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# An Integrated Testing Solution for Piezoelectric Sensors and Energy Harvesting Devices

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With the fast growth of wireless communications between nodes and sensor units and the increase of devices installed in remote places, and the development of IIoT applications, new requirements for power energy supply are needed to assure device functionality and data communication capabilities during extended periods of time. For these applications, energy harvesting takes place as a good solution to increase the autonomy of remote measuring solutions, since the usage of conventional power supply solutions has clear limitations in terms of equipment access and increased maintenance costs. In this context, regenerative energy sources such as thermoelectric, magnetic and piezoelectric based, as well as renewable energy sources, such as photovoltaic and wind based, among others, make the development of different powering solutions for remote sensing units possible. The main purpose of this paper is to present a flexible testing platform to characterize piezoelectric devices and to evaluate their performance in terms of harvesting energy. The power harvesting solutions are focused on converting the energy from mechanical vibrations, provided by different types of equipment and mechanical structures, to electrical energy. This study is carried out taking into account the power supply capabilities of piezoelectric devices as a function of the amplitude, frequency and spectral contents of the vibration stimulus. Several experimental results using, as an example, a specific piezoelectric module, are included in the paper.

Keywords: Power harvesting, piezoelectric sensors, vibration exciters, accelerometers, calibration, testing.

## 1. Introduction

In recent years there has been an increasing growth of wireless devices in industrial instrumentation systems and in distributed network solutions [1], leading to the implementation of distributed and wireless solutions that include a large number of sensors and actuators. The implementation of the, so called, industrial internet of the things [2] will expand this growth even more.

These developments have led to the creation of smart sensing units with an increasing number of functionalities, allowing to open the spectrum of new applications implemented in places with access limitations and sometimes isolated in remote locations. Generally, in these cases the access to conventional power source units is difficult or even impossible.

These smart sensing units commonly include sensing devices, actuators, voltage converters, signal conditioning and processors, and, typically, wireless communication modules. All these devices need to be powered, having different requirements in terms of power consumption, namely, which concerns average values and power peak values.

When these smart sensing units are intended to work in places where their power supply by cable is difficult or very expensive, batteries are normally used as an alternative power supply source but this powering solution requires periodic maintenance and replacement of batteries whenever they are depleted.

Thus, one strategy to minimize these limitations has been towards the creation of devices with lower power requirements and in an effort to extend the autonomy of the batteries by using, for example, power harvesting solutions.

These solutions can be implemented by using renewable energy sources, such as solar or wind energy sources. However, these energy sources do not always assure a uniform energy delivery to the system, satisfying its consumption requirements and, moreover, they have their intrinsic limitations, such as the existence of periods of little sun or at night, in the case of solar energy, and periods without wind, in the case of wind energy.

One way to minimize this kind of problems is based on the usage of regenerative energy sources, such as the ones that harvest power from temperature gradients, vibrations, and displacements, among others.

It is also important to refer that the development of new materials with electroactive properties, such as ceramics, semiconductor oxides, organic materials and composites, of different shapes and sizes, can increase the power levels

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generated by power sourcing devices based on thermoelectric, piezoelectric [3], and pyroelectric effects, among others. Regarding, for example, industrial power harvesting solutions based on piezoelectric devices [4]-[5], the power harvesting energy sources can be easily associated with piping [6] and pump devices [7] vibrations that exist in almost all industries and manufacturing units.

These developments to increase the power autonomy of smart sensing units based on piezoelectric devices served as a motivation for the work that was carried out. In this context, it is important to underline that an increase of power autonomy in smart sensing units is directly associated with a reduction of maintenance activities, which means that lower costs are needed to assure the required working performance of those smart sensing units.

Thus, the development of power harvesting testing platforms is of great importance to test and evaluate the performance of the different power harvesting solutions. Several research activities, regarding the implementation of testing platforms for power harvester piezoelectric devices had been presented [8]-[11], but some of them are questionable in terms of simplicity and flexibility.

In this context, this paper's focus is on the presentation of a testing platform to characterize and calibrate piezoelectric power harvesting devices. It is important to notice that the proposed platform is flexible in terms of frequency, waveform and amplitude of the vibration exciting signal enabling, for example, the tuning adjustment of the tip mass of the piezoelectric vibration units and a comparative performance evaluation of different piezoelectric power harvesting solutions.

This paper is organized as follows: this section presents the introduction; section two presents system description, that includes its hardware and software parts; section three presents some experimental results and, in the last section, section four, the conclusions are drawn.

