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Piezoelectric Energy Harvesting in Mining Locomotive

Alex Mouapi*[ab], Nadir Hakem[ab]

[a]Université du Québec en Abitibi-Témiscamingue (UQAT), Val d'Or, Canada

[b]Laboratoire de Recherche Télébec en Télécommunication Souterraines (LRTCS), Canada

*Corresponding author's mail: alex.mouapi@uqat.ca

Abstract

The mining industry is increasingly equipped with locomotives to transport minerals and staff. These locomotives are typically battery powered where diesel fumes or smoke would endanger crews, and where external electricity supplies cannot be used due to the danger of sparks igniting flammable gas. However, the cost and weight of batteries prohibit the using of the locomotive battery-powered on extended runs. Providing a green, virtually infinite alternative power source to traditional energy sources would extend the mining locomotive operating time. In this work, energy of mechanical vibrations present in the mining locomotive is converted into electrical energy using a piezoelectric transducer. A cantilever beam, with natural frequency of $15\ Hz$ corresponding to the principal frequency of the vibrations detected in the locomotive is designed and manufactured. By associating with the beam, the composite QP20W of Mide technology, an alternating voltage of amplitude $1.56\ V$ is obtained and a recovered power of $13.3\ \mu W$ is reached for optimum load resistance of $53.5\ k\Omega$.

Keywords: Energy harvesting; green energy; cantilever beam; piezoelectric composite.

1. Introduction

In the era of the great socio-economic upheavals, the mining industry continues to feed some economies such as the Canada, sub-Saharan Africa, China, South and Central America. Since the 1960s the mining remains the base of most of these economies. To remain competitive, the mining industry has several facilities like the locomotives for the transport of ores on rails, wagons for the transportation of staff etc. In the case of locomotives, they are often supplied with diesel. However, for hazardous areas explosion of coal dust and methane and in confined spaces, mining has rather for security reasons, battery locomotives. Due to the size and weight of the batteries, the use of such engines becomes difficult or impossible over extended runs. This replacement or battery charging operation can then be proved costly for the company. This work then proposes a solution to make these mining locomotives supply autonomous by providing a green, virtually infinite alternative power source which is a research area known under the name of Energy Harvesting.

Specifically, Energy Harvesting consist in the use of free available energy from the environment, vibrations [1,2,3], light [4], heat [5] or radio waves [6], to empower electronic systems with low-voltages and low-power consumption. The choice of primary energy depends on environment in which we find ourselves. In this paper, ambient mechanical vibrations available in a mining locomotive operation are used as an alternative source for energy harvesting.

There are three main transduction mechanisms to transform mechanical energy into electrical energy: electrostatic, electromagnetic and piezoelectric. Piezoelectric harvesters are popular today because they typically draw more power from kinetic energy in motion than electrostatic and electromagnetic systems [7]. This then justifies the choice focused on piezoelectric transducer in this work.

As it is well known, piezoelectric membrane generate an unregulated AC voltage. Thus they cannot be connected directly with the load because it generally requires a DC voltage. Therefore, three parts usually form a power scheme based on piezoelectric generators [8] (Fig. 1).

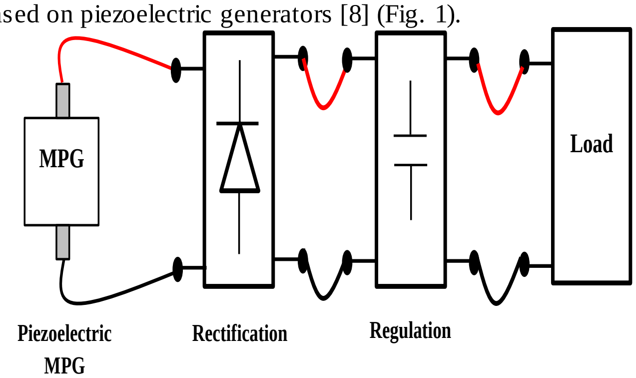


Fig. 1 Piezoelectric harvesting general architecture

The first stage is the piezoelectric transducer or Piezoelectric Micro Generator (PMG), which converts the mechanical vibrations into an alternative electrical energy. The second stage is the Rectification that converts the incoming AC signal wave of the PMG into a non-regulated DC voltage. Finally, the Regulation stage regulates and controls the non-regulated DC voltage coming from the second stage in order to transfer the energy to the load. This work proposes to size an appropriated PMG for the recovery of vibration energy available in a mining locomotive.

