Novel Low-cost Energy Harvester Based on an Arrangement of Piezoelectric Actuators

Novedoso Cosechador de Energía de Bajo Costo Basado en un Arreglo de Actuadores Piezoeléctricos

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KEYWORDS:

Finite Element Method, low-energy devices, vibration, piezoelectric transducer

ABSTRACT

This article provides the design, modeling, fabrication, and testing of an energy harvester from mechanical vibrations, based on a piezoelectric material. This device works on the principle of piezoelectric transduction, i.e., when mechanically deformed, it generates electrical energy due to vibrations. The piezoelectric material used in the fabrication was Lead Zirconate Titanate (PZT), and brass as structural base. In addition, finite element models were performed to predict the frequency of the first vibration mode of the device, and experimental setups for validation. The resonance frequency of the numerical model and the one obtained experimentally (19 Hz) show a deviation of 5.03% respectively. The generated power is 0.202 mW enough to power low power devices such as basic calculators, wristwatches, and transistors, among others.

PALABRAS CLAVE:

Método de Elemento Finito, dispositivos de bajo consumo, vibración, transductor piezoeléctrico

RESUMEN

En este artículo se presenta el diseño, modelado, fabricación y pruebas de un cosechador de energía proveniente de vibraciones mecánicas, basado en un material piezoeléctrico. Este dispositivo trabaja bajo el principio de transducción piezoeléctrica, es decir que, al deformarse mecánicamente, debido a las vibraciones genera energía eléctrica. El material piezoeléctrico usado en la fabricación fue Zirconato Titanato de Plomo (PZT), y latón como base estructural. Además, se realizaron modelos de elemento finito para predecir la frecuencia del primer modo de vibración del dispositivo, y arreglos experimentales para su validación. La frecuencia de resonancia del modelo numérico y la obtenida experimentalmente (19 Hz) muestran una desviación de 5.03% respectivamente. La potencia generada es de 0.202 mW suficiente para alimentar dispositivos de bajo consumo, tales como calculadoras básicas, relojes de pulsera y transistores, entre otros.

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1. INTRODUCTION

Piezoelectric Vibrational Energy Harvesters (PVEH) can be categorized by their energy sources, such as ambient vibrations, impacts, fluids, and human force. The vibrational energy generates a stress on the piezoelectric material, and by the direct piezoelectric

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effect, the input mechanical energy is converted into electrical energy.

Piezoelectric materials can be used to convert oscillating mechanical energy into electrical energy. This fact, together with innovative mechanical coupling designs, can form the basis for energy harvesting from mechanical motion. The piezoelectric effect converts mechanical stress into electrical stress. This effort can come from many different sources, for example: human movement, low frequency seismic vibrations and acoustic noise [1]. The piezoelectric effect can be applied to collect mechanical energy of walking. This energy can be converted into useful electrical energy that can be used to power portable electronic devices, such as Global Positioning System (GPS), sensors and receivers.

Piezoelectric energy harvesting can also be used to directly power some consumer electronic devices, such as mobile phones, two-way communicators, etc. Proof-of-concept generators have recently been developed to convert mechanical running energy into electrical energy. Each heel impact generator uses four elements to convert mechanical movement into electrical energy in the form factor of a boot's heel, where electrical energy is generated as the wearer walks [2][3]. The use of piezoelectric energy harvesters in household washing machines has also been reported [4].

The capture of vibrational energy consists of recovering the kinetic energy of the environment by transforming it into electrical energy through electromagnetic, electrostatic or piezoelectric devices [5][6].

Due to their effectiveness, lightness and small size, piezoelectric devices are widely used as an alternative to batteries in low-power devices. Piezoelectric materials can be integrated into lightweight structures, such as beams and plates, to convert electrical energy into mechanical energy (actuator mode) or mechanical energy into electrical energy (sensor mode or vibration energy harvesting mode).

The main mechanisms for kinetic energy harvesting are piezoelectric, electromagnetic, electrostatic, or using magnetostrictive materials. In [1], the current energy harvesting methods were reviewed, while focusing on piezoelectric energy harvesting. The piezoelectric energy harvesting technique is based on the property of materials to generate an electric field when a mechanical force is applied to them. This phenomenon is known as the direct piezoelectric effect.

