Double Beam Energy Harvester Based on PZT Piezoelectrics

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Abstract—This work presents a new design and performance evaluation of an energy harvester. The generator was built in the form of a double beam mechanical structure on which eight piezoelectric elements were glued and subjected to cyclic tensile and compression loads. Electrical energy is converted from mechanical vibrations generated by machines, by means of a piezoelectric material based on Lead Zirconium Titanate (PZT). Geometric dimensions of the beam structure were optimized by a finite element analysis prior to the practical construction of the device. Simulated and experimental results regarding the generator dynamics and the generated electric voltage are presented and compared. The device was evaluated for different excitations and vibration amplitudes at a frequency of 60 Hz in order to capture vibrational energy from machines at this frequency. Additionally, the generator’s performance was evaluated when operating under two different real-world conditions: First, the device mounted on a condenser of an air conditioner, then on a three-phase motor pump. As a load for the piezoelectric generator, an RF circuit transmitted the ambient temperature information to a nearby computer. Correct reception of the ambient temperature value demonstrates the ability to generate electrical power suitable for a low-power circuit. As contribution to the literature, this study provides sufficient power for a circuit transmitting information from a sensor. This allows monitoring the state of a machine, using energy dissipated by mechanical vibrations in order to power the electronic systems responsible for sensing.

Index Terms—Electric power generator, Energy harvesting, Mechanical vibration, Piezoelectric materials.

I. INTRODUCTION

The concept of Energy Harvesting has been considered for years as an option to minimize the exploitation of fossil fuel-based energy sources, which rise great environmental concerns. It aims at capturing atmospheric energy and convert it into electricity. Several large-scale applications make use of this concept, as the production of electricity from wind and photovoltaic parks.

Studies on generating electricity from environmental sources have been carried out with focus on low power consuming devices [1]. These surveys were driven by recent technological advances in micro and nanotechnology, which have promoted important developments to electronic devices, such as reduction in size and power consumption, considerable variety of wireless devices and an increase in demand for self-powered electronic systems. Examples are applications for industrial or environmental monitoring, implantable medical devices and wireless sensor networks [2]–[4]. Additionally, there is a large number of devices interconnected through intelligent infrastructure such as the Internet of Things (IoT), which is considered one of the fastest growing technological platforms.

According to Mallick et al. [5], in a few years, about 25 billion devices are expected to be connected in the IoT. However, a critical issue restricting the consolidation of this technology is the power consumption of all these wireless communication devices. Currently, such systems use conventional batteries as a power supply, requiring replacement (where possible), a procedure which can is sometimes risky, especially in the case of implantable devices. To overcome such problems, environmental energy pickup systems as independent power sources, are a promising alternative for feeding low power electronic devices, which can then operate truly independently [6]–[10].

Until now, various sources and forms for energy harvesting have been studied and presented as alternatives to power generation, including: electromagnetic (magnetic field) [11], [12], radio frequency [13] wind [14], solar radiation [15], [16] and biological sources [17]. All these sources differ in the amount available power. Within these examples, capturing kinetic energy from mechanical vibrations present in machines, household devices, air or water flow, moving structures (cars and planes) and others like biological systems, buildings, bridges and floors, is the field with the highest number of publications and real-world applications.

Some conversion mechanisms including electrostatic, electromagnetic and piezoelectric have been investigated for the production of an electricity from mechanical vibrations [18]. Vibration transducers with piezoelectric technology have been studied most intensively [19] and are considered as an advanced technology, with continuously ongoing research. Numerous application publications [20]–[25], show that the piezoelectric materials are most suitable candidates for converting mechanical deformation into electrical energy efficiently. No additional power source is required; piezoelectricss support a certain amount of deformation and a wide variety of piezoelectric materials is available. Established fabrication processes allow mass fabrication and their integration with
microelectromechanical (MEMS) and integrated circuit (IC) technologies.