## 2. TESTING PLATFORM

This section includes the description of the testing platform that is proposed to evaluate the performance of piezoelectric based power harvesting solutions. The first part includes the hardware description of the platform and the second part includes its software description.

### A. *Hardware*

Fig.1. represents the hardware of the testing platform that includes an accelerometer, a piezoelectric energy harvesting module, a vibration exciter (shaker), a voltmeter, a multifunction data acquisition board, a laptop or smartphone, a charge amplifier and a power amplifier. The main specifications of the piezoelectric accelerometer type 4370 [12] include: a sensitivity of 998 pC/(m/s-$^{2}$); a frequency range between 0.1 and 4800 Hz for a ±10 % and a mounted resonance frequency of 16 kHz. The vibration exciter, Bruel & Kjaer type 4808 [13], has the following main specifications: force rating of 112 N sine peak; first axial resonance frequency of 10 kHz; maximum displacement of 12.7 mm; maximum bare table acceleration of 71 g and a maximum velocity of 1.4 m/s. Regarding the charge amplifier, Bruel & Kjaer type 2635 [14], its main characteristics include: high sensitivity up to 10 V/pC; built-in integrators for displacement and velocity measurements; switchable low and high frequency limits; a maximum output voltage of 8 V and a built-in test oscillator. The main characteristics of the power amplifier, Bruel & Kjaer type 2712 [15], include: maximum output power od 180 VA into a 0.8 Ω exciter or resistor load; an output voltage capacity of 12 V RMS in a frequency range between DC and 15 kHz; a minimum output current capacity of 7.5 A at or below 5 Hz and a harmonic distortion lower than 0.2 % in the frequency range between 5 Hz and 5 kHz. The main characteristics of the multifunction data acquisition board, NI type myDAQ [16], include: a 2 differential analog input channels with 16 bits resolution; a maximum sampling rate of 200 kS/s; an input range of ±10 V and ±2 V; 2 analog output channels with similar specifications in terms of resolution, sampling rate and output voltage range; a timing accuracy of 100 ppm of sample rate; a timing resolution of 10 ns and a set of 8 DIO lines, being possible to program each line individually as input or output. Concerning the piezoelectric energy harvesting module, Midé type V25W [17], its main specification include: maximum piezo strain of 800 με; maximum tip-to-tip displacement of 0.15 in.; two electrically isolated piezo wafers with independent wiring connections; capability of series or parallel configuration using an adjustable natural frequency set-up with a variable tuning mass. The voltmeter, Keithley type 2110 Series [18], has the following main specifications: 5 ½ digit resolution; 200 readings/s at 5 ½ digits and up to 50000 readings/s at 4 ½ digits; basic DCV accuracy equal to 0.012 % of F.S.; store up to 2000 readings; AC TRMS measurement capability and USB remote interface communication capability.

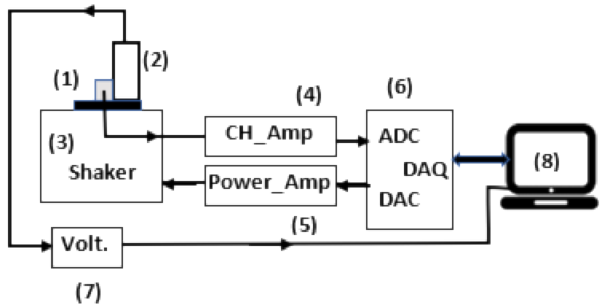



Fig.1. System block diagram: (1) accelerometer; (2) piezoelectric module; (3) vibration exciter; (4) charge amplifier (CH_Amp); (5) power amplifier (Power_Amp); (6) multifunction data acquisition board (DAQ); (7) voltmeter (Volt.); (8) laptop/smartphone.

Fig.2. depicts the main parts of the testing platform equipment where it is visible in the lower part, on the left side, the power and charge amplifier and in the lower part, on the right side, the vibration exciter and on its top the accelerometer that is used to measure the kinematic parameters, displacement, velocity and acceleration of the moving platform where the piezoelectric module is fixed. The top of the figure includes an oscilloscope, a function generator and a spectrum analyzer with FFT capabilities. It is important to refer that all the connecting accessories between the vibration exciter and the piezoelectric module were designed and machined in a 3D printer.

