial coherence in the values can be anyway observed. Reasons may be imputed to the absence of any simulation for the nonlinearities while experimental results showed a significant impact of such effect.

Moreover, the effects induced by phase mismatch or charge cancellation on generated power were neglected at this stage of the numerical analysis.

Nevertheless, on the base of working assumptions and simplifications, numerical predictions resulted in satisfactorily agreement with experimental measurements.

6. Conclusions

In this work an original device for train bogie energy harvesting is designed to supply a wireless sensors network for diagnostic purposes. Piezoelectric materials have inhere considered due to their established ability to directly convert applied strain energy into usable electric energy and their relatively simple modelling into an integrated system. The mechanical and electrical properties of the system are studied according to the project specifications. The numerical formulation is implemented with in-house code using commercial software tool and then experimentally validated through a proof of concept setup using an excitation signal by a real application scenario.

The proof of concept prototype is conceived in order to work in resonance; the system is based on symmetrically excited bender beams on which couples of piezo patches in co-located configuration are bonded. In order to design and test the device in operative conditions, real data measurements are at first acquired on a freight train. These data show harmonics at higher energy in the range 40-50 Hz. In operative conditions the assembled system can harvest 26.6 mW with 0.6 g of vertical acceleration at 43.7 Hz. Some numerical and experimental discrepancies are essentially due to nonlinearities and interferences, due to phase lag signal generated by each beam, which are not modelled at this stage of the research.

In the next and final part of this industrial research, the architecture design is finally optimized to be compliant with the installation and cost requirements.

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