Previous work [9] has shown that the recovered power is maximum when the frequency of the vibrations is equal to the natural frequency of the converter. Taking this into account, the spectrum of vibrations in locomotive will first studied in Section 2, the spectrum obtained is analysed to deduce the needed dimensions of the cantilever beam to be realized. Section 3 presents experimental and simulation results. In section 4, this paper ends with a conclusion in which a discussion on the prospect for improving this work is also set.

2. Detected vibrations and piezoelectric transducer

2.1. Vibration in the mining locomotive

For measurements, locomotive 27 (Fig. 2) of the Horne Foundry of Rouyn Noranda is used to obtain the vibration spectrum inside the locomotive. To acquire ambient vibrations, triaxial accelerometer is used as in [1]. The Fast Fourier Transform (FFT) software of MATLAB was used for data analysis.

Fig. 2 Overview of the used locomotive

The accelerometer is located on board the locomotive and it yields the results shown in Fig. 3. From Fig 3a, we can find that the maximum acceleration is about 0.03 m/s^2. In order to find the acceleration distributions in the frequency domain, the FFT software is used and the result is shown in Fig 3b. From the FFT results, the power spectral density of vibration is higher in the frequency range $14\,Hz - 16\,Hz$ with a maximum power density of $-16\,dB\,/\,Hz$ reached in the neighbourhoods of $15\,Hz$, more precisely at $15.37\,Hz$. It comes out from these measurements that the piezoelectric beam needs to be sized in a way to resonate around $15\,Hz$.