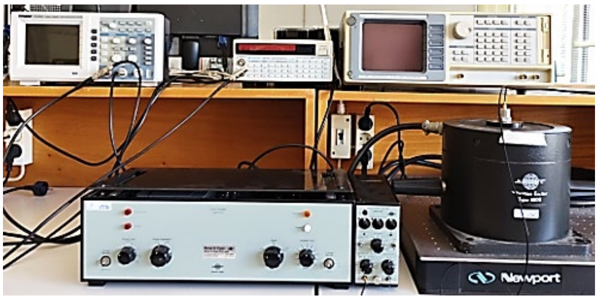
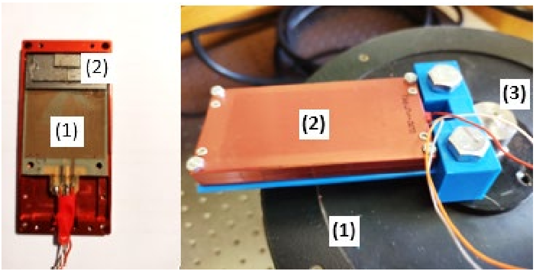


Fig.2. Equipment used in the testing platform for power harvesting piezoelectric devices.

Fig.3.a) depicts a detailed view of the power harvesting module, used for testing purposes, and Fig.3.b) depicts some assembly details of the interconnection between the piezoelectric module and the vibration exciter, that includes an accelerometer on the top that measures the kinematic parameter applied in the device under test. It is important to refer that the tip mass of the power harvesting module is used to adjust its natural resonance frequency and that the accelerometer data can be used for calibration purposes of the testing platform.




a) b)

Fig.3. Piezoelectric module and vibration exciter used for testing purposes: a) Detailed view of the piezoelectric module and dimensional scale reference: (1) piezoelectric wafers; (2) tuning tip mass; (3) 1 € coin relative dimensional scale;
b) Assembly details of the interconnection between the vibration exciter and the piezoelectric module: (1) vibration exciter; (2) piezoelectric module; (3) vibration exciter accelerometer.

It is also important to refer that the measurement calibration accuracy of the testing platform, in terms of mechanical parameter measurements, recommends the usage of an optical breadboard [18]. The main effect of the optical breadboard, namely, its damping and stiffness characteristics, assure a minimal influence of the measuring errors caused by external interferences. The damping characteristic of the optical breadboard is related with its ability to dissipate induced vibration caused by external interferences and its stiffness is related with its ability to resist the bending effect that can be caused by the vibration exciter. Both characteristics are essential to extract accurate kinematic parameters of the movements induced by the vibration exciter.

*B. Software*

The software part of the testing platform includes several routines that are used for measurement system configuration, data acquisition, and data processing. A laptop or smartphone, with HMI capabilities, can be used to implement a friendly interface with the testing platform user. Fig.4. represents the front panel of the LabVIEW virtual instrument (VI) that was developed to test the performance of the piezoelectric power harvesting devices. The user can access graphical representations of the following data: acceleration of the moving platform; piezoelectric voltage root mean square (RMS) value; piezoelectric voltage FFT, and piezoelectric voltage total harmonic distortion (THD). All data is updated in real-time and the user can access the full data that is stored in an experimental results storage file that can also be used to store measurement historical data. Regarding the configuration of the two piezoelectric wafers included in the piezoelectric device under test, it is possible to automatically select a series or parallel configuration using analog switching integrated circuits, such as MAX313 [19]. Series association doubles the open-circuit voltage compared to a single wafer and the effective capacitance is ½ of the single wafer capacitance. By its turn, parallel association doubles the current that can be delivered by a single wafer and doubles the effective capacitance value relatively to a single wafer. In this way, it is possible to automatically select the best configuration to maximize the electrical power transferred to a given load.

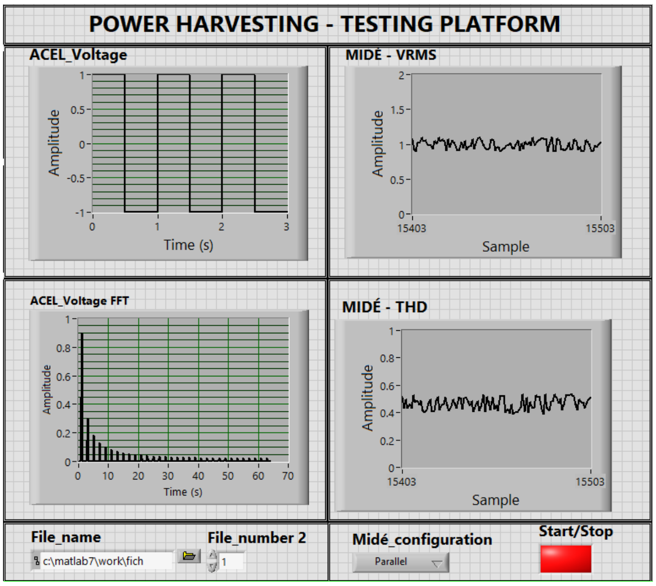



Fig.4. Front panel of the LabVIEW program used to display results of the acceleration data (left side) and power harvesting device (right side).

