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PIEZOELECTRIC HARVESTER PERFORMANCE ANALYSIS FOR VIBRATIONS HARNESSING

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The paper aims to assess the performances of a piezoelectric device for harnessing the inherent vibrations of industrial equipment. The transducer is intended to power wireless sensors used for monitoring the operation of that specific equipment. Tests were conducted on the shaker table and on a test engine in order to validate the finite element model analysed in COMSOL Multiphysics. The model was validated to a great extent by experimental tests, regarding the mechanical and electrical parameters. Consequently, based on the FEM model, it was possible to estimate theoretically the maximum output voltage that can be generated.

Keywords: energy harnessing, piezoelectric effect, FEM, vibrations, frequency

1. Introduction

The outstanding development of integrated circuits over the last few years encourages the use of low power energy sources. Since the size and power requirements of electronics continue to reduce dramatically, a wireless sensor can now be supplied with less than 100 μW. Moreover, materials advances enable a continuous improvement in the performance of energy conversion devices.

Hence, in the past few years, using energy harvesting as power supply for small-scale electronics has attracted large research interest. Piezoelectric devices gain interest due to their highly efficient energy conversion from mechanical vibrations, and to the challenge of finding ways to boost the output energy, which so far has been feeble. Piezoelectric harvesters use the piezoelectric effect for the direct conversion of mechanical vibrations into electrical energy and tap this energy by connecting the electrodes with an electric circuit [1].

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In order to achieve maximum electrical response, it is preferable to excite a given harvester at its fundamental resonance frequency (or at one of the higher resonance frequencies). The majority of studies in the literature have focused on the resonance excitation at the fundamental resonance frequency in order to investigate the maximum performance of the harvester [2]. Since the foremost requirement for energy scavenging devices is to operate in resonance, several methods have been studied for adjusting the resonant frequency, comprised in [3]. Even a slight deviation (± 1 Hz) from the resonant condition will result in a sudden drop in the generated power [4] for lightly damped systems.

For assessing the behaviour and performances, a FEM (Finite Element Method) analysis in COMSOL Multiphysics was made, the simulation results being validating through experimental tests. A Multiphysics approach must be used for modelling piezoelectric devices if it is desired to also evaluate the electrical response, besides mechanical aspects. So far, unimorph and bimorph beams have been modelled in literature [5, 6, 7]. The model proposed in this paper is a more complex quadmorph multilayer beam. It consists of 17 thin layers, including four PZT-5H (PZT – Lead Zirconate Titanate) piezoelectric wafers.

Researches regarding the practical implementation of an energy harvesting system using piezoelectric structures started in a previous work [8], this one constituting a base for verifying the applicability. The previous work used a simplified formula for resonance frequency, with a single set of tests performed using an electrical load similar to the input impedance of the harvesting circuit. That study focused on practical implementation aspects on a turbine engine and adjusting the frequency (influence of fastening and clamping, influence of tip mass, positioning on engine and validation in practical conditions).

The previous study has indicated the necessity of developing a more complex mathematical model, creating a complete FEM model to include the composite structure in detail and verifying in laboratory conditions resembling as much as possible the simulation conditions. This was the purpose of the work herein, leading to the development of a complex mathematical model for calculating the resonance frequency. This one was compared with the FEM simulation and also with experimental results.

2. The piezoelectric harvester analysed and its mathematical model

The device to be analysed is Midé PPA-4011 [9] shown in Fig. 1. This one was found adequate for our application regarding frequency range and power output. The piezoelectric harvester operates in d_{31} mode, meaning that when stress is applied on horizontal axis 1, it has electrical response on transversal axis 3 [10]. The piezoelectric transducer is intended for harnessing kinetic energy from the inherent vibrations of industrial equipment. The harvesting assembly was mounted on a Klimov TV2-117A gas turbine engine.