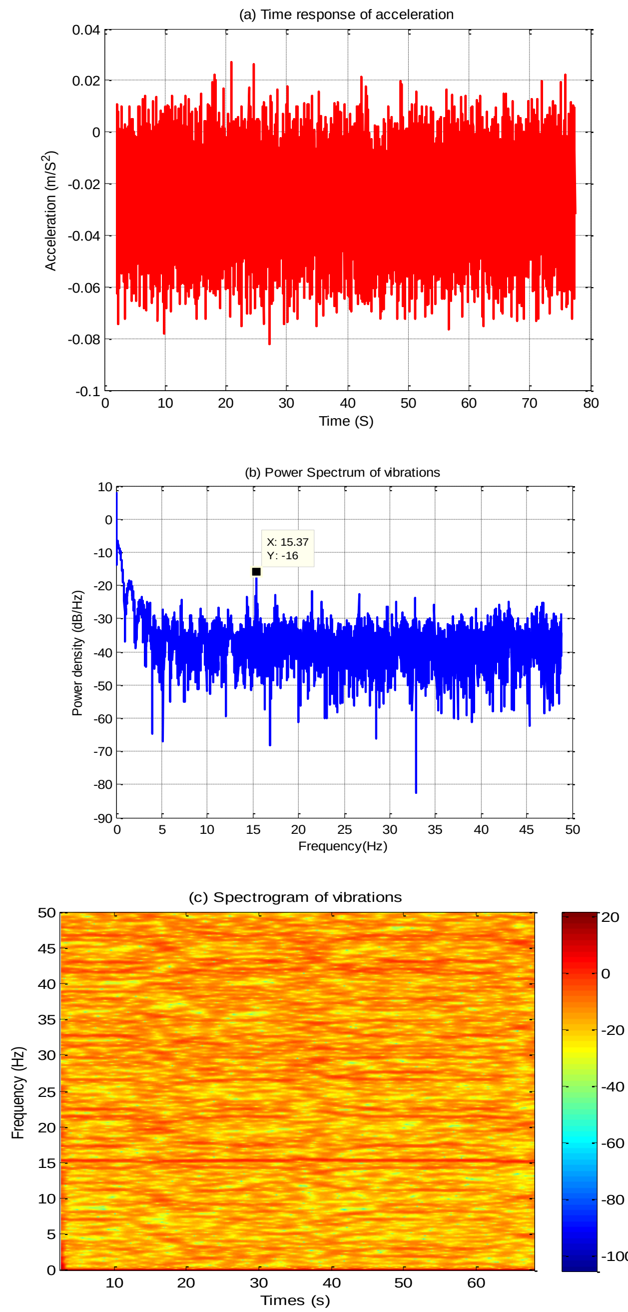


Fig. 3 Detected vibrations

2.2. PMG Design

The frequency of the vibration is very low ($15\,Hz$); it is difficult to directly use a massive piezoelectric material like elastic element. To obtain relatively flexible structure and authorizing important displacements, it is necessary to use action leverage. This action leverage is usually achieved by using a structure of the fix free beam type, better known as a cantilever structure [2]. The structure that we consider is a simple bimorph beam that was used in [10]. Fig. 4 shows the geometry of the cantilever beam which comprises three principal parts:

- The cantilever beam, which is used to amplify the relative displacement of the seismic mass to the displacement amplitude of the vibration source.
- The seismic mass: greater mass involves greater mechanical stress applied in the piezoelectric materiel producing a large output power.
- The piezoelectric composite, which is the active part of the structure, is used to convert mechanical vibrations into electrical energy.

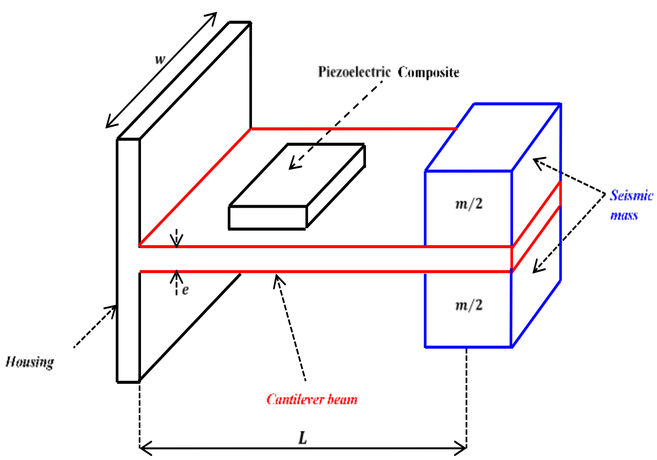


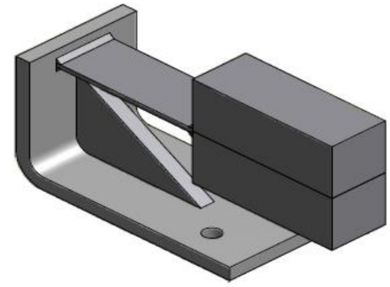
Fig. 4 Geometry of the cantilever piezoelectric transducer

Static analysis of the cantilever structure has been studied in [2] and the approximate expression of the natural frequency of the beam is given by the formula:

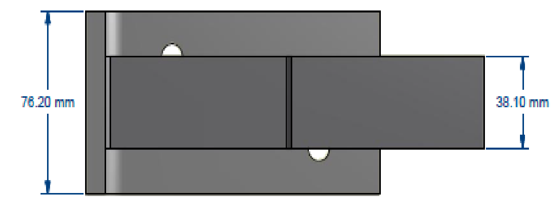
$$f_0 = \frac{1}{4\pi}\sqrt{\frac{Ewe^3}{mL^3}} \qquad (1)$$

with E representing the Young's modulus of the used material for the beam, w, e and L respectively represent the width, thickness and the length of the beam and m is the seismic mass. Expression (1) is obtained by neglecting the mass of the beam and that of the piezoelectric composite compared to the seismic mass.

