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Simulation and Modeling of Self-powered Wireless Sensor Node for Railway Vehicles

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***Abstract* – The purpose of this work is to model and simulate a harvester device whose purpose is to recover energy from the vibrations due to the irregularity of the railway and store it in order to subsequently feed a wireless sensor node.**
The use of a piezoelectric harvester, instead of traditional batteries, allows the achievement of an energetically autonomous system, which does not need periodic maintenance to replace the batteries themselves. Studies about dynamics of trains showed that the axle box represents one of the most stressed components of the wheelset due to the irregularities of the railway line. For this reason it has been chosen as the optimal place to install the piezoelectric harvester. The system designed allows a real-time monitoring for diagnostic and prevention.

I. INTRODUCTION

Real time diagnostic and structural monitoring operations are not simple actions for goods trains, due to the absence of onboard electrification. The sophisticated sensor systems already installed on passenger trains, in fact, have never been applied to goods trains (whose sensors are available only for few controls along the line). The opening of borders of the European nations and the free travelling of trains have unfortunately brought a reduction in the level of available information about vehicles, in particular about their maintenance and their safety. For this reason, the real-time monitoring for diagnostic and prevention is assuming a growing importance.

Last decade research efforts in low-power sensors and integrated wireless transmission modules have made more workable the possibility to generate the electric power demanded by simple diagnostic systems with devices directly set onboard of railways wagons [1-2]. From an operational point of view, it appears also possible to use these devices to monitor relevant diagnostic parameters.

Piezoelectric Energy Harvester devices, which convert the vibration mechanical energy (free and inexhaustible in some technical environment) into electrical energy [3-5], surely can find a promising application in this contest.

Studies about dynamics of trains showed that, due to the irregularities of the railway line, the accelerations of the axlebox are high, as explained in Table 2.D of [6]. So the axlebox is one of the safety-critical subsystems in railway vehicles [7] and one of the most stressed components of the train wheelset.

A good definition of 'axlebox' is provided by [8]: it is "the housing attaching the axle end to the bogie, which contains the bearing allowing the axle to rotate". Due to its constant state of stress during the railway vehicle service, the axlebox has been chosen as the optimal place to install the piezoelectric harvester. So the design of the system prescribes an axlebox transferring its acceleration to a piezoelectric cantilever beam. The transducer subsequently converts the acceleration into electric potential, useful to power a wireless sensor node.

Moreover, the analysis of the system vibrations frequency enables the self-powered sensor node to provide information about the state of health of the axlebox. This information, transmitted to an operational center opportunely, can provide an alert about defects or aberrations of the axlebox in real time. So the described system achieves energy harvesting and diagnostics goals simultaneously.

The system axlebox-cantilever has been simulated using the software Comsol Multiphysics. The studies were conducted in stationary and time-dependent conditions. The simulator provided a random input acceleration, which has been modelled as a normal distribution having prefixed mean value and standard deviation [9].

The analysis was closed assuming the existence of defects of the axlebox and comparing the output eigenfrequencies of the device with and without defects.

II. STUDY OF THE CANTILEVER

A. Device structure and mathematical model

An energy harvester device, with a cantilever beam structure, is designed in order to generate electric power from the vibrations acting on the axles and the axleboxes of the railway vehicle during its service.

Figure 1 reports a schematic, not in scale view, of the considered device. It is composed by a lower layer of steel, which acts both as a support for the piezoelectric material and as a ground electrode. The upper layer is made of Lead Zirconate Titanate PZT-8.

One end of the cantilever beam (the fixed end) is supposed to be rigidly connected to the axle box, as schematically represented in Figure 2.

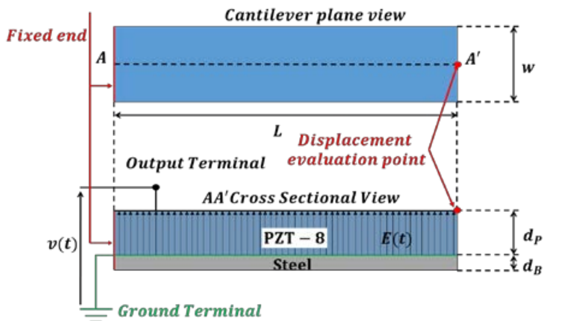

Fig. 1. Plane and cross sectional view of the device (not in scale).

