ENERGY VIBRATION HARVESTING FOR SUPPLIYNG SENSORS NETWORKS IN RAILWAY VEHICLES MONITORING

Aurelio Somà, aurelio.soma@polito.it
Giorgio De Pasquale, giorgio.depasquale@polito.it
Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino (Italy)

Abstract. *In the present work a study of energy harvester for vehicle monitoring design is carried out. Mechanical vibrations of railway vehicles were used to generate electric power by means of a piezoelectric energy harvester. The power was successively stored in a rechargeable battery and used to supply one node of the sensors network, which is used to monitor the structural integrity of the most critical components of the vehicle and to prevent their failure. The piezoelectric harvester was preliminary characterized to investigate its electric and dynamic performances, and then tested on a scaled railway bogie moved by a roller rig.*

Keywords*: energy harvesting, reliability, structural monitoring, self powering, wireless.*

1. INTRODUCTION

The possibility to generate electric power by converting energy available in the environment is at the basis of the diffusion of energy harvesters. Small devices like sensors may be supplied more easily than the others, leading to push the design of micro energy harvesters, based on the micro systems technology. Many applications of MEMS energy harvesters are addressed to low frequency vibrating environments, like human body, vehicles, buildings, etc in order to supply wireless sensors network.

Small and large vehicles (automotives, trains, aircrafts, etc.) are equipped with several sensors and other small devices to monitor the proper functioning of all sub-systems and components and to provide the instantaneous measurement of the most relevant environmental parameters. On-board sensors, or sensors networks, are usually supplied by the electric power generated by the engine and catch from the main battery by means of wires. The needing to monitor a large amount of parameters causes the proliferation of electrical wires, leading to very complicated sensing architectures and many other problems related to the maintenance and reliability. Furthermore some vehicles such as commercial trains are not equipped by extended electrical connections, making difficult their control by wired sensors. The investigation of new approaches for the supply of on-board sensing systems started recently, which is based on the self-powering provided by power generators (Paradiso and Starner 2005, Pelczar *et al.* 2008, Pohl and Seifert 1996). This idea starts from the evidence that a large amount of mechanical vibrations characterizes all vehicles and mass transportation systems during their operations.

Open problems and future challenges of this field are related to the design and fabrication of the devices able to convert the power with reasonable efficiency and reliability, with low-cost building processes and large scales applicability. Different solution in macro- and micro- scales were proposed but their characteristics in terms of conversion efficiency, reliability and industrial development and applicability are still not satisfactory (Roundy 2005, Yen and Lang 2006, Raghunathan and Chou 2006). For example, some devices based on the MEMS (micro electro-mechanical systems) technology are able to harvest energy from vibrations into electricity by exploiting capacitive (Tang *et al.* 1989), piezoelectric (Flynn and Sanders 2002) or magnetic-inductive (Williams *et al.* 2001) strategies.

This work presents the results of investigation activities about the energy harvesting from vehicles, with particular attention for railway applications. The final goal is the fabrication of a compact integrated platform including a harvester device, a small accumulation battery and an inertial sensor for the self-powered data acquisition. A roller rig and a train bogie (scale 1:4) were used to reproduce the vibrations generated by the train at different velocities. Multiple strategies for the energy conversion were analyzed, in micro- and macroscales: capacitive MEMS energy harvesters presented by the authors in previous works were considered, and macrodimensional piezoelectric cantilevers were used for preliminary experiments on the roller bench. Experimental analyses were addressed to the tuning of the harvester resonance frequency to the excitation frequency, and to the optimization of the electrical load for the output power maximization. A diodes bridge and a leveling capacitor were used to rectify the alternate harvested voltage and to charge the battery.

2. ENERGY HARVESTING STRATEGIES

In several papers piezoelectric generators were addressed to human-wearable systems, where the energy generated by pedestrian motion was converted into electric voltage by means of flexible elements. Transducers for higher frequencies, applicable to vehicles, are characterized by a cantilever structure with piezoelectric material attached to its surfaces; this shape is designed to operate in bending mode thereby straining the piezoelectric film and generating a charge. Because of the advantageous ratio between strain and applied force, the cantilever shape is an optimized solution for piezoelectric generators. A proof mass is usually introduced at the cantilever tip to amplify the oscillation amplitude of the structure and to tune its resonance frequency. The composite piezoelectric cantilever represented in Fig. 1a was developed by Roundy *et al.* (2003) using a PZT-5A shim to each side of a centre beam. A cubic mass made from an alloy of tin and bismuth was attached to the end and the generator tuned to resonate at 120Hz, producing a maximum power output of 80μW (250kΩ load resistance and 0.25g acceleration). The dimensions of the device are in the order of few millimeters. The detailed analysis of the mathematical models for this typology of piezoelectric transducers was presented in (Roundy and Wright 2004).