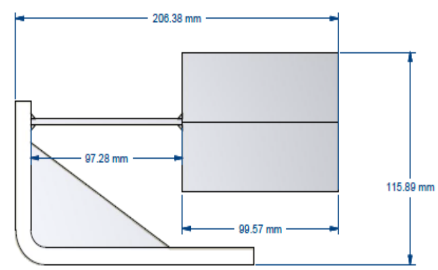
Among the most used materials, one can quote silicon, brass, steel and quartz. In our case, steel with Young's modulus of 210 Gpa has been used. The dimensions included in our concept are shown in Fig. 5 designed with Autodesk Inventor software which is a 3D mechanical design software. With these various dimensions, a natural frequency of the beam equal to 15.03 Hz has been achieved.



(a) Perspective view of the beam



(b) Top view of the beam



(c) Side view of the beam

Fig. 5 Dimensions of the cantilever beam

To complete the design of the transducer, a piezoelectric composite QP20W, manufactured by Mide technology has been used. This composite was used in [8] to design a DC / DC converter improving the conversion efficiency of a 53.8 Hz vibrational energy harvester. The QP20W is a composite beam made of 2 piezoelectric layers working as a bimorph, with an intermediate layer based on Polyimide. This composite beam is then located like shown in Fig. 6 with one end clamped to a vibrating body and the other end remaining free.

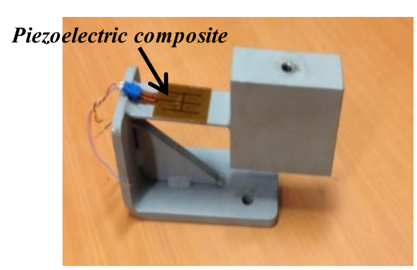


Fig. 6 Image of the MPG manufactured

The PMG shown in Fig. 6 operates as follows: the vibrations forced at the clamped end are propagated along the cantilever beam. This wave generates an induced strain in the membrane, which at the same time produces an electrical charge.

3. Prototype testing

3.1. Electrical Model of Piezoelectric transducer

To determine its power flow characteristics, a vibrating piezoelectric element is modeled in [8] as a sinusoidal current source $i_P(t)$ in parallel with its internal electrode capacitance C_P (Fig. 6.).

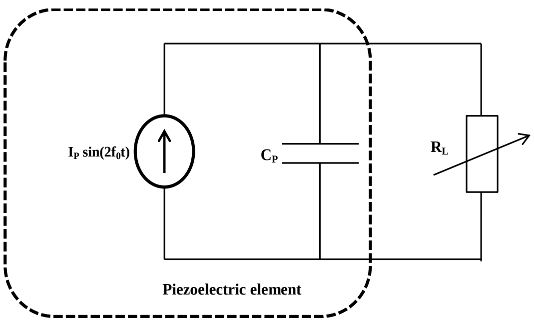


Fig. 7 Piezoelectric element model with resistive load

The magnitude of the polarization current I_P depends on the excitation level of the piezoelectric element. It was defined in [2] by the relation:

$$i_P(t) = wL_P d_{31} Y_P \dot{z}(t) \qquad (2)$$

L_P is the length of the piezoelectric composite, w is the width of composite, d_{31} is the piezoelectric constant, Y_P is Young's modulus and $\dot{z}(t)$ the speed of movement of the seismic mass in the end beam. Recall that a Quickpack QP20W was used as the piezoelectric energy source. Device specifications along with piezoelectric element properties are given in Table. 1. Substituting these values into (2), resulted in I_P equal to $29.7\ \mu A$.