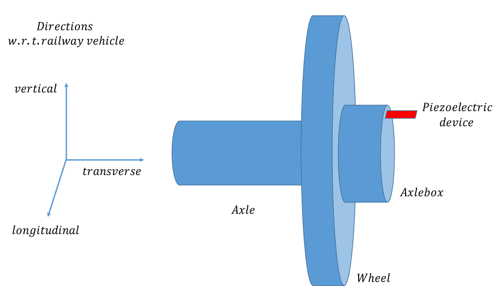

Fig. 2. Schematic representation of the system.

An in-service railway vehicle is subjected to vibrations and shocks, which are mostly due to the nature of railway tracks and the operational environment. The piezoelectric device is meant to harvest electrical power from these vibrations. Geometric and constitutive parameters of the device shown in Figure 1, are reported in Table 1 and 2 where the matrix c^E is the **elasticity matrix** of the piezoelectric compound, evaluated at constant electric field E, whereas matrix ε^S_r is the **relative permittivity matrix** at constant strain S. Their structures and that of the **coupling matrix** e, which defines the static relation between the electric field and the strain, are well known in literature.

Table 1. Geometric parameters of the cantilever beam.

L [mm]	w [mm]	d_p [mm]	d_B [mm]
50	10	0.15	0.125

Table 2. Constitutive parameters of the cantilever beam.

Material	Density ρ [Kg/m³]	Young's modulus [Pa]	Relative permettivity ε_r
Structural steel	7850	$200*10^9$	1
PZT-8	7600	c^E	ε^S_r

The mathematical model that describes the behavior of the device is expressed by the following Equations:

$$\rho \ddot{\boldsymbol{u}} = \nabla \cdot \boldsymbol{T} + \boldsymbol{F}_V \qquad (1)$$

$$\nabla \cdot \boldsymbol{D} = \rho_V \qquad (2)$$

$$\begin{bmatrix} \boldsymbol{T} \\ \boldsymbol{D} \end{bmatrix} = \begin{bmatrix} c^E & -e^t \\ e & \varepsilon^S \end{bmatrix} \begin{bmatrix} \boldsymbol{S} \\ \boldsymbol{E} \end{bmatrix} \qquad (3)$$

$$\boldsymbol{S} = \frac{1}{2}(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^t) \qquad (4)$$

where $\boldsymbol{u}$ is the displacement vector, $\boldsymbol{D}$ is the electric displacement vector, $\boldsymbol{S}$ is the strain tensor, $\boldsymbol{T}$ is the stress tensor, $\boldsymbol{F_V}$ represents the input mechanical action, $\boldsymbol{\rho_V}$ is the electric charge volumetric density and t denotes the transpose matrix.

B. Simulation setup and results

All the simulations reported in this paper have been carried out using Comsol Multiphysics. It is a general-purpose simulation platform, which adopts the finite element method (FEM) as numerical technique to find approximate solutions to boundary value problems for partial differential equations. Moreover, it provides the opportunity to simulate three-dimensional space domains in multiphysics environment.

With reference to the electrical boundary conditions, it has been applied a Terminal node to the upper face of the PZT domain. It provides a floating potential boundary condition for the connection to an external circuit. A Ground node has been imposed to the interface surface between the PZT and the steel domain, as shown in Figure 1. Terminal and Ground nodes correspond to the output voltage electrodes, whose thickness is considered negligible. The Zero Charge condition has been applied to all the remaining boundaries.

Mechanical boundary conditions provide a fixed boundary constraint on the end of the cantilever, which is rigidly connected to the axlebox as depicted in Figure 1. All the remaining portions of the cantilever are free to move.

As previously mentioned, the role of the piezoelectric transducer is to harvest energy from the vibrations acting on the axlebox during the railway vehicle normal service.

In [9] the result of a study, aimed at evaluating the acceleration levels on the railway vehicle during its service, is reported. In order to detect these accelerations, three different measuring points were selected: the axle, the frame (bogie), and the body.

The results of the investigation showed that the highest accelerations were detected on the axle. Measured signals can be represented by normal distributions, characterized by the values reported in Table 3, where directions are those depicted in Figure 2.

Table 3. Axle accelerations levels.

Direction	Average level r.m.s. [m/s^2]	Standard deviation
Vertical	24	14
Transverse	20	14
Longitudinal	11	6

The vertical acceleration reported in Table 3 can be reasonably assumed as completely transferred to the axle box and, subsequently, to the boundary of the cantilever beam, which is rigidly connected to the axle box. Its relative signal, in time domain, is represented in Figure 3.