Their fundamental property is a coupling between multiple physical domains characterizes them as one of the classes of smart materials [26]. The electromechanical interaction is governed by the constitutive equations which represent the physical coupling between the mechanical (stress $T$ and strain $S$) and electric domains (electric field $E$ and charge density $D$) as described in Equation 1:

$$
\begin{bmatrix}
D \\
S
\end{bmatrix} =
\begin{bmatrix}
 d^T & e^T \\
 s^E & d^T
\end{bmatrix}
\begin{bmatrix}
 E \\
 T
\end{bmatrix}
$$

(1)

Where $s^E$ is the compliance under a constant electric field, $e^T$ is the dielectric permittivity under a constant mechanical stress, and $t$ are the matrices of the direct and inverse piezoelectric effects and the superscript $t$ represents the transposed matrix. The direct effect is the basis for the operation of the piezoelectric converters, which are mostly based on beams or plates containing up to two piezoelectric elements, fixed in structures subjected to vibratory movements. From a practical point of view, these constructions have the drawback of only one region subjected to usable levels of mechanical deformation; this means when necessary to rise the electric power generation, the devices become large and requires a lot of space.

For these reasons, the main objective of this work is the development and evaluation of the performance of a compact piezoelectric generator capable of converting usable amounts of electric energy. The generator consists of two separate metal beams connected to small masses at both ends, allowing mechanical deformation (at both ends) which is coupled to eight piezoelectric elements. It was designed based on computational numerical and experimental analyses, considering geometry variations, aiming to determine the best condition for electric power generation. Such analyses are important not only to determine the energy output, but also for improving the geometric design parameters of the prototype, starting from the understanding of how the variation of each parameter affects the amount of electric energy generated.

Besides geometry, the chosen piezoelectric material has also a great influence on the functionality and performance of the converter. Therefore, it was first experimentally evaluated which piezoelectric material was most appropriate for the converter’s performance.

The device was projected to have a first natural frequency of 60 Hz; this frequency is available from various vibration sources, usually equipment powered by a 60 Hz electric network, such as air-conditioning devices [27], electric motors or high voltage transformers [28]. Depending on the available power, the electricity could initially be stored or directly used for feeding temperature, humidity or vibration monitoring circuits.

To evaluate the overall performance of the proposed generator, the output voltage was recorded for open circuit condition and the generated electrical power was measured considering a resistive load; all these evaluations were done for different excitation frequencies and vibration amplitudes. Then the experiments were repeated with the piezoelectric generator connected to an energy storage circuit, feeding a wireless device capable of reading and sending the ambient temperature via radio frequency (RF). Also, outdoor tests were performed making use of environmental vibration sources.

II. MATERIALS AND METHODS

A. Piezoelectric material selection

In order to improve conversion efficiency, besides an optimization of the generator’s geometric configuration, different piezoelectric materials have been developed and compared [19], [29]–[31]. Within these materials, polycrystalline ceramics have attracted most attention, due to their simple and well-established manufacturing processes. Among them, Lead Zirconium Titanate (PZT) ceramics have been widely used in sensors and actuators, including energy capture devices. Lead titanate (PbTiO3) and lead zirconate (PbZrO3) form the basic composition of the material. Variations in the Pb/Zr ratio can be used to control dielectric, elastic and other properties [32]. Moreover, special doping the ceramic with Ni, Bi, Sb, Mn and Nb allows a specific optimization of the piezoelectric and dielectric parameters [31], [33].

In view of the above, it was decided to use PZT ceramics as a generator element. After evaluating the piezoelectric properties of commercially available PZTs, three were pre-selected for experimental tests: PZT C-64, manufactured by Fuji Ceramics Corporation (Japan), and PIC255 and PIC181 PZTs, purchased from PI Ceramic GmbH (Germany). The piezoelectric parameters of each material are summarized in Table 1. These data are from the technical data sheet provided by the manufacturer of the respective piezoceramic.

In order to compare the amount of electric energy generated by each PZT material, three simple, geometrically identical swinging beam structures were assembled; piezoelectric elements were glued onto this structure, as shown in Figure 1. All beams were of 60 mm length, 12.72 mm width and 0.15 mm
Fig. 1. Beams with glued PZTs.

Fig. 2. Assembled test structure.

Fig. 3. Structure considered for static analysis.

thickness. Each of the PZTs had an area of $10 \times 12.72 \text{ mm}^2$ and 0.2 mm thickness. The structures were evaluated under the same frequency and amplitude conditions; vibration was forced by an electromagnetic exciter - mini shaker type 4810 from Labworks Inc., as shown in Figure 2. At the top of the shaker a base structure was attached, allowing the crimping of the beams. An accelerometer model 4507 (Bruel & Kjaer), recorded the vibration signal at the top of the base structure.