Energy harvesters have been widely investigated, using piezoelectric materials in [7], where a compilation of energy harvesters is made. Rectangular geometries are analyzed in [7][8]. The developed energy harvester using PZT (Lead Zirconate Titanate) collected 120 mW [8]. There are applications that consist of collecting energy, as mentioned above from sources such as the environment, impacts, external forces, in addition, energy can also be collected from human gait, in [9], which evaluates the potential of a cantilever beam with a piezoelectric patch attached to the end of the cantilever to collect energy from human movement.

It is important to mention that the selected materials are of paramount importance, since if they have a larger this constant, more energy can be collected. In [4], a piezoelectric nanogenerator based on vibrations composed of a double clamping beam with five multilayer cross sections is developed. This nanogenerator design has a central seismic mass (910 µm thick) and a substrate (125 µm thick) of polyethylene terephthalate (PET), as well as a zinc oxide film (100 nm thick) at the bottom of each end. Zinc oxide (ZnO) films have two aluminum electrodes (100 nm thick) through which the generated electrical energy is extracted.

Finally, in [10], the analysis is focused on the design, manufacture and performance characterization of piezoelectric energy harvesters (PEH) of cantilever type using the polyvinylidene piezoelectric polymer fluoride-trifluoroethylene (PVDF-TrFE). Due to its scale, it is considered in the field of microelectromechanical systems (MEMS). Examples of applications of piezoelectric devices range from PZT wafers, which power children's shoe LEDs, to elements that power MEMS. Shoe PZT wafers can generate 1.3 mW at 3 V when walking, at a charging frequency of 0.8 Hz [11]. The size of the piezoelectric is relatively large, so it could be replaced by a compact array.

On the other hand, the amount of electrical energy needed to run MEMS is usually on the order of μW. In [12], a MEMS was powered with a piezoelectric harvester (PEH) of cantilever design, generating 0.346 μW, driven at 112.3 Hz.

Piezoelectric energy harvesters (PEHs) can power devices directly or through a battery or capacitor. Another study showed that a 40 mAh battery can be charged effectively in a short period of time, from a PEH subjected to vibrations [13]. Non-polluting materials have been explored, in addition to ZnO, such as AlN [14][15][16][17]. On different geometries for energy harvesting, in [18][19] examples of bimorph cantilever are presented. In addition [20][21], arrays in tree-like structures are given.

A study at Virginia Tech evaluated 9 PEH designs, generating an average power of 3.1 mW per vehicle step. It was concluded that the parallel connection between piezoelectric disks is more efficient than in series. This configuration allows for lower output voltage peaks and lower matching impedance to maximize power [23].

In [24], a prototype PEH housing made of MC Nylon® with 9 PZT batteries was developed, producing an open circuit voltage of 280 V. In [25], PZT stacks of 36 layers of piezoelectric discs in parallel are described, generating 85 mW, with an excitation force of 1360 N at 6 Hz.

In [26], the fabrication of a piezoelectric vibrational energy harvesting (PVEH) device (footprint size 6 x 6 mm) composed of a micromachined silicon disc held by three interleaved piezoelectric springs is described. This device has a resonant frequency below 20 Hz and a power of 0.57 μW under an acceleration of 0.1 g, although, this amplitude of acceleration is less than that of car engines. In [27], a PVEH device composed of a microcantilever (footprint size 12 x 6 mm) with piezoelectric and phosphor bronze layers and a proof mass of silicon and tungsten is provided. These devices are an option to replace conventional batteries used in many electronic devices [28].

The content of this article is as follows: In section 1, information about energy harvesters is briefly presented, section 2 describes the principle of operation of the piezoelectric vibrational energy harvesting device (PVEH). Section 3 shows the design of the piezoelectric transducer. In section 4, the FEM models of the PVEH device, and the elaboration of the experimental arrangement are provided. The experimental results of the harvesting device are indicated in section 5. Finally, section 6 summarizes the findings and provides some concluding remarks.

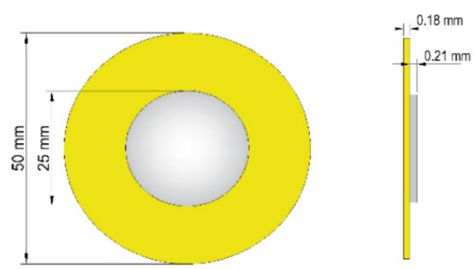
2. PIEZOELECTRIC TRANSDUCER OPERATING PRINCIPLE

In nature there are materials that produce electric current when subjected to mechanical stress, for example, quartz, topaz, sugar cane, bones, among others [29]. Others, like PZT, ZnO, AIN, BaTiO3, among others, have been synthesized.

