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Piezoelectric Micro-generator Characterization for Energy Harvesting Application

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***Abstract*—This paper presents analysis and characterization of a piezoelectric micro-generator for energy harvesting application. A low-cost experimental prototype was designed to operate as piezoelectric micro-generator in the laboratory. An input acceleration of 9.8m/s^2 using a sine signal (peak-to-peak voltage: 1V, offset voltage: 0V) at frequencies ranging from 10Hz to 160Hz generated a maximum average power of 432.4μW (linear mass position = 25mm) and an average power of 543.3μW (angular mass position = 35°). These promising results show that the prototype can be considered for low consumption load application as an energy harvesting micro-generator.

***Keywords*—Piezoelectric, microgenerator, energy harvesting, cantilever beam.

I. Introduction

NOWADAYS, most sensors that use wireless technologies are still powered by someone traditional sources of power or batteries. However, the advance electronic technologies and alternative power demand for wireless sensors supply make energy harvesting an attractive and feasible solution [1], [2]. Vibration is one of the mechanical phenomenon that has a great potential for energy harvesting. This phenomenon, combined with the monitoring of industrial equipments for predictive maintenance, introduce novel area of wireless sensors technologies. Electrical machines and electrical generators are typical equipment used in minihydro, micro-turbines fueled by natural gas or landfill gas, and wind turbines because of their low-inertias. The fundamental mechanical vibration of these machines is 50Hz/60Hz (3000RPM/3600RPM for 2-pole machines). However, the dominant mechanical frequency is below the 30Hz range. These vibration frequencies are associated to the horizontal movement and the vertical motion of equipments [3]–[5]. These low frequencies can be used like excitation source of piezoelectric micro-generators for energy harvesting application.

There are currently three basic types of transducers capable of generating energy from vibration: electromagnetic [6], electrostatic [7] and piezoelectric [8], [9]. Although electromagnetic and electrostatic generators have a high generation capacity. These transducers are more difficult to miniaturize, making their application more restricted compared to piezoelectric transducer. The piezoelectric crystals are obtained from doped layers of Zirconate Titanate (PZT 5H), having a high degree of minimization and can be designed in different ways, that gives the adaptability and versatility characteristic to the device [10].

The generators built for vibration energy harvesting are designed with the primary purpose of spreading the vibration in order that the system is in resonance with the operating frequency of the equipment in which it is coupled. There are two simple configurations that are typically used as the basis for energy harvesting generation, these are defined as a single support or double support cantilever structure [11]. Each type of generator has different properties such as the operating frequency range, signal amplitude generated and bandwidth of generation capacity.

This paper presents the piezoelectric micro-generator characterization for energy harvesting application. We performed the characterizations of the piezoelectric micro-generator for a linear and angular mass distribution relative to the attachment point. The paper is organized as follows. The second section describes the experimental procedures. The third section overviews the micro-generator principles used in this work. The results and discussions are presented in the fourth section, and conclusions are drawn in the last section.

II. Experimental Procedures

Figs. 1 (a) and (b) show the schematic block diagram and the low-cost experimental prototype for an alternative piezoelectric micro-generator prototype for energy harvesting application, respectively.

The experimental setup was composed by a computer, data acquisition system, audio amplifier, speaker, bushing, mass and piezoelectric capsule. A piezoelectric capsule (model: 7BB-35-3L0, brass plate: 35mm, resonant frequency: 2.8kHz, resonant impedance = 200Ω and capacitance: 30nF at 1kHz) produced by muRata Company and a speaker (model: 20120911, diameter 6.5 inch, impedance 4Ω, maximum power: 90W) produced by Sony Inc were used as main parts of experimental setup. Two National Instruments multifunction data acquisition system (NI DACX) modules (NI-9205 and NI-9263) were used. The NI-9205 module is 32-channel, 200mV to 10V, 250kS/s, 16-Bit analog input converter, and the NI-9263 is an analog output module composed 4-channel, 10V, 16 Bit, 100kS/s/ch. An acquisition software was developed in LabVIEW to generate excitation signal input (type: sine signal, peak-to-peak voltage: 1V, offset voltage: 0V) at frequencies ranging from 10Hz to 160Hz, and to storage of the voltage and current signals of the piezoelectric.

We used a total mass of 2.6g to realize all experiments and measurements of the piezoelectric micro-generator