Piezoelectric generators offer the simplest approach whereby structural vibrations are directly converted into a voltage output. There is no requirement for having complex geometries and these generators are simple to fabricate; a wide range of materials are available for different application environments. The piezoelectric materials is required to be strained repetitively, therefore their mechanical properties will limit performance and lifetime. The transduction efficiency is limited by electric properties of materials employed; their output impedance is typically high (>100kΩ), they are capable of producing high voltages but only at low electrical currents that increases the time required to charge the storage battery.

Electromagnetic induction is the generation of electric current in a conductor located within a magnetic field. The factors affecting the amount of power generated are the strength of magnetic field, the velocity of relative motion and the number of turns of the coil. One of the most effective methods for energy harvesting is to produce electromagnetic induction by means of permanent magnets, a coil and a restoring structure (usually a double-clamped beam, a cantilever, or a membrane). Generally it is preferable to hold the coil to the external frame and to mount the magnets on the elastic vibrating structure; by this solution the magnets can act as inertial mass (Beeby *et al.* 2006). An electromagnetic energy harvester was developed by Huang *et al.* (2007) and is represented in Fig. 1b. The device has a resonance frequency of 100Hz and is reported to be capable of generating a maximum power of 0.35μW with 10 turns of the coil.

Electromagnetic converters offer a well-established technique of electrical power generation and a large variety of configurations can be used. High current levels are achievable at the expense of low voltages (typically <1V). However the efficiency of this type of harvesters in terms of power generated per unit of mass is not particularly high; there are some problems in the tuning process because the proof mass is usually imposed by the electrical dimensioning. Therefore, wafer-scaled microsystems are quite difficult to achieve owing to the relatively poor properties of planar magnets, the limitations on the number of turns in planar coils and the restricted amplitude of vibration.

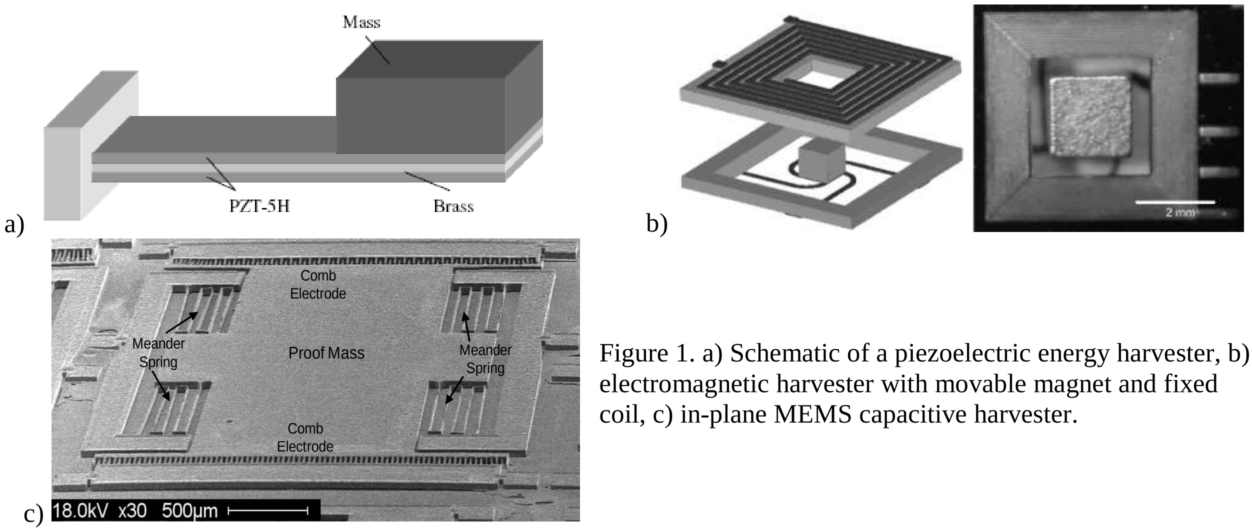


Figure 1. a) Schematic of a piezoelectric energy harvester, b) electromagnetic harvester with movable magnet and fixed coil, c) in-plane MEMS capacitive harvester.