The piezoelectric effect is classified as: direct or inverse. The first case occurs when a mechanical stress is transformed into electrical energy, while the reverse piezoelectric effect generates a deformation in the material, that is, mechanical movement by applying an electric field on the surface.

The use of mechanical energy consists of converting it into electrical energy and using it in low-consumption devices, which requires a mechanical system that couples the mechanical force to a transducer. The mechanical system must be designed to maximize the coupling between the mechanical energy sources and the transducer, depending on the characteristics of the vibrations. For example, energy due to vibrations can be converted using inertia generators, with the mechanical component attached to an inertial frame [30].

In this work, a piezoelectric transducer was used as a vibration energy harvesting element. It is commercially available and is commonly named "buzzer". It is made with two materials, an alloy and a synthesized material, brass and PZT, respectively. Brass serves as a circular flat structural base. The PZT, a circular layer adhered to brass, is shown in Figure 1.



(a) (b)

Figure 1. (a) Front view and (b) Cross-sectional view of the circular piezoelectric transducer.

The piezoelectric transducer works as an energy generator, since, when subjecting the PZT layer and consequently the brass disc to a deformation, there is a potential difference between the upper and lower electrode. It should be noted that the principle of operation is the direct piezoelectric effect.

There are mainly two ways to induce deformation in the piezoelectric transducer to generate electrical energy, the first is by means of a direct force on the piezoelectric material, such as a blow or an intermittent pressure. The second way is to keep the disc anchored at one end, that is, in a cantilever configuration such as a cantilever, and subject it to environmental vibrations or frequency generators, consequently, the transducer will oscillate.

In this work, the oscillation method of the transducer is used, where the voltage generated by the device will directly depend on the magnitude of the deformation of the PZT layer, which is related to the acceleration and the frequency of oscillation. To increase the deformations in the PZT material and increase the voltage generated, the transducer must operate in resonance with a bending vibration mode.

3. PIEZOELECTRIC TRANSDUCER DESIGN

As mentioned in the previous section, the proposed energy harvester prototype harnesses the vibrational energy of a medium to cause an oscillation in the cantilever transducer and generate energy. However, the circular geometry of the piezoelectric transducer is not the most suitable for such an arrangement, a rectangular geometry is more adequate. Although rectangular piezoelectric transducers are commercially available, they have a higher cost than circular buzzers. The solution to maintain a low-cost prototype was to cut the buzzers.

3.1. Transducer Design Process

The circular piezoelectric buzzer was cut, considering two designs, the first one with rectangular shape and the second one with trapezoid geometry. In [31], it is mentioned that triangular or trapezoid-shaped geometries can increase the efficiency of energy harvesters. Increments up to 30% in the efficiency of trapezoid-shaped harvesters compared to rectangular have been reported.

Figures 2 and 3 show the piezoelectric transducers and their possible dimensions considering the limitation given by the buzzer geometry data shown in Figure 1.

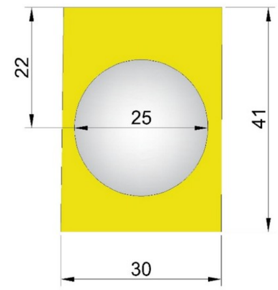


Figure 2. Rectangular piezoelectric transducer.

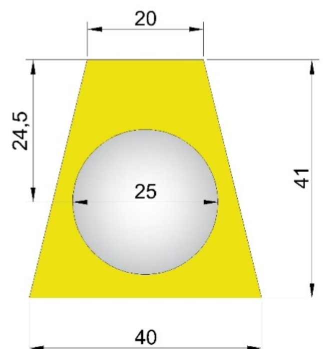


Figure 3. Piezoelectric transducer with trapezoid shape.

3.2. Transducer cutting process

The necessary cuts were made to the piezoelectric buzzers with a CNC (Computer Numerical Control) milling machine, with the aim of making precise cuts and minimizing current losses due to imperfections in the devices and obtaining larger efficiency values in the operation of the piezoelectric transducer. The cutting process in a CNC is shown in Figure 4.