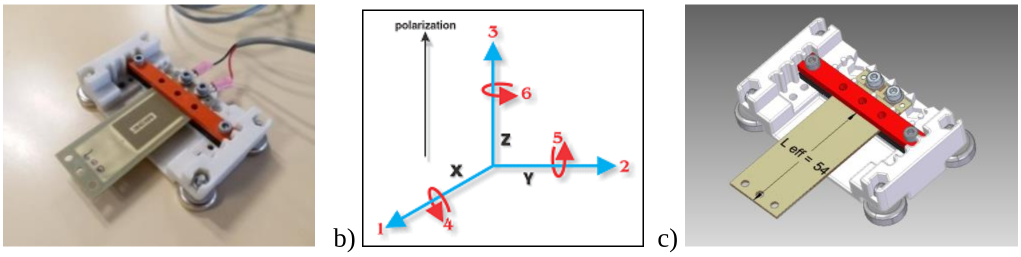


Fig. 1. Harvesting assembly; b) Piezoelectric polarization axes [10]; c) CAD model (L_{eff} = 54mm)

The harvester is a quadmorph, consisting of four PZT-5H active layers. In this configuration, the wafers are wired similarly to bimorphs but as two sets of pairs. First two wafers act in unison but in opposite direction to the other pair.

The beam overall dimensions are 71.0 mm x 25.4 mm x 1.32 mm, and the total mass is 7.6 grams. The piezoelectric layers are sandwiched between copper electrodes, each of the four such sets (copper, PZT-5H, copper) being separated by a FR4 protection and insulation layer (Fig. 2). The PZT-5H wafers are smaller in length and width than the other layers. All wafers are affixed together by epoxy layers with a smaller thickness than the other layers (<0.02 mm).

a)

Layer	Thickness [mm]	Length x Width [mm]
FR4_1	0.08	65 x 25.4
Copper_1	0.03	65 x 25.4
PZT-5H_1	0.15	46 x 20.8
Copper _2	0.03	65 x 25.4
FR4_2	0.08	65 x 25.4
Copper _3	0.03	65 x 25.4
PZT-5H_2	0.15	46 x 20.8
Copper _4	0.03	65 x 25.4
FR4_3	0.08	65 x 25.4
Copper _5	0.03	65 x 25.4
PZT-5H_3	0.15	46 x 20.8
Copper _6	0.03	65 x 25.4
FR4_4	0.08	65 x 25.4
Copper _7	0.03	65 x 25.4
PZT-5H_4	0.15	46 x 20.8
Copper _8	0.03	65 x 25.4
FR4_5	0.08	65 x 25.4
Total thickness	**1.24** *without considering epoxy layers	

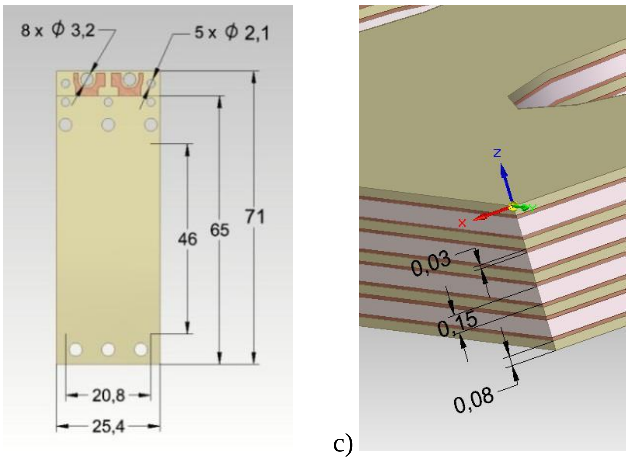


Fig. 2. Dimensions of the cantilever pack

The mounting kit provides three clamping positions. The specified resonant frequency for the middle clamp (Fig. 3b) is 245.8 Hz [9]. The front clamp (Fig. 3c) is useful for increasing the resonant frequency, decreasing the effective length. The beam was clamped in the rear clamp (Fig. 3a), with an effective length L_{eff} = 54 mm (Fig. 1c) and lower frequency. At the same time, the lower strain exerted in rear clamp can lengthen the lifetime of the device.

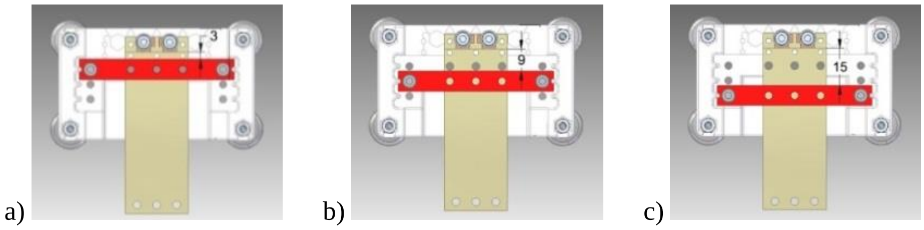


Fig. 3. Clamping positions on 3D CAD model: a) Rear clamp; b) Middle clamp; c) Front clamp

In order to get maximum electrical energy output, the fundamental frequency of the harvester must be equal or very close to that of the vibration source, to enter into resonance. The rotational speed of the test turbine engine is maintained constant at around 11,400 rpm. The frequency at this speed is 190 Hz. In the mounting point, the acceleration was measured at 0.9*g* (~8.83 m/s^2).