Table 1. Size and piezoelectric properties of QP20W composite [8]

Properties	Units	Values
Clamped capacitance of the piezoelectric composite: C_P	μF	0.2
Piezoelectric dielectric constant: d_{31}	m/V	-179×10^{-12}
Length of the piezoelectric composite: L_P	mm	45.97
width of the piezoelectric composite: w	mm	33.02
Young Modulus: Y_P	Gpa	67

3.2. Output Voltage

A photograph of the setup environment is shown in Fig. 8. The PMG is placed on the boarder of the locomotive in the same place where was placed the acceleration sensor. To record the AC signals given by the manufactured transducer, a portable oscilloscope is used in order to not influence the vibration spectrum of measurement environment. It is the DSO Nano oscilloscope which is a pocket-sized oscilloscope and is compatible with 32-bit storage oscilloscope.

Fig. 8 Prototype testing

Fig.9 shows the time response of the experimental Open Circuit Voltage. We observe that the open circuit voltage of the transducer is periodic with a period of 70 ms corresponding to a frequency of 14.28 Hz, which is very close to the main frequency of vibrations. It also appears that the amplitude of voltage is not constant in time. This is certainly due to an inconsistency in the vibration amplitude which depends on the engine operating.

The results obtained by simulation in Advanced Design System (ADS) software of the schematic shown in Fig. 7 in comparison to the experimental results are shown in Fig. 10. We observe a good agreement between the experimental and simulations results.

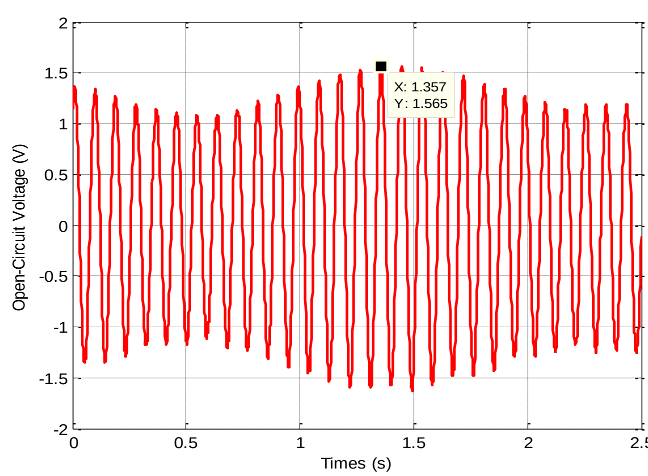


Fig. 9 Time response of open circuit voltage

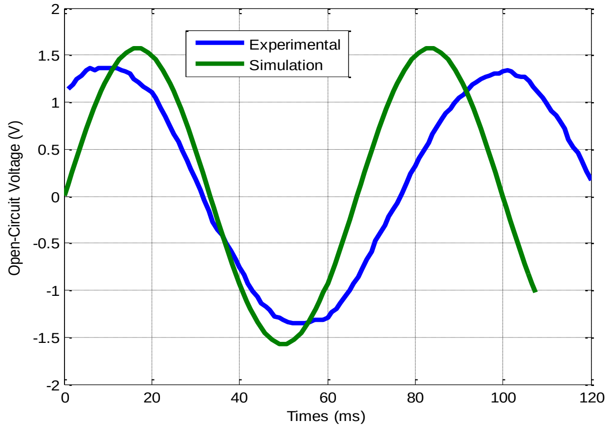


Fig. 10 Experimental and simulation waveform of Open-Circuit Voltage

3.3. Output Power

Fig 11 shows a plot of the output power versus the load resistor. Piezoelectric transducer was driven at a constant frequency of 15 Hz and resistors of various values were inserted across them. A maximum power of 11.5 μW is achieved for a load resistance equal to 53.5 $k\Omega$.