A second VI was also developed for power measurements. In this case, different load configurations can also be selected by using analog switches and the data that is acquired includes: output voltage, current, and electrical power delivered to the load. In the tests that were carried out it was verified that, regardless of series or parallel configuration, the power generated by the power harvesting module is the same and that the power increases until it peaks when the operating voltage is about half its open circuit value, which confirms the maximum output transfer power that can be transferred between a voltage source with internal resistance and a given resistive load.

## 3. Experimental results

The evaluation of the performance of the testing platform was carried out through the implementation of some experimental tests. It is important to refer that many other tests can be carried out since the system provides a large number of kinematic and electrical variables that can be processed and cross correlated. Regarding data acquisition and voltage measurement, the sampling rate used for data acquisition was equal to 1000 S/s and the multimeter used for voltage measurements had an accuracy of ±(0.12 % of reading+0.05 % range) and the TRMS selected voltage range was equal to 10 V. As an example, Fig.5. represents the sinusoidal voltage applied to the vibration exciter (black curve) and the open-circuit output voltage delivered by the power harvesting device (red curve). The sinusoidal voltage applied to the vibration exciter has null offset, 2 V amplitude and a frequency of 50 Hz that is equal to the natural frequency of the piezoelectric module. According to the set-up of the power amplifier, the velocity of the vibration exciter is proportional to the applied voltage and its gain, in terms of acceleration, is for the testing sinusoidal voltage, used for testing purposes, approximately equal to 0.375 g.

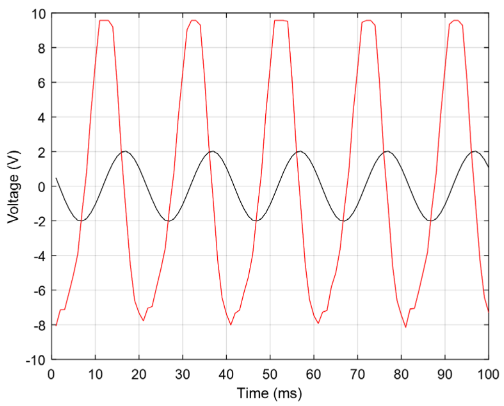



Fig.5. Experimental results obtained for a sinusoidal voltage with null offset, 2 V amplitude and 50 Hz frequency applied to the vibration exciter (black curve) and the open-circuit output voltage delivered by the power harvesting module (red curve).

As it is clearly visible from the graphical representation of the signals, it can be verified that the derivate relation between acceleration and velocity corresponds to a phase shift between the curves almost equal to 90° (quadrature relationship). Moreover, the saturation effect that is visible, particularly in the positive peaks of the acceleration signal, corresponds to almost peak-to-peak amplitude approximately equal to 16 V that agrees with the maximum open circuit voltage specified when the piezo wafers are connected in parallel.

### *A. Frequency response*

The relationship between the piezoelectric cantilever tip mass and its natural frequency is a critical parameter for the performance of the piezoelectric based harvesting modules. If the natural frequency is far away from the vibration bandwidth, the harvested power is very small or even negligible. In other words, if the natural frequency is successfully tuned to the vibration source bandwidth, the most energy will be harvested and that means an increased performance of the piezoelectric module. The frequency response of the power harvesting module was evaluated using different vibration frequencies with the same amplitude. In this test, the vibration exciter was set up using the following parameters: sinusoidal excitation waveform; peak-to-peak voltage equal to 4 V; a null offset and a frequency variation between 40 and 80 Hz, with 5 Hz increments. Fig.6. represents the results that were obtained in this test.