The capacitive energy harvesting relies on the relative displacement between two charged parallel plates which are connected to a suspended proof mass by elastic springs. A good efficiency of this conversion strategy is limited to small devices at microscale, because the plates charge requires too high power consumption for larger capacitors. This makes the MEMS technology the preferred one for the building process. In order to obtain the high capacitance and maximize power output, substantial displacement is then required and achieved by kinematics of the mass. Among the different solutions, the in-plane displacement strategy is more convenient than the out-of-plane for the maximization of armatures surface. Both variable area of electrodes (overlap strategy) and variable gap between electrodes (gap closing strategy) can be selected in the design. The electrostatic conversion is easily realizable as a MEMS and much processing know-how exists on the realization of in-plane and out-of-plane capacitors. Energy density can be increased by reducing the armatures spacing, facilitating miniaturization. The energy density, however, is also decreased by reducing the capacitor surface area. Electrostatic generation requires an initial polarizing voltage or charge, which can be provided by the battery associated to the harvester. Electrets can be utilized to provide the initial excitation level and these are capable of storing charge for many years. The output impedance of the devices is often very high and this makes them less suitable as a power supply; the generated voltage is also relatively high and often results in a limited current supplying capability (Beeby *et al.* 2006). Therefore the small dimensions of the device causes high resonance frequencies not well suited for vehicles dynamic spectra of vibration. Figure 1c reports a nickel MEMS capacitive harvester fabricated by the authors (Wei *et al.* 2009); a huge proof mass and weak elastic springs were introduced in order to lower the dynamic response of the device, giving a resonance frequency of about 300Hz.

3. RESONANCE TUNING

Tuning the resonance of vibrating energy harvester to 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 those applications, like vehicles, which have a wide dynamic vibration spectrum. A common solution adopted by the designers is building up a set of harvesting structures with different geometry (e.g., piezoelectric beams of different length), all tuned on a specific resonance frequency; this results to an amplification of the bandwidth of the whole device. Other strategies are based on the softening and/or stiffening process of the elastic components of the harvester: by applying, e.g., an axial load to a flexible beam or plate, the resonance frequency of the structure can be easily tuned thanks to the variation of its effective stiffness. An external force can be applied to the tip of a piezoelectric vibrating beam to tune its resonance. If a permanent magnet acting as proof mass is attached to the tip of the beam, the magnetic field generated by a conductor can provide the necessary tuning force to the structure.

4. PIEZOELECTRIC HARVESTER AND TESTS SETUP

The piezoelectric transduction principle was selected among described conversion strategies because the characteristics of the electric output power are the most suitable for the proposed application. The relatively high levels of currents achievable make easier the charge of a storage battery in short time, and the dynamic properties of the harvester can be easily modified to tune the resonance on the excitation frequency provided by the vehicle. The commercial availability of piezo transducers is another advantage compared to the electromagnetic and capacitive harvesters that require dedicated design, fabrication and assembling processes.

The P-876.A12 DuraAct piezoelectric transducer was used in the cantilever configuration represented in Fig. 1a for its experimental characterization. The beam is constituted by two PIC255 piezo-ceramic layers (thickness 200µm each) and an insulating polymeric package, constituting a bimorph configuration; electrical properties and geometrical dimensions of the packaged beam are listed in Tab. 1. The dynamic response of the cantilever were 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. In the characterization procedure, the length of the beam was also adjusted by changing the position of the constraint to tune the resonance frequency. The variable proof masses used and the properties of PVC layers are also indicated in Tab. 1. An image of the piezoelectric cantilever is reported in Fig. 2a.