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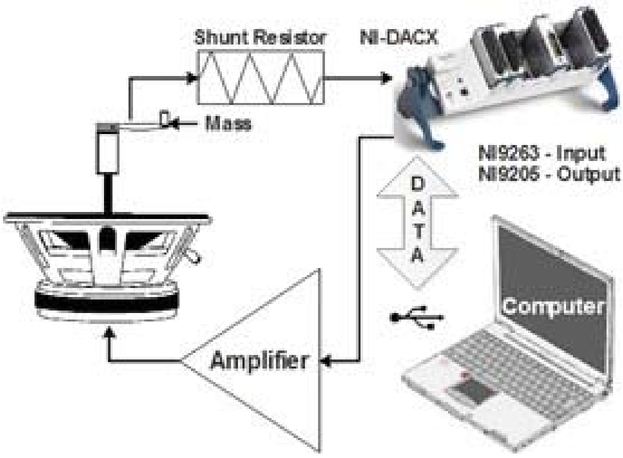
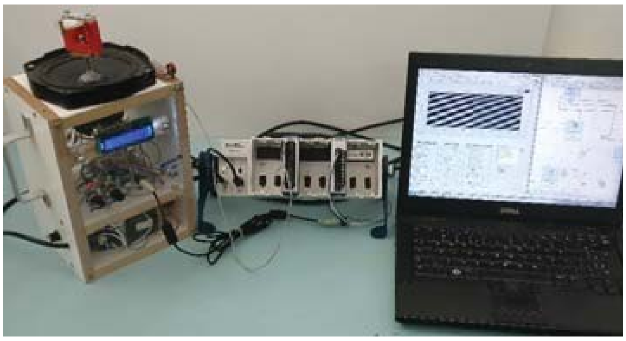
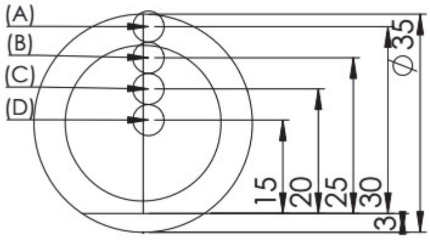


(a) Schematic block diagram

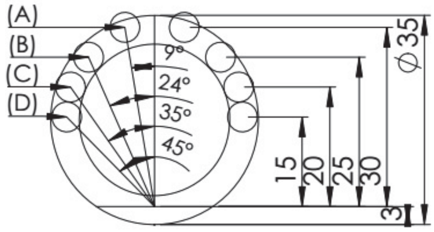


(b) Low cost experimental prototype designed in the laboratory

Fig. 1 Experimental prototype for an alternative piezoelectric micro-generator for energy harvesting application



(a) linear mass distribution: (A) 30 mm, (B) 25 mm, (C) 20 mm, and (D) 15 mm



(b) angular mass distribution: (A) 10°, (B) 25°, (C) 35°, and (D) 45°

Fig. 2 Experimental piezoelectric micro-generator characterization procedures

characterization. It was used two pieces (each mass of 1.3g) for linear mass distribution experiments and four pieces (each mass of 0.65g) for angular mass distribution experiments. The tests were executed using points pre-defined over piezoelectric capsule. Fig. 2 (a) shows the linear mass distribution that starting to 15mm going up to 35mm (with increments of 5 mm) of the attachment point and Fig. 2 (b) shows the angular mass distribution that starting to 45°going down to 10°(with increments of 10°).

An input acceleration of 9.8m/s^2 generated from a sinusoidal signal (peak-to-peak voltage: 1 V, displacement voltage: 0 V) at frequencies ranging from 10 Hz to 160 Hz was used as an excitation source. This frequency range was determined as it covers a large number of electrical machines, electrical generators and equipment commonly used in industry [12]. The amplitude of the excitation signal was set at 1 gand measured using an accelerometer connected to the NI DACX by a LabVIEW tool for vibration analysis. The sampling rate (1000S/s) provides a data packet of 10,000 samples at the end of each test.

III. Energy Harvesting Process

The most common piezoelectric geometry used for energy harvesting is rectangular or trapezoidal with multiple layers. These piezoelectric geometries present a simple manufacture, good performance and easy application in microelectronic systems. A simple brass plate of 30 mm radius with a circular ceramic deposit of 25mm is able to generate powers in the order of 400μW [1], [13]. In the energy harvesting process using circular piezoelectric transducers, the cantilever beam is the most suitable configurations to deal with environments or machines where the vibrations occur at low frequency due to the great intensity of energy propagated in the piezoelectric [14], [15].

Fig. 3 shows the deflection scheme of the piezoelectric cantilever beam from the propagation of vibration. The mass is used to increase the deformation of this beam and increase power generation. The piezoelectric micro-generator is an electromechanical system that can be analyzed in the coupled or uncoupled form. In the coupled mode, mechanical and electrical phenomena are analyzed and in the uncoupled mode only the vibration propagation phenomenon is used in the modeling of the piezoelectric micro-generator [15]. Modeling of the piezoelectric cantilever beam micro-generator is performed using theories of vibrational forces and piezoelectric effect that has resistive, inductance and capacitance characteristics. These considerations allows the use of an RLC circuit for electric modeling of the piezoelectric cantilever beam micro-generator [10], [16], [17].