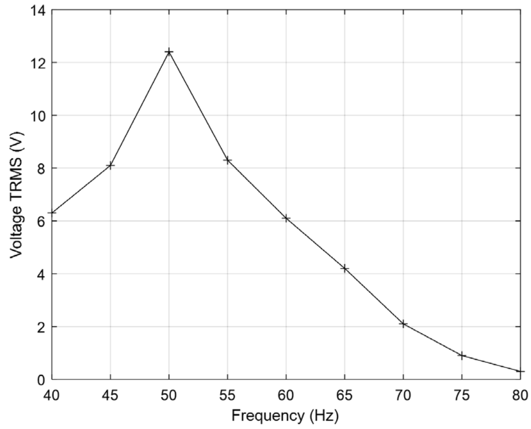



Fig.6. Frequency response of the power harvesting module tuned for a natural frequency of 50 Hz.

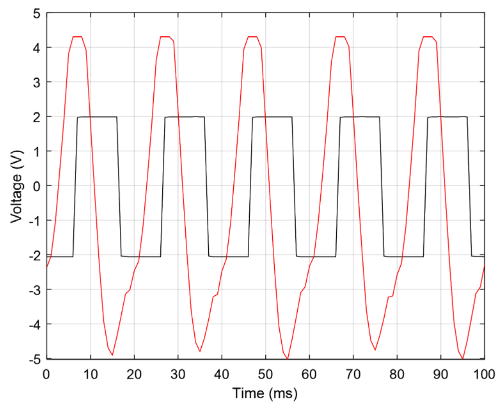



Fig.7. Time response of the power harvesting module for a square waveform excited vibration with a null offset and an amplitude equal to 2 V.

The results show clearly a maximum output voltage around the frequency of 50 Hz. This value agrees with the datasheet characteristic of the V25W Midé module, used for testing purposes, since it uses a tip mass of 7.8 g that, according to the device manufacturer, corresponds to a vibration natural frequency equal to 50 Hz. Regarding time response of the piezoelectric module, Fig.7. represents the time response of the piezoelectric module when a square excitation waveform, with the same peak-to-peak voltage and frequency, is applied to the vibration exciter. As expected from the low-pass filter characteristic of the system, in this case, the output voltage has some distortion but approximates a sinusoidal signal that corresponds to the fundamental frequency of the square waveform signal. As previously verified, the maximum output power is obtained for the maximum slew-rate variation of the exciting voltage signal.

### *B. Amplitude response*

The amplitude response of the power harvesting module was evaluated using different voltage excitation voltage amplitudes for a sinusoidal natural frequency equal to 50 Hz. In this test, the vibration exciter was set up using the following parameters: sinusoidal excitation waveform; peak-to-peak voltage varying between 1 and 8 V, with increments of 1 V; a null offset and a vibration excitation frequency equal to 50 Hz. Fig.8. represents the results that were obtained by the piezoelectric wafers connected in series.

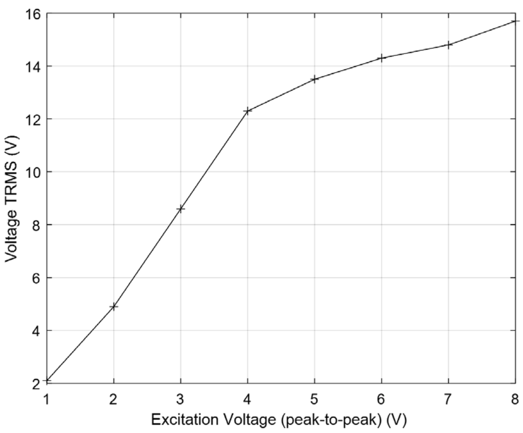



Fig.8. RMS voltage delivered by the piezoelectric module for a sinusoidal exciting voltage with a frequency equal to 50 Hz with amplitude values varying between 1 and 8 V with increments of 1 V.

From the figure it is possible to conclude that a monotonic variation between the vibration excitation voltage amplitude and the open voltage amplitude delivered by the power harvesting device exists. However, the incremental rate of voltage variations decreases with the increasing of excitation voltage amplitude. This reduction is due to the limitations associated with the maximum deformation of the oscillating cantilever piezoelectric module.

### *C. Power harvesting testing*

The presented platform can also be used to test piezoelectric power harvesting devices. Power harvesting capabilities of piezoelectric devices can be evaluated as a function of vibration amplitude, frequency, spectral contents and load resistance. LabVIEW software is used to perform power harvesting testing in almost real time conditions. Electrical parameters' results and waveform charts are displayed on a PC screen and measurement data and test configuration parameters, including piezoelectric wafer association (serial or parallel) and the load impedance configuration, can be dynamically adjusted. Results and test configuration parameters are stored in a historical data file for later post-processing.