An electro-mechanical shaker was used to apply the alternate force on the constrained side of the piezoelectric cantilever to simulate the environment vibration. The acceleration level imposed by the shaker was controlled by an accelerometer, while the dynamic response of the excited piezo beam was detected by measuring its output voltage. The alternate voltage generated by the piezo material when it is bended must be rectified prior to be used to supply the storage battery. At this purpose a four diodes bridge and two leveling capacitors were used; the rectification circuit was assembled using a perforated plate holding electronic components and small circuits. The lithium-vanadium rechargeable battery Panasonic VL3032 was selected to store the power generated and was assembled in the electronic circuit. The characteristics of the battery are: 30mm diameter, 3.2mm thickness, 100mAh capacity, -20÷60°C temperature range. The rectification circuit including the storage battery is represented in Fig. 2b.

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	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

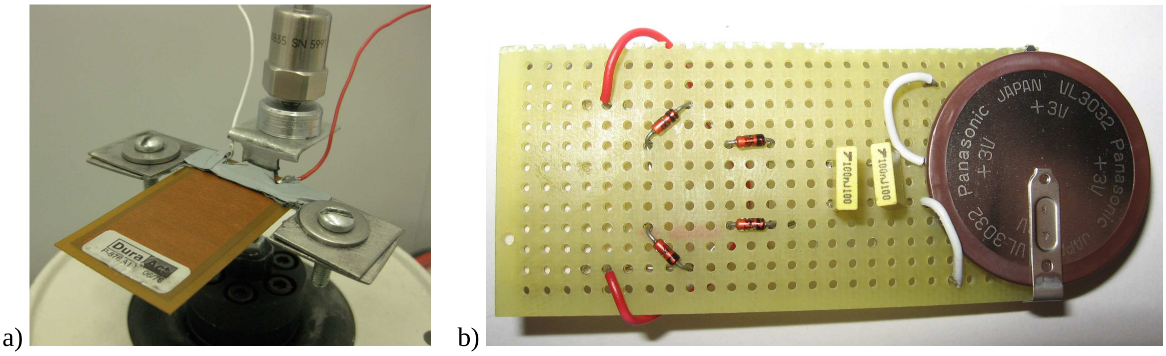
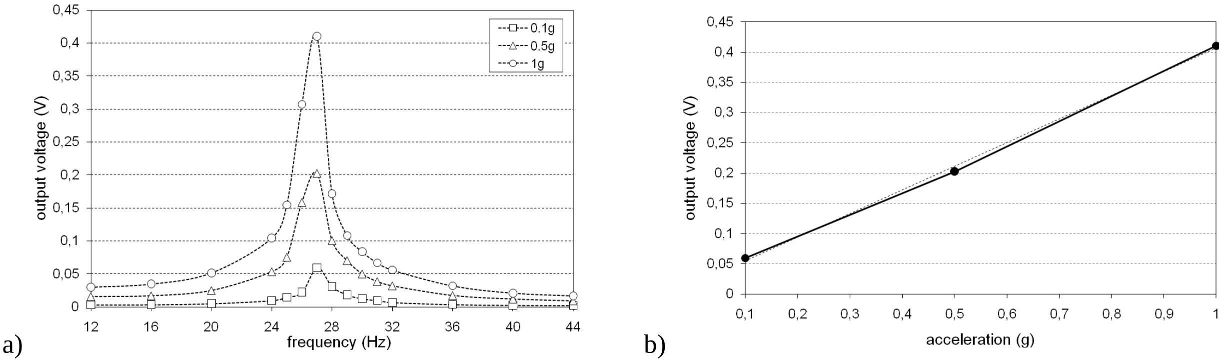


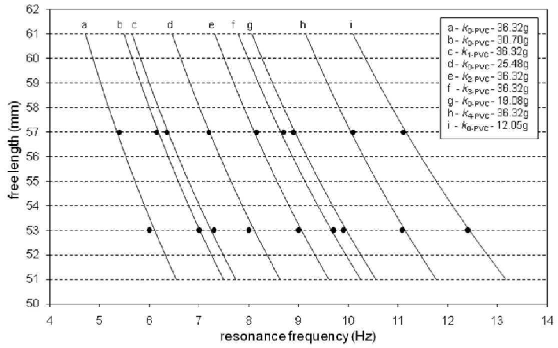
Figure 2. a) Piezoelectric cantilever for energy harvesting, b) electronic circuit for output voltage rectification and storage battery.