B. Numerical modeling

Model testing and simulations are fundamental strategies in the initial phase of scientific research projects, providing important information for the construction of experimental prototypes. The numerical models for the computational simulations of the piezoelectric generator developed in this work are based on the finite element method (FEM). It is an important tool in the study of generator efficiency, since it allows geometry optimization and virtual testing of the converter device.

In order to define the geometric dimensions of the constituent parts of the generator, an ANSYS tool, called “parameter optimization”, was used. Data such as the width and height of the beams and the piezoelectric, as well as the information that the first natural frequency of the system should be as close as possible to 60 Hz, were set as boundary condition. As a result, the simulation presented some possible geometries. The geometry with natural frequency closest to 60 Hz is shown in Table 2.

Next, a static analysis predicted the mechanical behavior of the structure without the piezoelectric elements, determining points of maximum deformation. For this, the structure was excited to vibrate with maximum amplitude of 1 mm. Equivalent strain was evaluated along six paths created along the beam, as shown in Figure 3. Figure 4 confirms that the regions with highest strain are close to the masses, at both beam ends; here exactly the piezoelectric elements have to be glued.

The natural frequencies and vibration modes of the structure were obtained by means of a modal analysis. Then, a harmonic analysis was developed, aiming to expose the behavior of the generator structure when subjected to a cyclic displacement rate within a frequency range, varying from 0 to 500 Hz.

C. Experimental setup

The experimental structure, schematized in Figure 5, was constructed from the parameters shown in Table 2. When
mechanically excited, it will vibrate according to the mode shown in Figure 6, providing cyclic tensile and compressive load to the piezoelectric elements. Their strain level depends directly on the vibration frequency and amplitude.

A photo of the generator, composed by the beams, masses and piezoelectric elements is given in Figure 7. As a source of vibration, the shaker shown in section 2.1 was used again. The assembly of the structure on top of the electromagnetic driver is shown in Figure 8.

The experimental plant, outlined in Figure 9, was controlled via hardware and software from National Instruments. The frequency and vibration amplitude data supplied to the generator were adjusted by means of a program developed in the LabView environment, which commands the output of a sine wave voltage from the NI USB-6216 board to a power amplifier which then feeds the shaker. The vibration signal picked up by the accelerometer and the generated electrical voltage are captured by the NI USB-6216 module, sent via USB to a computer equipped with LabView, treating and exposing these data to the user via a dynamic analysis interface. The electrical voltage generated by the PZT, besides being captured by the acquisition board, was also analyzed directly with a 10 MΩ oscilloscope.

III. RESULTS AND DISCUSSION

A. Piezoelectric material

The piezoelectric for the generator proposed in this work was selected based on the electric power generation results presented in Table 3, obtained after the beams were submitted to different vibration amplitudes. The experiments show that the electric voltage of the three piezoelectric attained maximum values at 68 Hz, which is the natural frequency of both structures. Gluing a mass of 0.696 g at the free end of the beams decreases the natural frequency of the structure and raises the mechanical strain in the piezoelectric elements. This modification shifts the natural frequency of the beams from 68 Hz to 30 Hz. In order to transfer the generated electric power, the internal impedance of each piezo element was estimated experimentally by means of the maximum power transfer theorem.

From Table 3 can be concluded that the PZT C-64 element provided more electrical power output than the other elements; this holds for all evaluated situations. Thus, all further experiments dealing with the development of the piezoelectric generator were performed considering the C-64 as the active generator element.

| PZT | Voltage (Vrms) | Imped. (kΩ) | Power (µW) | Frequency (Hz) | Accel. (g) |
|-----|---------------|------------|-----------|---------------|-----------|
| C-64| 6.18          | 190        | 201       | 68            | 0.5       |
| C-64| 10.02         | 174        | 577       | 68            | 1         |
| PIC255| 5.95          | 185        | 191       | 68            | 0.5       |
| PIC255| 9.01          | 158        | 514       | 68            | 1         |
| PIC181| 2.38          | 260        | 22        | 68            | 0.5       |
| PIC181| 5.03          | 290        | 87        | 68            | 1         |