A cantilever subjected to vibrations behaves like a mass-spring-damper system for the first resonance frequency. For cantilever (beam fixed constrained at one end), the frequency has the following expression [11]:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}} \tag{1}$$

where: f – frequency; k – beam bending stiffness constant; m_{eff} – effective mass.

The bending stiffness constant k of the beam is calculated depending on the cross-sectional stiffness K [11]:

$$k = \frac{3K}{L^3} \tag{2}$$

Knowing the modulus of elasticity of the materials specified in [9] and layers thicknesses, we determined K, considering all the 17 layers [12]:

$$K = b \cdot \left[\sum_{i=1}^{17} Y^{(i)} h_i \left(z_0^2 - z_0(H_i + H_{i-1}) + \frac{H_i^2 + H_{i-1}^2 + H_i H_{i-1}}{3}\right)\right] = 0.223\ \frac{kg \cdot m^3}{s^2} \tag{3}$$

where: $Y^{(i)}$ – Young's modulus for layer *(i)*; h_i – layer *(i)* thickness; z_0 – neutral fibre coordinate; $H_i = \sum_{j=1}^{i} h_j$.

The neutral fibre is the line whose length remains constant after deformation. Its coordinate z_0 is calculated as [12]:

$$z_0 = \frac{\sum_{i=1}^{17} Y^{(i)} \cdot h_i \cdot \frac{H_i + H_{i-1}}{2}}{\sum_{i=1}^{17} Y^{(i)} \cdot h_i} = 0.62\ mm \tag{4}$$

Relying on the formula in [11], the resulting fundamental frequency is:

$$f = \frac{1}{2\pi} \cdot 1.875^2 \sqrt{\frac{K}{\rho_{ech} \cdot A \cdot L_{eff}{}^4}} = 241.68\ Hz \quad (5)$$

The equivalent density ρ_{ech} in equation (5) above was calculated as:

$$\rho_{ech} = \frac{m}{b \cdot L \cdot H} = 4469\ kg/m^3 \quad (6)$$

The piezoelectric beam was clamped in the rear clamp, the farthest position on the support, leaving the maximum effective length subjected to vibrations. In this position, the strain is lower and the tip amplitude is higher, resulting both in longer lifetime and higher electrical response.

3. FEM simulation

The FEM simulation was performed in COMSOL Multiphysics using the MEMS (Micro-Electro-Mechanical Systems) Module, for analysing piezoelectric microscale behaviour. The simulation considers two intertwined physics, namely:

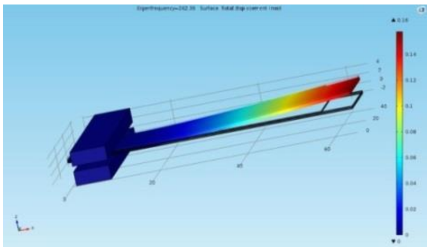
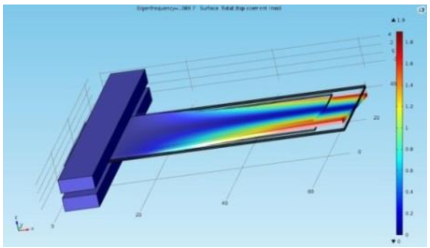
- ***Solid Mechanics,*** where materials are assigned, PZT-5H layers being declared piezoelectric. Fixed constraints and loads (base acceleration) conditions are set.
- ***Electrostatics***, where boundary and initial conditions are declared and an electric charge conservation condition is introduced for the piezoelectric layers. Terminal and ground conditions are also set for copper electrodes.

The two physics are coupled by activating Multiphysics – Piezoelectric effect, which allows simultaneous numerical solving of equations from solid mechanics, electrostatics and constitutive equations of the piezoelectric material.