5. DYNAMIC CHARACTERIZATION

The goal of the present characterization is to investigate the electro-mechanical properties of the piezoelectric harvester converting the mechanical vibrations of rail vehicles to electric power. The output power is used to charge a battery or a storage capacitor and then to supply on-board sensors for structural monitoring safety-related purposes. Figure 3a reports the dynamic response of the piezo beam (without proof mass and additional stiffening layers) in terms of output voltage for three levels of acceleration. The relationship between acceleration level and output voltage at resonance condition is approximately linear for the range of frequencies considered, as the diagram of Fig. 3b testifies.

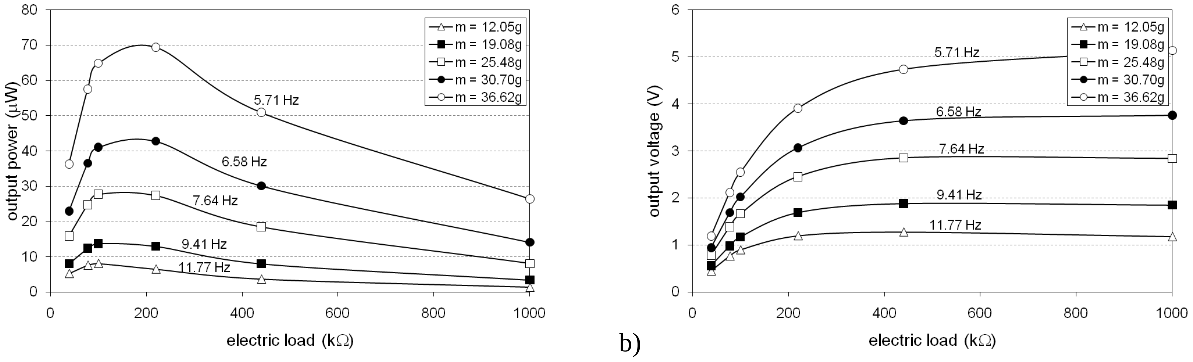
A preliminary analysis on the resonance frequency of the piezoelectric cantilever was performed; a finite element method (FEM) simulation of the beam, where only the geometrical and structural properties were considered, was used to investigate the dynamic response. The effects of the variable proof mass, structural stiffness and free length of deflection of the beam were studied. The results predicted by the simulations were validated by experiments for some configurations. Figure 3c reports the results obtained at two lengths of the beam, respectively 53 and 57mm; the stiffness of the beam is indicated as $k_{\text{i-PVC}}$, where i corresponds to the number of PVC layers attached to the surfaces. The beam stiffness without additional PVC layers is indicated as $k_{\text{0-PVC}}$. The alternate voltage generated by the piezoelectric beam for different configurations of proof mass and stiffness was measured and the RMS value was calculated. The generated power was calculated as $P=RI2$, where the current I was measured at the output. The maximum level of voltage and power can be obtained in presence of the optimum electric load. Figure 4 reports the measured values of the output power and voltage of the piezoelectric beam with stiffness $k_{\text{0-PVC}}$, where the proof mass was varied. The characterization was performed on the shaker with 0.2g acceleration at resonance condition; the resonance frequencies for the different configurations are in the range from 5.7 to 11.8Hz depending to the proof mass considered. Figure 5 reports the measured output power and voltage of the piezoelectric beam with proof mass m=36.62g and variable stiffness. The 0.2g acceleration was imposed and the measurements were performed at resonance condition; the resonance frequencies for the different configurations are in the range from 6.8 to 10.6Hz depending to the stiffness of the beam.