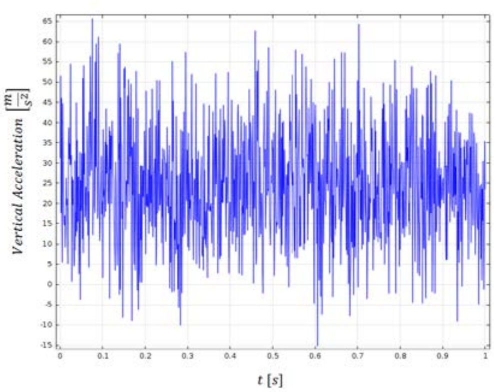

Fig. 3. Axlebox vertical acceleration in time domain.

In order to simulate the response of the piezoelectric device to such an input solicitation, a boundary load has been applied to the fixed surface of the cantilever. It is a force per unit area, directed along the vertical direction of Figure 2 and expressed as follows:

$$F = -\rho\, a(t)\, L\, 10^{-3} \quad [N/m^2] \qquad (5)$$

where ***a(t)*** is the signal represented in Figure 3 and $\boldsymbol{\rho}$ is the material volumetric mass density, which Comsol automatically assigns to the appropriate domain. Parameter ***L*** is the length of the cantilever, which is reported in Table 1.

The choice to transfer the axlebox acceleration to the fixed boundary of the cantilever has been made in order to overcome difficulties related to multi-scale meshing arising trying to represent the whole axlebox-cantilever system. A time dependent study has been carried out, in the described conditions. The simulating time window is 0.5 s long, with a step of 0.01 s. Figure 4 reports an example of a 3D plot of the electric potential distribution along the deformed cantilever, at time t=0.4 s while Figure 5 reports the open circuit output voltage v(t) in time domain.

Figure 6 reports the electric charge collected on the upper face of the piezoelectric compound in time domain.

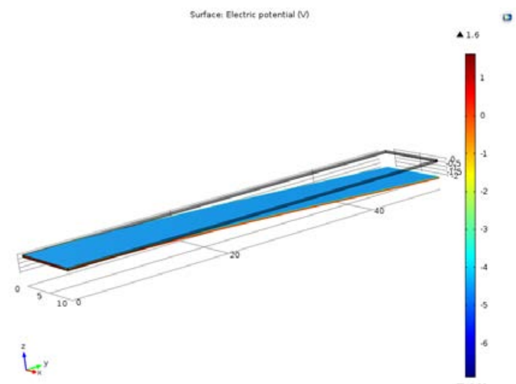

Fig. 4. 3D plot of a cantilever at instant time 0.4 *s: Electric potential distribution.*

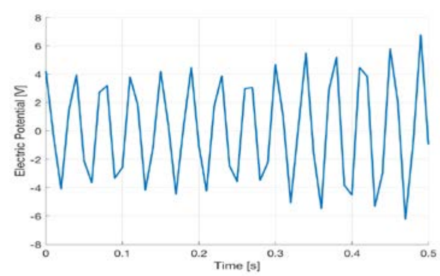

Fig. 5. Open circuit voltage developed.

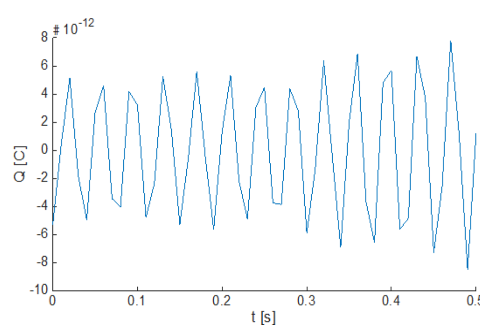

Fig. 6: Electric charge on the upper surface of the piezoelectric material.

Figure 7 reports the vertical displacement of an evaluation point (shown in Figure 1) located at the free end of the cantilever.

Figure 8 reports, in time domain, the absolute value of the electric potential energy. The dashed line represents the mean value.