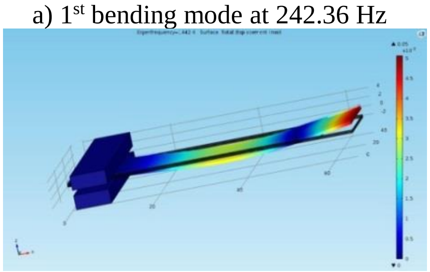
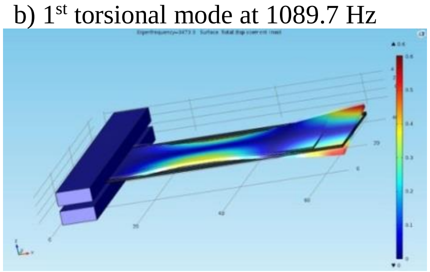
COMSOL allows coupling an electrical circuit at structure's terminals (declared in *Electrostatics*). However, impedance conditioning circuits used in practice have complicated diagrams. At the time being, a model including the electrical circuit has not been realized because equivalent components have not been identified in COMSOL library. Consequently, the simulation was realized considering infinite terminals impedance (null electric charge), pursuing to perform experimental validation in similar conditions. Subsequently, further tests were conducted in conditions resembling real operation.

The simulation did not only suppose obtaining the vibration modes, rendering the simulation purely mechanic, but the piezoelectric effect was also considered by evaluating the electric potential developed for each eigenfrequency. For this, the terminal impedance was considered to be infinite (free terminals with zero charge condition). It was desired to avoid a resonant frequency that would produce a torsional mode, because no electrical charge is produced then, because one side bends upwards and the other side bends downwards, one side giving positive charge and the other giving negative charge, which cancel each other, resulting in a net zero charge.

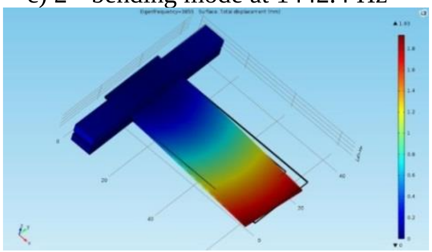
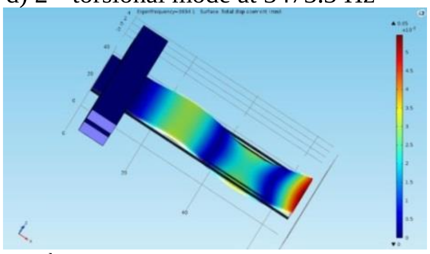
The materials were declared accordingly, also modifying the default materials in COMSOL with the values given in product specifications. An acceleration of 0.9*g* was applied to the base of the inferior clamp bar. The first 6 eigenfrequencies computed and their vibration modes are shown in Fig. 4.

a) 1st bending mode at 242.36 Hz b) 1st torsional mode at 1089.7 Hz

c) 2nd bending mode at 1442.4 Hz d) 2nd torsional mode at 3473.3 Hz

e) Bending in horizontal plane at 3855 Hz f) 3rd bending mode at 3934.1 Hz

Fig. 4. Vibration modes at the first 6 eigenfrequencies computed

Relying on the values extracted from simulation, it was possible to estimate the maximum voltage that can be generated at each eigenfrequency, the interest falling on the first bending frequency. The data from modal simulation is relative, as the input to produce that vibration is unknown. Nevertheless, scaling this data depending on maximum stress gives it real significance.

The component material of the harvester with the lowest strength is copper (tensile yield strength 40-80 MPa). Therefore, the values in the table above were calculated considering maximum stress allowed σ_{max} = 40 MPa. A correction coefficient was established as ratio between tensile yield stress and the maximum stress obtained from FEM simulation for cooper layers, this coefficient being used for all layers. PZT-5H is a soft piezoceramic material with a superior breaking limit of 114.8 MPa [13]. Being a ceramic material, it does not exhibit tensile yield strength, but breaks directly at its ultimate tensile strength.

Table 1

Transducer properties calculated on the basis of FEM simulation results

f_n [Hz]	σ [MPa]	d [mm]	V [V]	$\frac{\sigma_{max}}{\sigma}$	V_{max} [V] $\left(V \cdot \frac{\sigma_{max}}{\sigma}\right)$	d_{max} [mm] $\left(d \cdot \frac{\sigma_{max}}{\sigma}\right)$
242.36	30.476	0.158	3.361	1.313	4.411	0.207
1089.7	874.51	1.897	0.171	0.046	0.008	0.087
1442.4	40.848	0.051	3.213	0.979	3.146	0.050
3473.3	731.99	0.602	0.094	0.055	0.005	0.033
3855	6027	1.925	1.085	0.007	0.007	0.013
3934.1	104.31	0.055	3.484	0.383	1.336	0.021

where: f_n – Eigenfrequency; σ – von Mises stress; d – Total displacement; V – Voltage; $\frac{\sigma_{max}}{\sigma}$ – correction factor; V_{max} – Maximum voltage; d_{max} – Maximum displacement allowed.