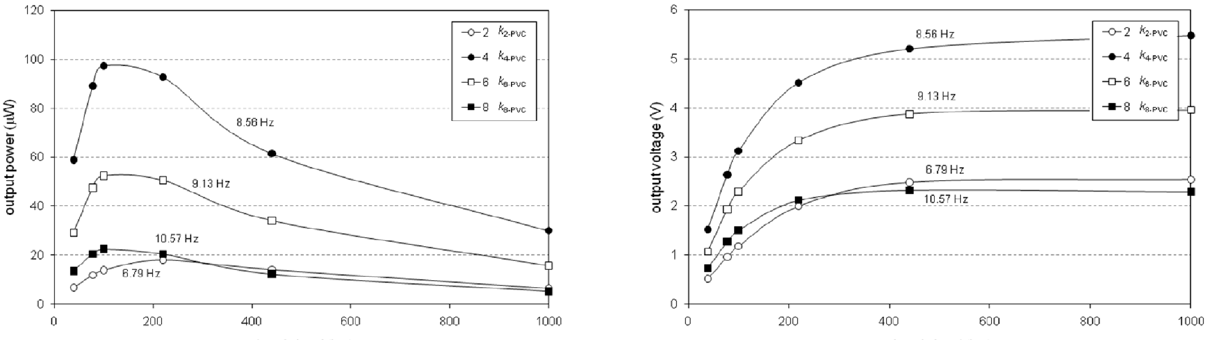
c)

Figure 3. a) Output voltage measurements at variable acceleration amplitudes, b) linear relationship between acceleration and output voltage at resonance, c) FEM simulations and experimental measurements (black dots) of resonance frequency at different configurations.



a) b)

Figure 4. Output power (a) and voltage (b) for variable proof masses at resonance and 0.2g acceleration.



a) b)

Figure 5. Output power (a) and voltage (b) at different bean stiffness at resonance and 0.2g acceleration.

6. EXPERIMENTS ON A SCALED RAILWAY BOGIE

Rail vehicles, especially those addressed to commercial transportation, are not supplied by on-board sensing systems and electrical wires. This makes the self-powered sensing strategy particularly attractive. The introduction of sensors on rail vehicles allows to monitor the structural integrity of the most critical components, to provide information about the motion parameters (velocity, acceleration, vibrations, angular velocity, etc), and eventually to identify the position of the vehicle through the GPS system. These information are vital to continuously monitor the reliability of the vehicle and its components, and to track the travel story of each carriage in order to schedule its maintenance. The sensors network must be distributed all over the train to be able to detect the parameters of interest, e.g. the increase of temperature in those loaded components where a damage process is starting. Many parts of the rail 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 can be detected and used to prevent the failure of the damaged component. The detection of acceleration on three axes is also useful to monitor the vibrations caused by the rail-wheels contact and the history of load transferred to the vehicle. Anomalous peaks of vibrations caused by the presence of debris can be recognized as well as their eventual effect on critical components. A transmission system is also required to send the data measured by each node to a central host were they can be received, processed and analyzed. A RF device with a specific communication protocol can be integrated to the sensing node at this purpose and the power generated by the harvester can be used for its supply. The schematic of the proposed sensing node is represented in Fig. 6; the self-powered node, after an optimization of dimensions and assembling in relation to the specific application, can be easily applied closely to critical components of the vehicle.

The piezoelectric harvester was applied to a scaled model of railway bogie to characterize the performances of a sensing node. The system considered is composed by the piezoelectric harvester, the linearization electronic circuit and the storage battery. Two acceleration sensors and a RF transceiver were supplied with the power generated.

6.1. Scaled bogie and roller rig description

The bogie used for the characterization is scaled in the proportion 1:4 and reproduces the geometric characteristics of the actual vehicle (Fig. 7). The prototype reproduces a trailing bogie but is designed to accept two motor gears in order to simulate also the motor bogie. The rollers of the rig were machined in order to obtain the same transversal rail profile UNI50 canted to 1:20. The wheel profiles are characterized by two interchangeable conical profiles (0.05 and 0.3 rad) and a profile S1002; the curvature profiles are designed to obtain the same shape of the rail-wheel actual contact area. The stiffness of the bogie was designed and tested experimentally in order to have dynamic characteristics equivalent to those of actual vehicle. The single rubber element used as primary suspension in the actual vehicle was replaced by four hinges supported by disc springs for longitudinal and vertical directions. The lateral stiffness was obtained using 12 helical compression springs. The system allows adjustment of wheelset preload and position. The secondary suspension is represented by an air spring that gives a ratio between lateral and vertical stiffness equal to that of actual springs. Several similitude methods were used to convert the parameters measured on the scaled model. The similitude law proposed by Jaschinscki (1990) was used to design the bogie; this method provides the equivalence of wheelset dynamics and keeps the accelerations unscaled on the prototype. Thus, the accelerations measured on the scaled bogie corresponds to those on the actual vehicle. A detailed description of the roller rig and bogie is reported in (Bosso *et al.* 2008) where the design and the experimental validation of the test bench components is described.