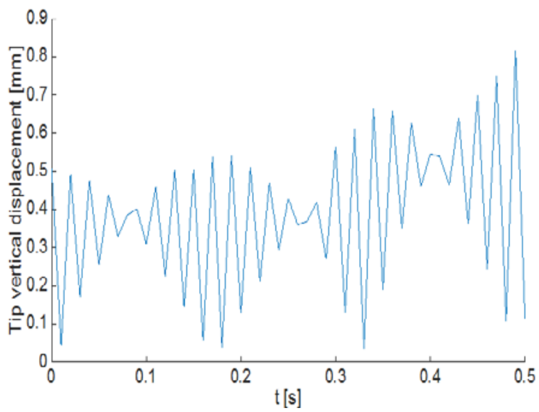

Fig. 7: Cantilever tip vertical displacement

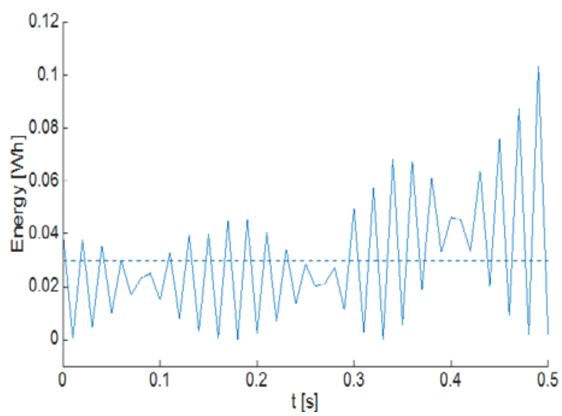

Fig. 8: Electric potential energy and its mean value.

The energy developed is enough to power a wireless sensor node for railway vehicles.

III. STUDY OF THE AXLEBOX

In order to make a non destructive test and diagnosis about the state of health of the axlebox, an eigenfrequency study was carried out.

The axlebox was locked on its back surface. The first case analyzed was that of an axlebox without defects. The first six eigenfrequencies of the axlebox were detected. Figure 9 shows that the value of the first natural frequency of the object is 4311,6 Hz.

Macroscopic effects of axlebox defects like corrosion have been simulated and analyzed removing material from the surface of the device. Figure 10 shows the first eigenfrequency of a damaged axlebox. On its surface 32 holes, with an hemisphere shape, having a 5 mm radius, were created.

Figure 11 and 12 show the same situation of Figure 10 where holes have an increased radius.

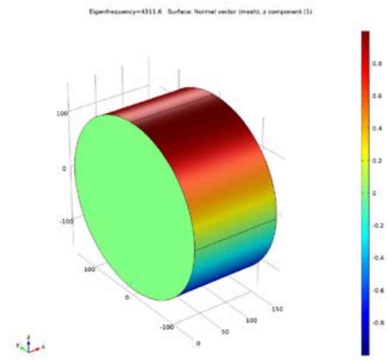

Fig. 9. First natural frequency of the axlebox without defects.

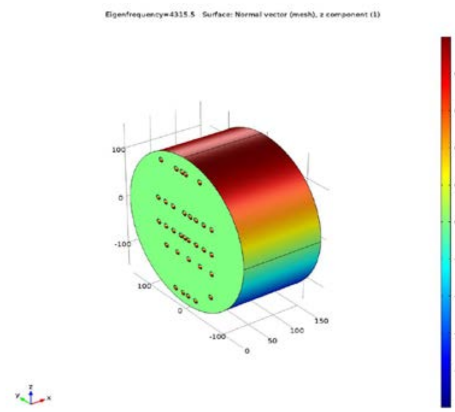

Fig. 10. First eigenfrequency of the axlebox with 5mm holes' radius.

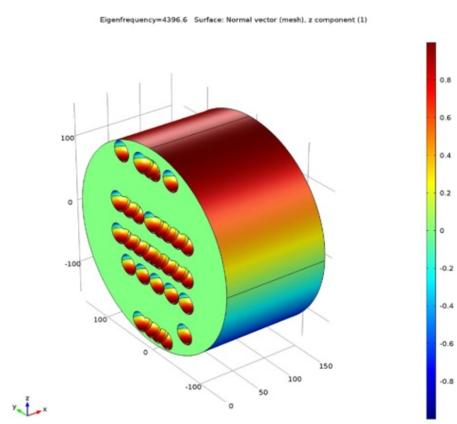

Fig. 11. First eigenfrequency of the axlebox with 15mm holes' radius.