Since the design was done in ANSYS® it was necessary to export the geometry to AutoCAD design software to generate the dxf2010 format, which is essential to be able to open the file in Aspire software. With this program, the required cut profiles are carried out and then the G code is generated. Finally, the G code is executed in Match 3 software to manufacture the geometries. The same process of cutting to another buzzer was made to obtain in transducer in trapezoid shape. Figures 5 and 6 show the rectangular and trapezoid transducers, respectively.

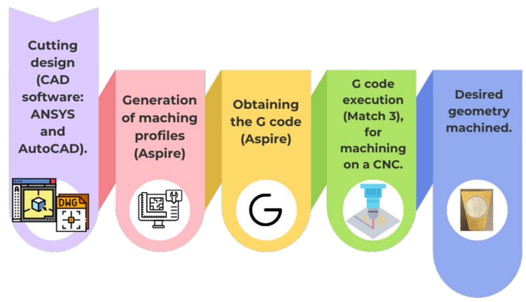


Figure 4. Fabrication process.

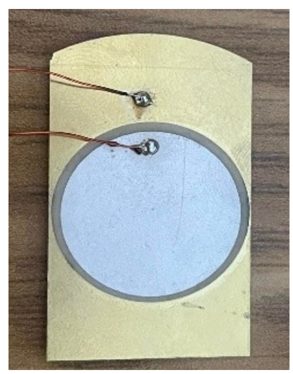


Figure 5. Rectangular piezoelectric transducer.s.

Figure 6. Piezoelectric transducer with trapezoid shape.

4. FEM MODELS OF THE PVEH DEVICE

The design of the harvesting cantilever piezoelectric transducer. The trapezoid-shaped transducer is chosen to perform the simulations because it provides a higher probability to produce higher power generation than the rectangular one. In section 5, the comparison of the power generated from each proposed transducer is presented.

The dimensions of piezoelectric trapezoid transducer are lower base of 20 mm, larger base of 40 mm and height of 41 mm. The slightly curvature in the smaller base serves as subjection part. It is formed by a structural layer of brass (0.18 mm thick) and a circular layer of Zirconate Lead Titanate (PZT) (0.21 thick) in addition a proof mass was placed with different magnitudes in the range of 0.2 g to 1.85 g. to obtain the corresponding resonance frequencies and select the right mass for an application.

For this analysis, ANSYS Workbench 2018 software was used, where the general process consists of:

- Define the mechanical properties of the materials to be used in the analysis.
- Generate a geometric model using Computer-Aided Design (CAD) software.
- Divide the CAD model into elements joined by nodes. This process is known as geometry meshing.
- Introduce appropriate bordering conditions and restrictions.
- Calculate the first four vibration modes and their corresponding frequencies.
- Solution of the finite element model.
- The parameters of the corresponding materials considered in the simulation are shown in Table 1.

Table 1. PZT, Brass and Steel Parameters [32].

Material	Young's modulus (GPa)	Density (kg/m^3)	Poisson's ratio
PZT	70	7500	0.31
Brass	110	8700	0.34
Steel	210	7750	0.27

Figure 7 shows the result of the first 4 frequencies for a proof mass 0.85 g. From the analysis it was obtained that the first vibration mode (Figure 7a) corresponds to 18.089 Hz which is the vibration mode chosen for the transducer operation.