Figure 6. Block diagram of self-powered sensing node for rail vehicles application.

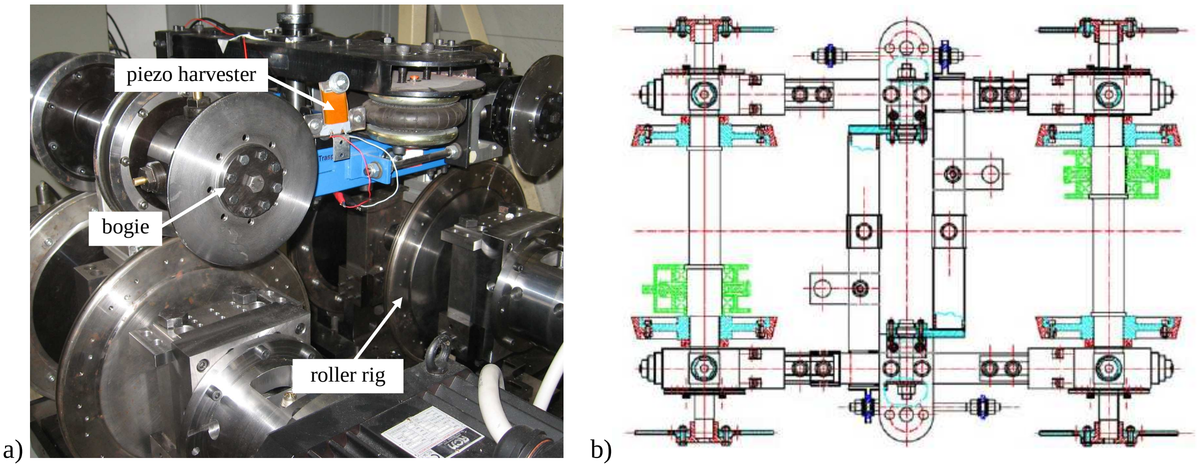


Figure 7. Scaled bogie prototype mounted on the roller rig (a) and its drawing (b).

6.2. Harvester System validation

The dynamic response of railway bogie was preliminary characterized by detecting the acceleration levels in the lateral direction, where the excitation is the most relevant. The FFT measured on the bogie is reported in Fig. 8a, where the resonance peak is situated at 5.5Hz. A proof mass m=36.62g was added on the tip of the piezoelectric beam and the stiffness $k_{0\text{-PVC}}$ was used. The resonance frequency of the piezoelectric beam was tuned to 5.71Hz by the described configuration, producing the maximum oscillation amplitude; the acceleration measured at resonance is a=1.53g.

The railway bogie equipped with the piezoelectric harvester is represented in Fig. 7a. The output power and voltage characteristics measured after the electronic rectification are reported in Fig. 8b for different electric loads. The harvested power, which was stored in the battery, was then used to supply three different devices for sensing and transmissions purposes: a 2-axes linear accelerometer (LIS2L02AS4 ST Microelectronics: ±3g/±6g), a 3-axes linear accelerometer (LIS3L02AS4 ST Microelectronics: ±3g/±6g) and a RF transceiver (CC2520 Texas Instruments: 2.4GHz, ZigBee protocol). Starting from a completely charged battery and assuming the sensors/transceiver are working for 1s, the time required by the harvesting system to restore the initial level of the battery is reported in Tab. 2. Different configurations of the sensing system are considered, by coupling sensors and transceiver in various combinations.