The first resonant frequency computed with FEM was found at 242.36 Hz, close to the value obtained analytically using relation (5). The maximum voltage that can be generated at the first resonance was estimated at 4.41 V (Table 1).

4. Experimental tests

Tests were conducted with a shaker table as vibration source, driven by a swept-sine function generated from the impedance analyser (SR785) (Fig. 5a). Since piezoelectric devices have high output impedance, the measurement circuit should have higher input impedance. This was done by connecting the output to a vibration meter designed for piezoelectric sensors. The input vibrations were monitored using a precise calibration accelerometer mounted on the shaker table.

a) b)

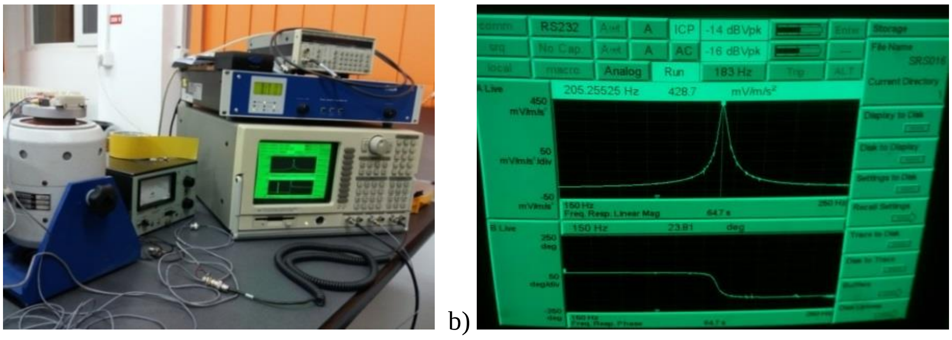


Fig. 5. a) Experimental setup and b) Transducer response for the first set of tests

For the first set of tests, the assembly was mounted with screws on the shaker platform. The signal was adjusted so that to approach the yield strength in copper layers. The results show a voltage peak of 428.7 mV/(m/s^2), occurring at a resonant frequency of 205.25 Hz (corresponding to 4.40 V/*g*) (Fig. 5b). Due to the high input impedance of the charge-voltage converter, the FEM simulation condition can be considered verified. The experimentally obtained resonance frequency is lower than the one obtained in the simulation because the beam was declared solidary with the clamping bars (perfectly stiff) in the FEM model, and also because the adherent epoxy resin layers were neglected (no data regarding exact thicknesses and elasticity modulus from manufacturer, stating that for simulation purposes these layers can be ignored). The voltage response is close to the one obtained with finite element analysis.

Another set of tests was conducted without additional resistance, by connecting piezoelectric harvester output directly to the signal analyser, without using the vibration meter. However, voltage drops and losses do occur due to analyser input impedance of 1 MΩ, cables resistances and connectors, therefore the transducer is not exactly operating in no load conditions.

A peak voltage of 358.8 mV/(m/s^2) was recorded at the resonance frequency of 203.65 Hz (3.52 V/*g* or ~3.17 V at 0.9*g*) (Fig. 6). The measured frequency is with 2.4 Hz lower than previously, because the electrical resistance has a damping effect.

a) b)