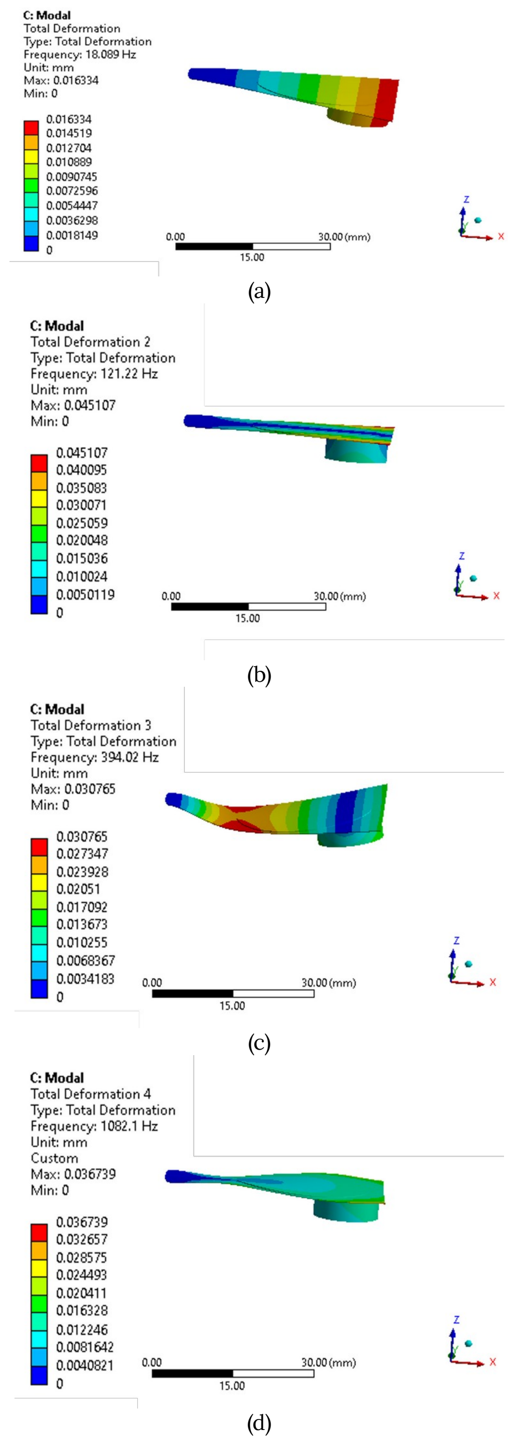


Figure 7. First four vibration modes of the vibration-based piezoelectric generator: (a) first mode (18.089 Hz), (b) second mode (121.22 Hz), (c) third mode (394.02 Hz) and d) fourth mode (1082.1 Hz).

Figure 8 shows the resonance frequencies obtained by applying different proof masses to the transducer. It is observed that increasing the proof mass at the free end of the transducer decreases the resonance frequency.

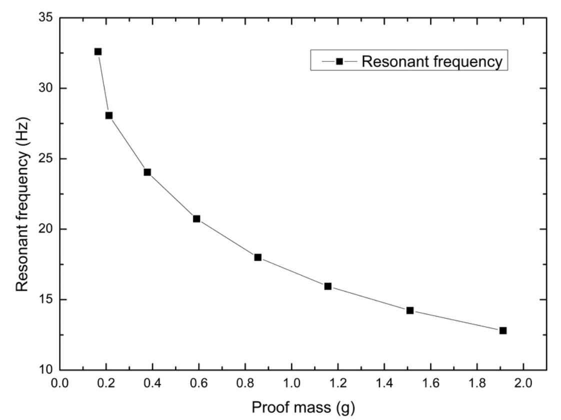


Figure 8. Resonance frequency behavior with different proof masses.

5. ELABORATION OF THE EXPERIMENTAL ARRANGEMENT, AND RESULTS

Two analyses were performed with two different experimental arrangements. With the first one the resonant frequencies of the two proposed piezoelectric transducers were determined. In the second analysis, an array of 4 piezoelectric transducers was implemented using the geometry which provided the best performance in the first analysis, with the purpose of increasing the generation of electrical energy and being able to feed low consumption.

In general, the procedure for both analyses are described below.

1. A horn is used to generate vibrations at different frequencies. The horn incorporates an audio amplifier powered by a power sound source.
2. Using the Two channels Frequency Generator software and connecting the audio output of the PC to the audio amplifier, the mechanical vibration at the desired frequency was generated.
3. Using CAD design software, a structural support for the piezoelectric transducers was made, which was subsequently printed in 3D with PLA (Polylactic Acid), to the diaphragm of the horn, with the aim of fixing the bases of piezoelectric transducers corresponding to each analysis.
4. A complete wave circuit was implemented to convert the voltage output of the piezoelectric transducer from alternating current to direct current. The basic circuit consists of 4 Schottly 1N5819 diodes and a 47 µF 35 V capacitor, in addition the transducer output and rectifier output are monitored, as shown in Figure 9.