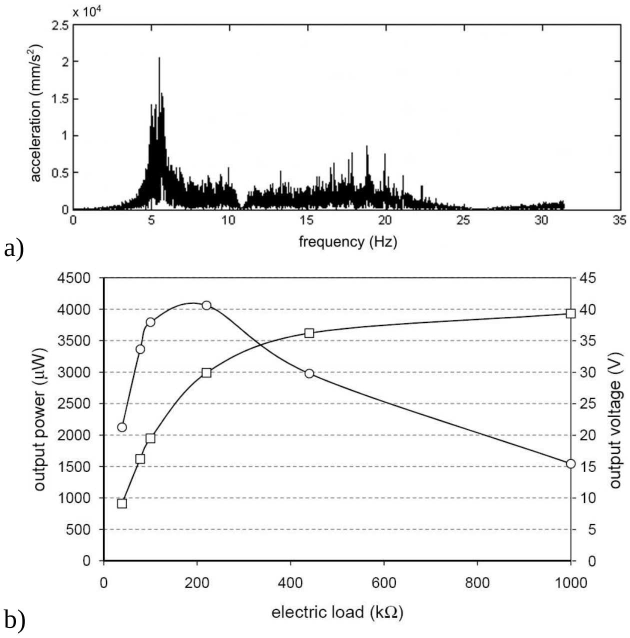


Figure 8. a) Acceleration spectrum on railway bogie, b) output power (circles) and voltage (squares) generated by the piezoelectric harvester.

Table 2. Efficiency of the self-powered sensing system.

Devices supplied	**Residual battery charge after 1s**	**Harvesting time to restore the initial charge**
2-axes accelerometer	99.8%	0.3s
2-axes accelerometer 3-axes accelerometer	97.6%	2s
2-axes accelerometer RF transceiver	78.6%	16s
2-axes accelerometer 3-axes accelerometer RF transceiver	77.4%	17s

7. DISCUSSIONS

The dynamic characterization at variable proof mass reported in Fig. 4 reveals, for the experimental configurations considered, a proportional relationship between the mass and the output power and voltage; this can be easily explained by considering the oscillation amplitude of the beam at resonance: higher the mass on the tip, higher the flexural deflection and the electric output of the piezoelectric material. This relationship is valid for ratios of dimensions not too far from those considered in the experiments. This is particularly evident for a constant level of acceleration, which was imposed at 0.2g in the characterization. The diagrams reported in Fig. 5 reveals the existence of an optimum stiffness, to which corresponds the maximum power and voltage output. In fact the electric output at k4-PCV is higher than those obtained at the lower stiffness level $k_{2\text{-PVC}}$ and at the higher stiffness level $k_{6\text{-PVC}}$. These results can be motivated considering that the measurements were performed at the resonance condition of the beam; thus an increasing stiffness determines the increase of resonance frequency giving a benefit on electric output (more oscillation cycles per unit of time). However, when the stiffness becomes too relevant, the oscillation amplitude of the beam is reduced for that acceleration level and an opposite effect on the electric generation is produced.

The output power measured with a tip mass m=36.62g and stiffness $k_{0\text{-PVC}}$ at 0.2g acceleration (Fig. 4) is sensitively higher than the power measured with the same proof mass and higher stiffness (Fig. 5). This depends to the fact that the measurements were performed at resonance and with constant acceleration, which implies smaller oscillation amplitudes for higher frequencies. With the experimental setting adopted, the configurations where higher stiffness values are introduced cause the increase of resonance and, consequently, the lowering of oscillation amplitude and output power.

The experimental validation of the sensing platform on the railway bogie reveals that the cycle time of the self-powered device does not allow a continuous acquisition and transmission, but indicates that a recharging time is required after each operation. This limitation is compatible to the structural monitoring purposes, as an optimized strategy may be used to detect accelerations as well as different parameters (temperature, angular velocity, etc) at specific time intervals, or when a given threshold is reached. The capacitance of the piezoelectric material used in the characterization is not particularly high; the global efficiency of the device can be sensitively increased if a high-capacitance piezoelectric material is adopted.

The optimization of the final device configuration is needed in order to reduce the dimensions of the self-powered system; the electronic circuit used to rectify the harvested voltage also requires additional optimization. Furthermore a package must be provided to protect the device from mechanical shocks, debris and dust; the package has not to introduce interferences affecting the RF transmission.

8. CONCLUSIONS

The energy harvesting strategy was explored to generate power from mechanical vibrations of railway vehicles. The prototype of a self-powered sensing system is presented, which is addressed to structural monitoring of critical components. After a preliminary characterization of electrical and dynamic propertied of the piezoelectric transducer, the harvester was applied to a scaled railway bogie associated to a roller rig able to simulate the accelerations on actual rail vehicles. The final efficiency of the device was measured in terms of time needed to recharge the battery by the harvester after sensing and transmission operations.

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5. RESPONSIBILITY NOTICE

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