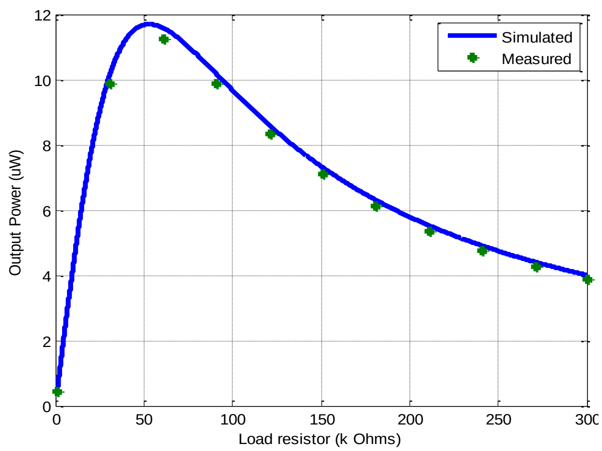


Fig. 11 Variation of power as a function of load

4. Conclusions

This paper has presented a feasibility of self-powered mining locomotives by using piezoelectric energy harvesting. For this, we first studied the spectrum of vibration available in the running locomotive. Measurements have shown that maximum power density of -16 dB / Hz is reached around 15 Hz. To obtain relatively flexible structure and authorizing important displacements, a steel cantilever beam with a natural frequency around 15 Hz is then designed and manufactured. The manufactured piezoelectric harvester has been characterized by applying vibration available on the locomotive. For an optimal load resistance of 53.5 $k\Omega$, a maximum power of 11.5 μW has been measured and an magnitude of 1.56 V of open circuit voltage is observed. A good agreement is observed between experimental and simulation results. However, the system could be improved significantly by using several composites instead of the one used in this work.

Abbreviations

PMG: Piezoelectric Micro Generator
FFT: Fast Fourier Transform

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The 1st International Conference on Energy, Environment and Economics (ICEEE 2016) was held at Heriot-Watt University, Edinburgh, EH14 4AS, UK, 16-18 August 2016. ICEEE2016 focused on energy, environment and economics of energy systems and their applications. More than fifty eight delegates from 31 countries with diverse expertise ranging from energy economics, solar thermal, water engineering, automotive, energy, economics and policy, sustainable development, bio fuels, Nano technologies, climate change, life cycle analysis etc. made conference true to its name and completely international. During conference total 51 oral presentations and six posters were shared between delegates. The presentations showed the depth and breadth of research across different research areas ranging from diverse background. ICEEE2016 aimed:

- To identify and share experiences, challenges and technical expertise on how to tackle growing energy use and greenhouse gas emissions and how to promote sustainability and economical, cost effective energy efficiency measures.

In total 11 technical sessions and two invited talks both from academia and industry provided insight into the recent development on the proposed theme of the conference. Preparation, organisation and delivery of the conference started from July 2015 and further co-ordinated by vibrant team of Conference Centre, Heriot Watt University. Conference organisers would like to acknowledge support from the sponsors particularly World Scientific Publication ltd and its team members for the delivery of the conference. Organisers are also thankful to all reviewers who contributed during peer review process and their contributions are well appreciated. At the end and during vote of thanks following awards have been announced and we would like to congratulate all well deserving delegates.

- Best Paper –Academia: Amela Ajanovic, EEG, TU Vienna, Austria
- Best Paper – Student : Christian Jenne,University of Duisburg-Essen, Germany
- Best Poster – Student: Yoann Guinard, University of New South Wales, Sydney, Australia
- Best Poster – Academia: E. Salleh, Universiti Kebangsaan Malaysia, Malaysia
- Active Participation Award - Yoann Guinard, University of New South Wales, Sydney, Australia

At the end we would like to extend our gratitude to all of you for your participation and hopefully welcome you again during ICEEE2017.

Editors:

Dr. Singh is Senior Scientist at Indian Agricultural Research Institute, New Delhi, India. Her area of expertise are bio energy and bio fuels, environmental engineering, carbon accounting and renewable energy integration for rural development.

Dr. Kumar is visiting faculty at Prince of Songkla University, Thailand. He have 16 years of research and teaching experience in the field of solar energy, drying and energy efficiency.

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