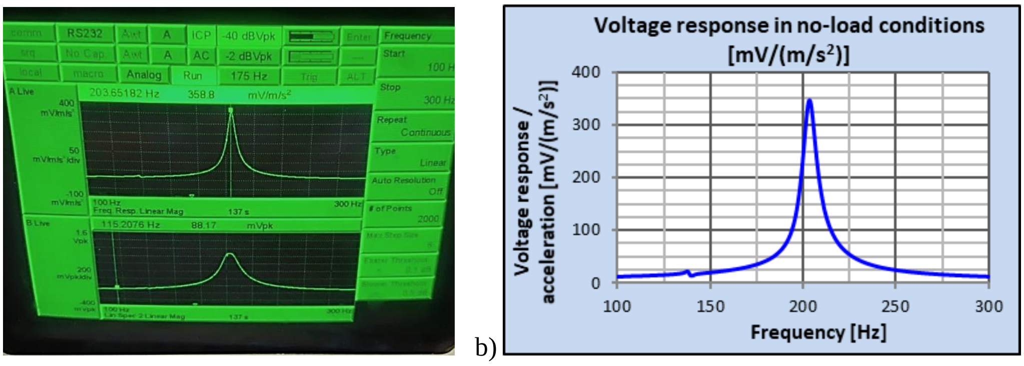
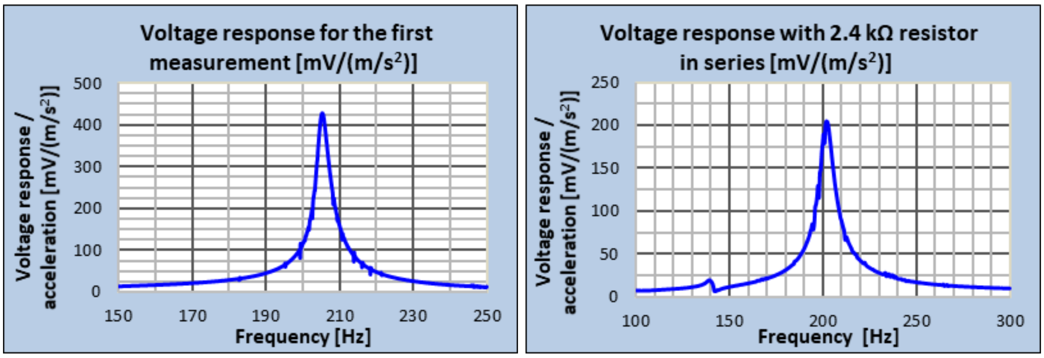


Fig. 6. Voltage response with direct connection: a) Signal analyser display and b) Graph

Usual energy harvesting circuits are not as complex as signal conditioners for piezoelectric sensors, the former having much lower input impedance. For the last set of tests, the assembly was fixed with double-sided adhesive tape on the shaker platform and a 2.4 kΩ resistor was wired in series with the transducer (equivalent to the 2.5 kΩ input resistance of the harvesting circuit). This is the electrical resistance of the load to be electrically supplied by the harvester. A peak voltage of 225.6 mV/(m/s^2) and a frequency decrease with 4 Hz comparing to the first set of tests were recorded, from 205.25 Hz to 201.25 Hz. This can be due both to the lower electrical resistance and attaching with adhesive tape, which is more elastic than screws fastening. The graphs drawn with the imported data extracted from the signal analyser are presented in Fig. 7 below.

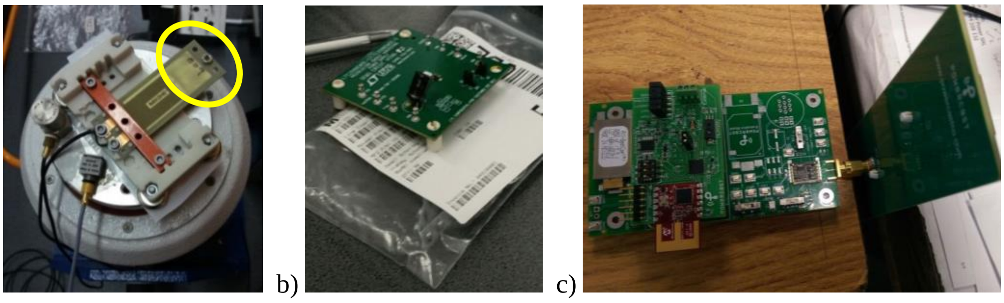


a) First set of tests b) With 2.4 kΩ resistor

Fig. 7. Voltage response graphs as function of frequency

The voltage values read on the impedance analyser are per m/s^2. The voltages per 1*g* are: for first measurement ~4.2 V/*g* and respectively with 2.4 kΩ resistor ~2.21 V/*g*. On the test engine, in resonance conditions, at an acceleration of 0.9*g*, we would theoretically record a voltage of ~3.8 V with infinite input impedance and almost 2 V with the 2.4 kΩ resistor in series.