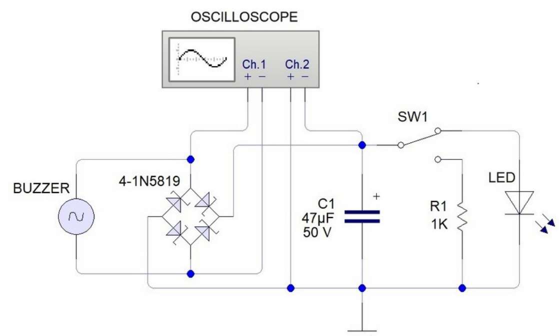


Figure 9. Circuit used to rectify the voltage output of the piezoelectric transducer, represented as an alternating current source V1.

5. An oscilloscope is placed at the outputs of the piezoelectric transducer to record rectified voltage and frequency values.
6. Finally, in the outputs of the rectifier circuit is placed an application unit to verify that the energy necessary to power low-consumption devices is being collected, as well as two multimeters to record current and voltage values.

5.1. Individual test of the proposed piezoelectric transducers (rectangular and trapezoid-shaped cantilevers)

Individual tests were performed in a simple arrangement composed of the following elements:

1. Frequency generator.

2. Horn.
3. Piezoelectric transducer.
4. Full wave rectifier circuit.
5. Oscilloscope.
6. LEDs array.

This experimental setup is shown in Figure 10.

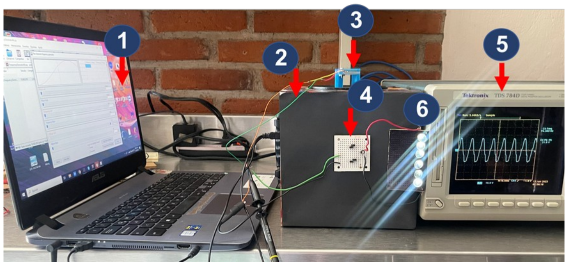


Figure 10. Experimental setup for individual tests of the proposed transducers.

The test procedure is summarized as follows:

1. The horn amplifier circuit is powered by a 5 V power supply.
2. The rectifier circuit is connected to the transducer with a load resistance of 1 kΩ.
3. The oscilloscope is connected at the transducer output to record the rectified voltage and frequency values.
4. Subsequently, the two channels Frequency Generator is started, with the purpose of performing a frequency sweep and determining the resonance frequency of the devices.

The individual tests consisted of performing a frequency sweep in a range of from 30 up to 85 Hz, with increments of 5 Hz. The resonance frequency for the rectangular transducer is 65 Hz, generating a maximum current value of 0.3798 mA, a potential difference is 0.373 V, and a consequent power of 0.1416 mW. The results obtained with the trapezoid shaped transducer were 0.45 mA, 0.446 V, and 0.202 mW. As mentioned above, by modifying the geometry of the piezoelectric transducer it is possible to increase the efficiency until 30%, in our case, with the trapezoid transducer the increment is 42.65% for power. Table 2 summarizes the results obtained.

Table 2. Results of individual transducer tests using a resistance of 1 kΩ as test load.

Piezoelectric transducer	Resonant frequency (Hz)	Current (mA)	Voltage (V)	Power (mW)
Rectangular	65	0.3798	0.373	0.1416
Trapeze	75	0.45	0.446	0.202

Figures 11a-11c show the graphical results obtained from the rectangular and trapezoid-shaped transducer for voltage, current and power. In each of these graphs the maximum peaks are observed, which correspond to the natural frequencies of each proposed piezoelectric transducer.