With mass

| PZT | Voltage (Vrms) | Imped. (kΩ) | Power (µW) | Frequency (Hz) | Accel. (g) |
|-----|---------------|------------|-----------|---------------|-----------|
| C-64| 19.97         | 570        | 700       | 30            | 0.5       |
| PIC255| 12.55         | 300        | 525       | 30            | 0.5       |
| PIC181| 7.95          | 550        | 115       | 30            | 0.5       |

TABLE III

RESULTS FROM EXPERIMENTAL PERFORMANCE TESTS, COMPARING THREE DIFFERENT PZTS.
B. Numerical model

Parameter optimization by simulation and static analysis determined the methodological actions of the generator assembly; the latter were presented in section 2.1. Modal analysis showed that the first natural frequency of the generator is 60.3 Hz, confirming the prediction of the geometric optimization tool. The vibration mode of the structure is shown in Figure 10.

In the harmonic analysis modelling, the following boundary conditions were considered: no movement in the X and Z-directions and estimated displacement of 0.3 mm in the Y-direction, as shown in Figure 11. When the structure is excited, the resulting nodal displacement in the Y-direction was significant, thus causing traction and compression in the piezoelectric elements. The graph shown in Figure 12 refers to the displacement behavior of node 14111 in a frequency range from 0 Hz to 500 Hz. This node belongs to the upper region of PZT 2, which - when excited at 60 Hz - shows the highest displacement value.

C. Experimental results

Initially the program transmitted a frequency signal ranging from 0 to 500 Hz to the shaker. In order to analyze the amount of generated electric energy, besides the individual reading of the piezoelectric elements, the terminals of the generating units were interconnected in parallel. Figure 13 shows the electrical voltage generated by this parallel arrangement and the acceleration of the structure as a function of frequency.

The maximum voltage generated was 5.2 V, reached when the structure was submitted to a frequency of 60 Hz with an acceleration of 0.5 g. The acceleration and the electric potential show maximum values around 60 Hz since the excitation frequency provided by the actuator coincides with the natural frequency of the system. This demonstrates a good correspondence between the numerical model and the experiment.

In order to transfer the converted electric power, the internal impedance value of each generator element was estimated experimentally using the maximum power transfer theorem. Maintaining the vibration conditions of the previous analysis, the estimated impedance for each PZT was 98 kΩ at 60
Hz. When the piezo units are interconnected in parallel, the obtained impedance was 14 kΩ. Figure 14 shows the electrical impedance behavior for the parallel arrangement, with the electrical voltage signals measured before (Voltage 1) and after the association of the impedances (Voltage 2) as a function of the frequency. After this procedure, the electrical power generated by the cells can be calculated. Figure 15 shows the voltage and electric power as a function of frequency.

Afterwards, the maximum output voltages were recorded for different levels of mechanical vibration. Table 4 summarizes these experiments. The electric power was calculated taking into account the optimum resistive load for each situation.

### D. Application test

In order to evaluate the applicability of the generator, a temperature sensor was fed with its output. This sensor transmitted the environmental temperature data wirelessly. For this, the module EH300A was used, responsible for receiving and storing the energy output of the piezoelectric generator. It contains a rectifier circuit and two capacitors connected in parallel (total capacitance 6.6 mF) [34]. It is used to power the eZ430-RF2500 development tool from Texas Instruments. It is a low-power wireless communication system (RF), consisting of two separate boards (End device and Access point), each containing an MSP430F2274 microcontroller and a CC2500 RF transceiver as main elements, as well as a temperature sensor. The RF communication between the boards is governed by the SmplicITI network protocol, (Texas Instruments). Figure 16 shows the operation scheme of the application test.

According to the scheme in Figure 16, the generated energy is sent to the EH300A which, after being charged, feeds the End device (ED), which in turn reads the ambient temperature and sends it to the USB connected Access point (AP) to the computer 2, that monitors the temperature by means of the Sensor software. The NI-6216 acquisition board recorded the electrical voltage generated, the capacitor voltage ($V_C$) and the output voltage ($V_O$) released to the ED simultaneously.