To perform power harvesting tests the piezoelectric module is mechanically coupled, by screws, to the vibration exciter that generates vibrations with different frequencies, amplitudes and signals with different spectral contents. The tip mass of the piezoelectric module, mounted in a cantilever beam, can also be tuned, in terms of mass and position, to optimize energy harvesting performance according to the spectral contents of the vibrations. The piezoelectric output voltage is rectified and applied to a capacitive load. The capacitor value is chosen using the following relationship for average harvesting power [17]:

$$(\mathrm{P})_{\mathrm{av}} = \frac{1/2 \cdot \mathrm{C} \cdot \mathrm{V}^2}{\Delta \mathrm{t}} \tag{1}$$

where C represents the capacitance value, V is the open voltage delivered by the piezoelectric module, and Δt represents an acceptable charging interval that was considered equal to 10 s. From (1) it is possible to obtain the capacitor value that is given by:

$$C = \frac{2 \cdot (\mathrm{P})_{\mathrm{av}} \cdot \Delta \mathrm{t}}{\mathrm{V}^2} \tag{2}$$

Fig.9. and Fig.10. represent experimental results of the harvested power as a function of the operating voltage and the relative error between experimental and second order polynomial curve fitted values, respectively. From the graph, represented in Fig.9., it is possible to verify that the extracted harvesting power increases until it peaks (maximum value) when the operating voltage is approximately equal to half of the open voltage value [21]. The testing conditions include a sinusoidal excitation voltage equal to an amplitude of 8 V and 16 V, peak-to-peak, a frequency of 50 Hz, and these values are associated with a 0.5 g acceleration and 1 g acceleration for the upper and lower curves represented in Fig.9.

Thus, it is possible to refer that the experimental results confirm the theoretical expectation and specifications of the piezoelectric module used, as a reference, in this test. Obviously, the proposed platform can be used to evaluate the power harvesting performance of different piezoelectric power harvesting modules, as long as the mechanical connection between the module and the vibration exciter is properly adapted.

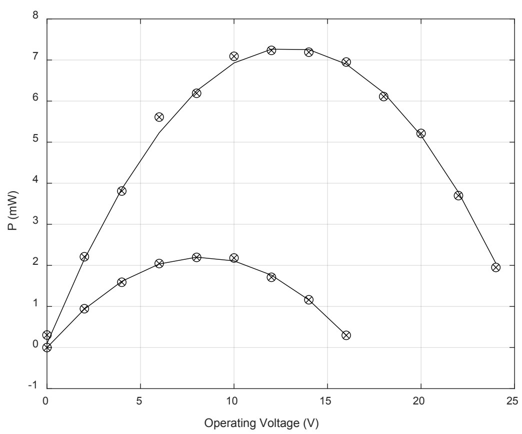



Fig.9. Experimental results of the harvested power as a function of the operating voltage (upper curve- 1 g acceleration; lower curve- 0.5 g acceleration; dotted points- experimental values; continuous line- polynomial curve fitted values).

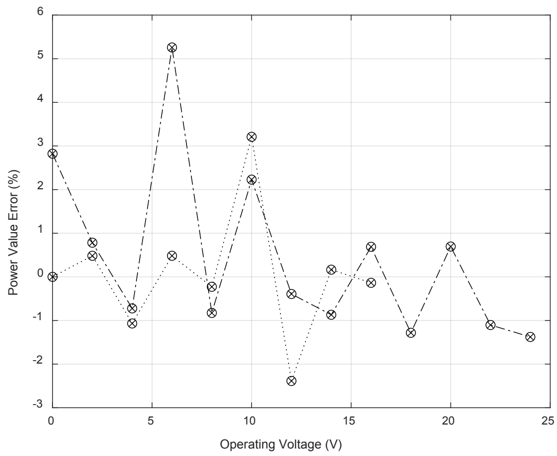



Fig.10. Relative error between experimental and polynomial curve fitted values.

## 4. CONCLUSIONS

This paper presents a flexible platform that can be used to characterize piezoelectric devices and to evaluate their performance in terms of harvesting energy. A complete platform mainly based on the piezoelectric device under test, a vibration exciter and a piezoelectric accelerometer is proposed to evaluate the capabilities of different power harvesting solutions. Calibration and tuning of the piezoelectric power harvesting devices can also be easily implemented based on acceleration and electrical data provided by the accelerometer and power harvesting device, respectively. Last, but not least, it is important to refer that the experimental results presented in the paper are coherent with the theoretical expectations and device's specifications under test.

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