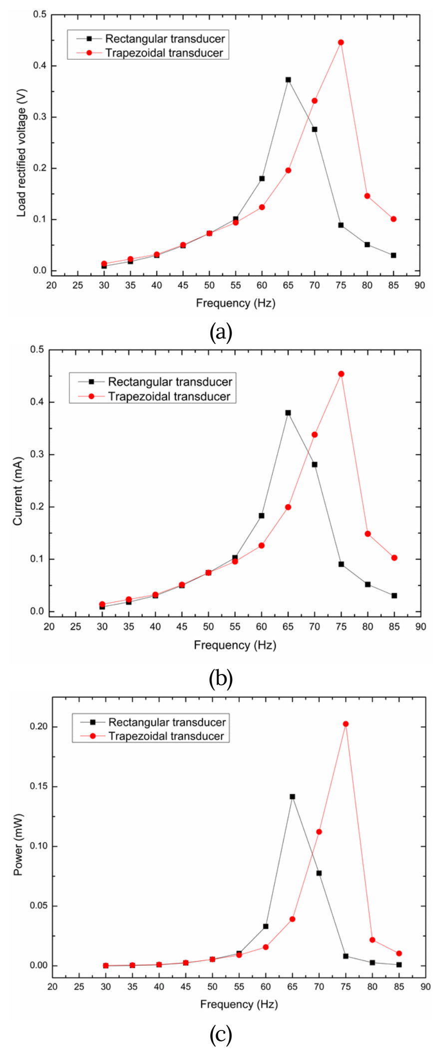


Figure 11. Graph of (a) voltage, (b) current, and (c) power for piezoelectric transducers when they are subjected to vertical oscillations over the frequency range.

According to the data in Table 2 and the graphs in Figure 11, it is confirmed that the change of geometry from rectangular to trapezoid shape of the transducer generates a higher power generation. Therefore, this geometry is chosen to design an array of 4 trapezoid-shaped transducers, considering a new base fabricated with PLA.

5.2. Tests of the arrangement of 4 piezoelectric transducers (trapezoid shape)

For the second experimental analysis an array of 4 trapezoidal shaped transducers was implemented, a mass of 0.85 g was chosen because it corresponds to the first natural frequency 18.089 Hz, numerically determined. This value allows to use vibration sources such as: train tracks, trucks, ships, among others [33].

The elements used for the piezoelectric energy harvester shown in Figure 12 are listed below. The harvesting device consists of:

1. Power supply.
2. Frequency generator.
3. Audio amplifier.
4. Horn.
5. Adapted base for piezoelectric transducer attachment.
6. Piezoelectric transducer.
7. Oscilloscope.
8. Rectifier circuit.
9. Application unit.
10. Multimeter for current measurement.
11. Multimeter for voltage measurement

Figure 12 shows the schematic diagram of the experimental setup. The implementation of the experimental setup is shown in Figure 13. In this picture the power supply and oscilloscope are not shown, due to space limitations.

Figure 14 shows a frequency sweep implementing a single piezoelectric transducer in the shape of a trapezoid with a proof mass of 0.85 g.

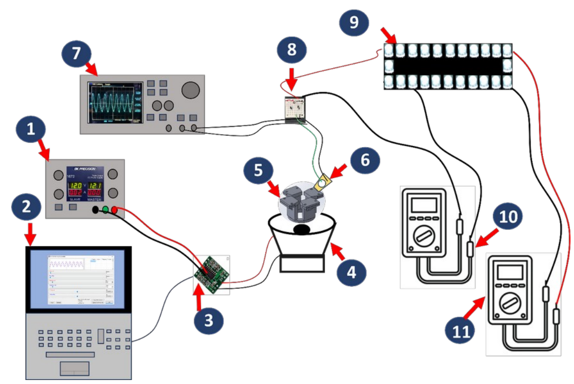


Figure 12. Schematic setup.

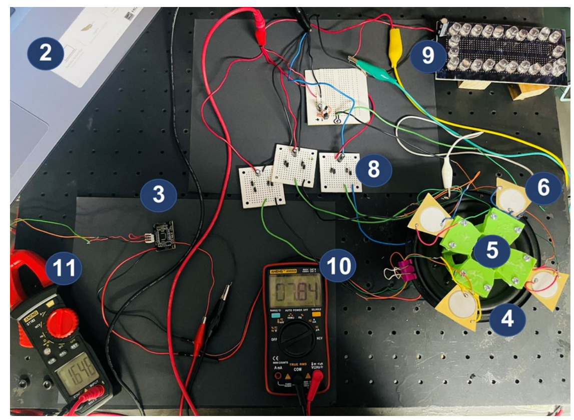


Figure 13. Experimental setup.