The storage module was configured to operate between two voltage limits, 3.5 V ($V+$) and 1.8 V ($V−$), which is the operating range of the wireless communication device. In practice, this means that energy will not be supplied to the ED when $V_C < V+$. When the voltage on the capacitor reaches 3.5 V, the ED is energized and remains active while $V_O > V−$. 

| Freq. (Hz) | Acel. (g) | PZT | Voltage ($V_{rms}$) | Imp. (kΩ) | Power (µW) |
|------------|-----------|-----|---------------------|-----------|------------|
| 60         | 0.5       | Cell 1 | 2.79                | 95        | 82         |
|            |           | Cell 2 | 2.07                |           | 45         |
|            |           | Cell 3 | 2.21                |           | 51         |
|            |           | Cell 4 | 2.14                |           | 48         |
|            |           | Cell 5 | 2.64                |           | 73         |
|            |           | Cell 6 | 2.77                |           | 80         |
|            |           | Cell 7 | 4.24                |           | 189        |
|            |           | Cell 8 | 2.42                |           | 61         |
|            |           | Parallel | 2.70             | 14        | 520        |
| 60         | 0.75      | Cell 1 | 4.49                | 98        | 205        |
|            |           | Cell 2 | 3.89                |           | 154        |
|            |           | Cell 3 | 4.17                |           | 177        |
|            |           | Cell 4 | 3.96                |           | 160        |
|            |           | Cell 5 | 4.8                 |           | 235        |
|            |           | Cell 6 | 4.98                |           | 253        |
|            |           | Cell 7 | 7.39                |           | 557        |
|            |           | Cell 8 | 4.49                |           | 205        |
|            |           | Parallel | 4.95             | 14        | 1750       |
| 60         | 1         | Parallel | 6.40             | 14        | 2925       |
| 60         | 1.5       | Parallel | 8.55             | 15        | 4873       |
| 60         | 2         | Parallel | 12.1              | 15        | 9600       |
Taking into account the vibration levels described in section 3.3, the system was initially set to vibrate at 60 Hz with an acceleration of 0.5 g. Under these conditions, it took 880 seconds to fully load the storage module and initialize the temperature monitoring application. Figure 17 shows the voltage across the capacitor during charging as well as the voltage across the load, when \( V_C = V_o + \). The energy accumulated during the 880 seconds was 29.73 mJ, estimated from the energy variation in the storage module, which corresponds to a power harvested of approximately 33.8 \( \mu \)W, for this specific case.

It can be seen that as soon as power is supplied to the load, there is a considerable drop in the voltage (Vo), since more energy is required to initialize the ED transceiver system and synchronize it with the AP. Shortly afterwards, the consumption curve becomes less and less accentuated until it stabilizes 2.8 V, meaning there is an equilibrium between the energy consumed by the transceiver and that generated by the piezoelectric device. This allows a continuous operation of the application.

During all experiments, the ED was programmed to read and send the temperature value to the AP every 5 s. Between the transmission intervals, the device remains in power saving mode.

The total initialization time of the module (or system startup time) depends on the energy input, determined by the generator, minus the module's loss of energy (about 1 to 2 \( \mu \)W [34]). As seen in Figure 17, the system initialization time was 880 s, with the generator vibrating at 60 Hz at 0.5 g acceleration. In the following experiments, the vibration frequency was maintained and the acceleration was raised to 0.75 g and 1 g. As a result, the system startup time decreased to 228 s and 143 s, corresponding to a harnessed power of approximately 130.4 \( \mu \)W and 207.9 \( \mu \)W, respectively.

The behavior of the generator was also evaluated when the
acceleration was maintained at 0.5 g and the frequency was adjusted first to 59 Hz and in the sequence to 61 Hz. Under these conditions, the system initialization time was 1244 s and 1447 s respectively. Thus, tests indicated that a sufficient amount of power was also generated when the excitation was somewhat outside the natural frequency (60 Hz). Considering accelerations higher than 0.5 g, the frequency range in which energy can be captured increases. But it is clear that the maximum amount of electrical energy will always be associated with the resonance of the structure.

It was found that the lowest vibration level at which the generator was able to load the storage module was 0.4 g at 60 Hz. Under these conditions, the system initialization time was 4300 s.