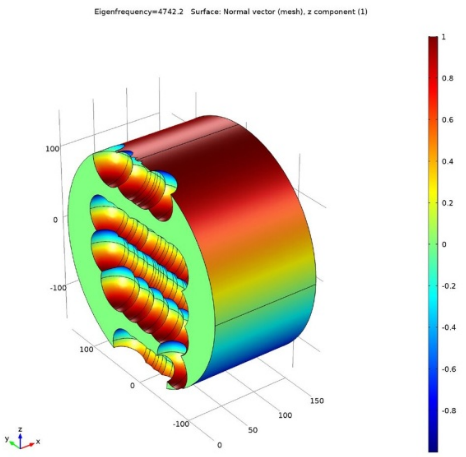

Fig. 12. First eigenfrequency of the axlebox with 30mm holes' radius.

Table 4 shows the first and the sixth eigenfrequency of the axlebox with and without defects.

Table 4. Comparison of natural frequencies of intact and damaged axlebox.

Axlebox status	First natural frequency [Hz]	Sixth natural frequency [Hz]
Intact	4311,6	8513,7
With 32 holes (5 mm of radius)	4315,5	8518,4
With 32 holes (10 mm of radius)	4340,3	8548,3
With 32 holes (15 mm of radius)	4396,6	8609,3
With 32 holes (20 mm of radius)	4488,3	8696,5
With 32 holes (25 mm of radius)	4607,2	8790,6
With 32 holes (30 mm of radius)	4742,9	8887,8

Figure 13 and 14 show the graphical representation of data of Table 4. The different reaction of the axlebox with and without defects to the eigenfrequency analysis enables a non destructive diagnosis about the integrity of the axlebox itself.

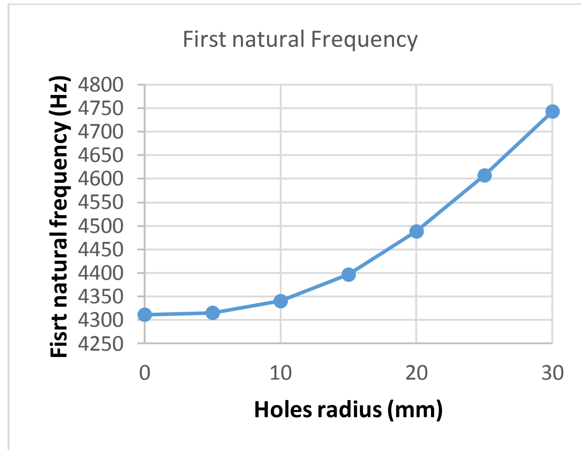

Fig. 13. First eigenfrequency of the axlebox function of holes' radius.

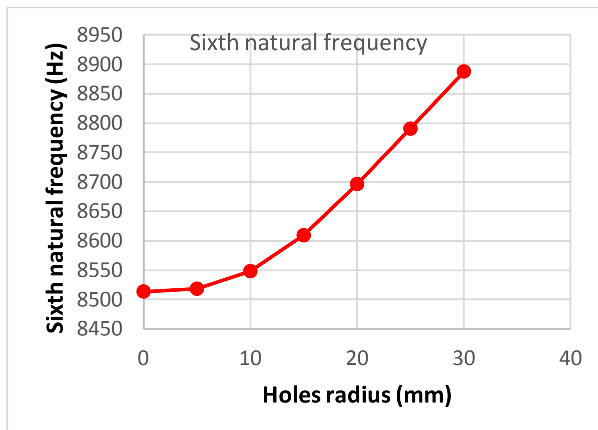

Fig. 14. Sixth eigenfrequency of the axlebox function of holes' radius

IV. CONCLUSION

In this paper simulation results of a system made of a piezoelectric cantilever energy harvester and an axlebox are presented.

The considered system is constituted by an axlebox that undergoes to the vibrations due to the irregularity of the railway track and transmits them to the piezoelectric cantilever beam.

The piezoelectric transducer converts acceleration into electrical potential, because of the direct piezoelectric effect, useful to power a wireless sensor node. Therefore, the self-powered sensor node is able to 'read' information about the state of health of the axlebox and to transmit them to an operational center that provides an alert about defects or aberrations of the axlebox in real time. The harvester device gives a good response as transducer and the simulated data confirm that the device is valid also for a diagnostic analysis, because of its different reaction in terms of eigenfrequency developed with or without defects.

In this paper the simulation of the cantilever beam and the axlebox have been separated but in a future paper the acceleration obtained from the movement of the axlebox, with and without defects, will be given as input data to the cantilever beam and its response, in terms of electrical potential developed, will be studied.

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