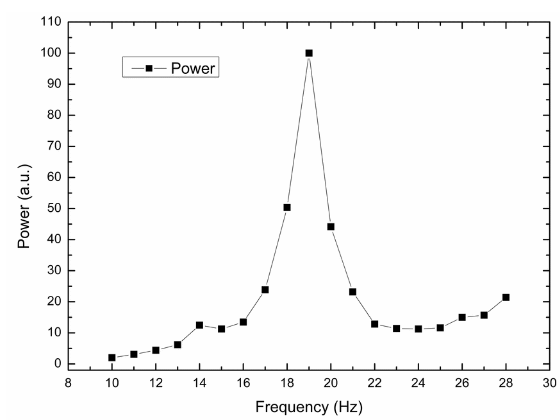


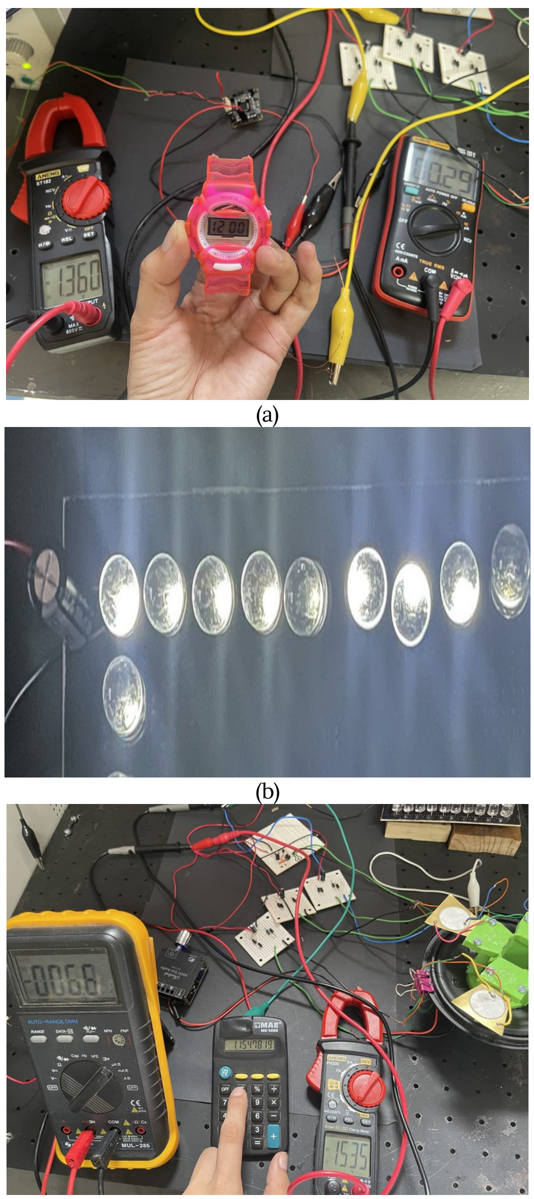
Figure 14. Frequency vs. power.

The first modal frequency value of 18.089 Hz, obtained numerically, while from experimental analysis was of 19 Hz, therefore, there is a percentual error of 5.03%.

Considering the arrangement of 4 trapezoidal transducers, equal to the one used to generate to Figure 14, the power generated with this novel harvester allows to energize different low-power devices such as the ones shown in Figures 15a-15c. Table 3 summarizes the frequency, current, voltage, and power used to energize 24 LEDs.

Table 3. Results obtained for an arrangement of 4 trapezoid-shaped transducers, feeding 24 LEDs.

Resonant frequency (Hz)	Direct Current (mA)	Voltage CD (V)	Power (mW)
19	0.612	2.54	1.5113



(a) (b) (c)

Figure 15. Output power of the energy harvester used to energize (a) a wristwatch, (b) 24 LEDs and (c) a basic calculator.

6. CONCLUSIONS

With low-cost devices commonly used in electronics, piezoelectric microgenerators can be designed, optimized, and implemented for energize to low-power electronic devices. It is also possible to obtain higher power by implementing an array of more transducers and making modifications in the geometry, as well as on the support base.

It has been shown that resonant frequency decreases as the proof mass increases. Then, varying the proof mass is a useful strategy to reduce the frequency operation value, making possible the use of several sources of vibrations of very low frequency.

The increment of the energy harvested using trapezoidal geometries is validated.

The prototype developed is novel, with low implementation cost, and to a certain extent sustainable since it is composed of several recovered elements from waste electronics, the bases were made with biodegradable material.

The experimental results for the first modal frequency are adequate since the comparison with numerical results has an acceptable percentual error (5.03%).

As future work, once the performance of the array has been validated, the intention is to replace the PZT with a sustainable piezoelectric material suitable in cost and performance so as not to excessively increase the total cost of the energy harvester.

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