E. Real-world application performance

The energy available in the environment in the form of mechanical vibrations generally does not present itself as a single sinusoidal signal. To date, this work, as well as the majority of research in the literature, has focused on investigating the performance of the generator under a single sinusoidal vibration input, idealized in the laboratory. This method is valuable in gaining insight into the behavior of the system, but it is not enough to understand how a piezoelectric energy collection device would actually behave subject to a source of ambient vibration.

In view of this, we have resolved to submit the developed generator to existing sources of vibrations in our environment. The sources selected were the condenser of an air conditioner (Figure 18) and a three phase induction motor (Figure 19) coupled to the water pumping system of the Federal University of Paraíba. Figure 20 shows the vibration data of the selected sources.

Considering the condenser, it can be seen that the dominant acceleration peak of approximately 0.5 g is at 56 Hz. The vibration measured on the motor casing indicates a peak of 0.68 g at 59 Hz. The results of the experiments with the generator coupled on both the upper face of the condenser and the upper part of the motor housing are shown in Figures 21 and 22.

Using the condenser as a source of vibration, the generator took 1446 s to charge the power module, which, had a residual voltage below 1 V at the beginning of the experiment. As the AP was not in operation, the ED consumed all the energy available in just over 1 s, seeking synchronicity with an available AP. While the generator was charging the module again,
While the equipment is in operation.

the elevation of the ambient temperature in the engine room of the engine, the pressure or the flow in the water line, or provided that the monitored variable refers to the source of intermittently. This fact does not present itself as a problem, both the vibration source and the monitoring system operate on the water consumption of the tank. In this application, this cycle. The time the engine stays on or off depends directly

behavior of a vibrating beam structure based on computational

ments. The focus was the verification of the electromechanical
tion source can be seen because the water pumping system

when the reservoir level was low and the generator loaded the

the air conditioner was turned off, stopping energy conversion for 208 s. On re-operation, the module was fully charged and powered the ED transceiver again,. The latter, when initialized and synchronized with the AP, started consuming only what is necessary for reading and sending the temperature data. The increasing value of the voltage over the load (the final part of the graph) indicates that the amount of energy generated is higher than that consumed by the application. It can also be seen that, even if there was a period without generation, the second load cycle (888 s) was smaller than the first one, which is due to the preexistence of 1.8 V of load at the beginning of the second cycle. Approximately 43.7 $\mu$W were harvested in the second cycle.

In case of the motor, the behavior of an intermittent vibration source can be seen because the water pumping system is automatic, controlled by level sensors. The engine started when the reservoir level was low and the generator loaded the module in 523 s. As soon as ED was energized the engine was shut down for having supplied the water consumption. Since there was no energy being generated at the time, the ED was consuming all the energy previously accumulated, remaining in operation for a few seconds. When the water level went down again and the engine was running, a new charge cycle started and the system start-up time was 370 s, which corresponds to an electric power output of 80.3 $\mu$W in this cycle. The time the engine stays on or off depends directly on the water consumption of the tank. In this application, both the vibration source and the monitoring system operate intermittently. This fact does not present itself as a problem, provided that the monitored variable refers to the source of vibration itself. Examples could be the temperature or rotation of the engine, the pressure or the flow in the water line, or the elevation of the ambient temperature in the engine room while the equipment is in operation.

IV. Conclusion

This work describes development and performance evaluation of an electric power generator with eight piezoelectric elements. The focus was the verification of the electromechanical behavior of a vibrating beam structure based on computational simulations and experiments. The computational simulations applying the finite element method proved to be of great relevance for the converter design, since it was possible to predict a generator with first natural frequency of around 60 Hz, besides verifying the mechanical deformations along the beams when the structure was submitted to relatively low levels of harmonic excitation.

The experimental results demonstrated the capacity of electric energy generation from relatively small vibrations, where the maximum electrical power of 9.6 mW with an acceleration 2 g at a frequency of 60 Hz was extracted considering a resistive load of 15 kΩ. Both experimental conditions, the excitation of generator in the laboratory and excitation from natural sources of vibration allowed the harvesting of a sufficient amount of electrical energy for the operation of the transceiver. This was observed even when the generator was vibrating outside its natural frequency (60 Hz). It is clear that the maximum amount of electrical energy will always be associated with the resonance of the structure. This fact determines the optimum operating point of the generator.

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