The frequency of the harvester had to be furthermore decreased to fulfil the resonance condition with the engine frequency of 190 Hz. Thus, a tip mass of 0.2 grams was fixed on the cantilever. The frequency decrease was optimum, to 189.72 Hz. The images below present the seismic mass added (Fig. 8a), the piezoelectric harvesting load circuit (Fig. 8b), and the wireless transmission circuit to be supplied with the harnessed energy (Fig. 8c).



a) b) c)

Fig. 8. a) Proof mass added; b) Piezoelectric harvesting circuit; c) Wireless transmission chip

A magnetic mounting was used for attaching the assembly on the test engine, in no load conditions. With no additional voltage losses (besides cables resistance, electrical connections, internal damping, friction between layers, friction with air, etc.), an output voltage of 4 V was previously measured [14], using a charge amplifier with inputs designed for very high impedances.

a) 
b) 

Fig. 9. Harnessing vibrations: a) Gas turbine engine and b) Piezoelectric harvester mounted

5. Results and discussion

The effective length of the cantilever, the overall mass and the stiffness of the tested assembly were adjusted so as to set the fundamental frequency of the piezoelectric harvester as close as possible to the test engine frequency.

The FEM analysis resulted in a first resonance frequency (242.36 Hz) that is close to the fundamental frequency calculated analytically (241.68 Hz). The value indicated by the producer (245.8 Hz) is slightly larger due to the clamping in the middle position, while both FEM simulation and calculus consider clamping at longest effective length. Therefore, the simulation was validated, considering perfectly stiff fastening and infinite external impedance (Table 2).

The experimental tests have shown a close similitude with the simulation results. Thus, the finite element model was also successfully validated by tests. A slightly lower frequency was found experimentally (205.25 Hz with screw mount). This can arise from declaring the beam perfectly clamped on all its width in the FEM analysis, producing an ideal stiffness.

Table 2

Frequency value results comparison

	Analytical	**FEM**	**Experimental**
Frequency value obtained [Hz]	241.68	242.36	205.25
Percentage error comparing to experiment	17.75%	18.08%	-

As it was observed experimentally, tightening the screws with a quarter of turn increases the resonance frequency with 15-20 Hz. Therefore, it is more than plausible that the frequency would increase with almost 40 Hz if the clamp bars were ideally solidary with the beam (similar to gluing with strong resins).

On the engine, other factors such as thermal dilatations and thermal stresses can also contribute to the frequency decrease. The simulation and product specifications suppose constant temperature, but in real test conditions important temperature fluctuations do occur.

Since the simulation model has proven to be reliable, it was possible to estimate the maximum output voltage by introducing a correction factor depending on von Mises stress computed and the lowest strength of the materials.

The voltage computed in the simulation has the value of 4.41 V, for infinite input impedance and perfectly stiff fastening, with vibrations up to maximum material stress allowed. The voltage determined experimentally, with an input base acceleration of 0.9*g* was around 3.8 V with infinite measurement impedance, of almost 2 V with a 2.4 kΩ resistor in series, and around 3.17 V with 1MΩ load resistance. A voltage of 4 V was recorded on the test engine, in no electrical load conditions. This is comparable to the level of a small battery, but has the advantage that theoretically it can function for an unlimited period of time, without the need of replacement. It is not desirable to stress or stiffen the harvester close to the maximum limit allowed because premature ageing can occur, lowering materials strength, and thus shortening product lifetime.

6. Conclusions

The experimental results show a good similitude with the FEM model. Therefore, the finite element model was successfully validated by the tests conducted and by the product data communicated by the manufacturer. Since the simulation model demonstrated reliable, it was possible to estimate the maximum output voltage that the transducer is able to generate.

The results are encouraging for harnessing the kinetic energy from vibrating machinery for the energy supply of low-power wireless sensors. By harnessing the inherent vibrations, it is possible to eliminate batteries and electrical cables. Theoretically, such an energy source can function for an unlimited period of time, rendering the wireless sensors autonomous.

For more accurate results, the FEM model must be integrated in a complete simulation, to include both the piezoelectric transducer and the load circuit, after establishing the final circuitry. This will make the object of future research. The integration of all the elements of the system leads however to a high demand of computational resources and, at the same time, to a very high computing time. The influence of real mounting conditions (clamping stiffness) and also of temperature variations will be studied in future research work.

Further tests will be done with three harvesters electrically connected in series. There is a high risk that two of the harvesters to oscillate in antiphase, giving opposite sign charges, which can nullify each other if connected in the same electric circuit. To avoid this, a rectifying and storage circuit with Schottky diodes and capacitors will be used, to convert the alternate current yielded by the piezoelectric transducers into direct current cumulated from all the three devices.

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