Considering that the higher power generated occurs in the resonant frequency and that the behavior of the structure occurs in a single direction (one degree of freedom). The piezoelectric cantilever beam micro-generator can be modeled as a damped spring-mass system [16], [17]. The equations that represent the coupled system are:

$$f(t) = m\frac{d^2z(t)}{dt^2} + c\frac{dz(t)}{dt} + kz(t) - vk_{pzt} \qquad (1)$$

$$q - k_{pzt}\theta - \frac{1}{c_{pzt}} = 0 \quad (2)$$

Equation (1) represents a typical damped spring-mass system with the addition of a coupling constant k_{pzt} which is used in piezoelectric systems to represent the relationship of the mechanical strain to the voltage produced. In addition, we have the constants m representing the mass, c the damping coefficient and k the stiffness of the sheet. The displacement/deflection model is represented by $z(t)$, $f(t)$ is the external force applied to the system and v is the potential difference between the terminals. Equation (2) represents the electric characteristics of the piezoelectric phenomenon. The variable q corresponds to the charge between the terminals and the constant c_p is the piezoelectric intrinsic capacitance. Lu et al. [17] also observed the load accumulated at the terminals of the piezoelectric generated crystal during deformation beam, arriving at (3).

$$Q = \int^{A} D_z dA = b\int_{l_1}^{l_0} (e_{31}\varepsilon_x + \epsilon_{33}E_z)dx \quad (3)$$

$$I = Q\omega \quad (4)$$

$$I = \frac{v}{R} \quad (5)$$

The electrical current depends of the terminal load and the signal frequency. In this way, (4) [10] represents the voltage produced by the mechanisms of the piezoelectric cantilever beam micro-generator.

$$v = \frac{\omega bhe_{31}\Delta\varphi_l}{2(1 + bL\epsilon_{33}\frac{R\omega}{d})} \quad (6)$$

where: L is the lenght of piezoelectric layer on the beam plate, e_{31} is a piezoelectric internal dielectric constant, ω is an angular frequency (rad/s), h is a blade thickness, b is a brass plate width and $\Delta\varphi_l$ is a ratio of the length of the piezoelectric.

The equation represents a mathematical model for piezoelectric linear geometry, however, it could be applied in the case of a circular piezoelectric to estimate the possible output peak voltage. Table I shows the values calculated from the modeling in comparison with the values measured during the experiment.

TABLE I
THEORETICAL VOLTAGE CALCULATED BY THE VOLTAGE MODELING EQUATION (6)

Position	Frequency	Theoretical voltage	Measured voltage
30mm	23Hz	7.67V	8.89V
25mm	33Hz	9.15V	9.09V
20mm	38Hz	8.42V	9.44V
15mm	43Hz	7.14V	8.71V

IV. RESULTS AND DISCUSSION

It was perform the characterizations of the piezoelectric micro-generator for a linear and angular mass distribution relative to the attachment point.

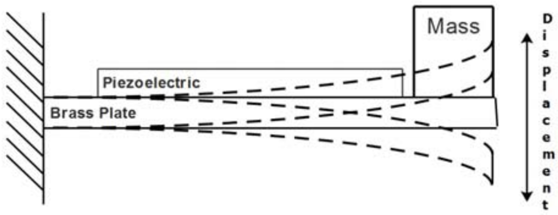


Fig. 3 Schematic Cantilever piezoelectric

A. Characterization of Linear Mass Distribution

Fig. 4 shows the peak-to-peak voltage of the piezoelectric generator for speaker excitation (type: sine wave, peak-to-peak voltage: 1V, offset voltage: 0V) at frequencies ranging from 10Hz to 160Hz for linear mass distribution. One can note that different mass positions change the voltage peak frequency. The peak for the mass position at 30mm in the piezoelectric generator has the maximum peak-to-peak voltage located at 23Hz, which is the resonance frequency of the system for this configuration. One can also observe that the voltage peak frequency increases (33Hz, 38Hz and 43Hz) when the distance of the mass distribution relative to the attachment point decreases (25mm, 20mm and 15mm). The presence of these peaks is justified by the interaction between deflection of piezoelectric disc, mass position, and speaker excitation voltage. In this way, the prototype device can operate in a frequency range from 23Hz to 43Hz [18].

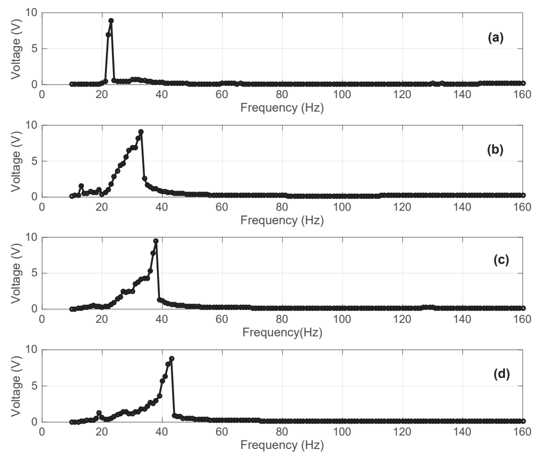


Fig. 4 Typical piezoelectric generator response for a speaker signal at frequencies ranging from 10 Hz to 160 Hz and linear mass distribution at: (a) 30mm, (b) 25mm, (c) 20mm, and (d) 15mm

Fig. 5 shows the piezoelectric generator behavior when the speaker is submitted to resonant sinusoidal excitation to maximum peak-to-peak voltage of each linear mass position. We observed that mass positions 30 mm (Fig. 5 (a)), 25 mm (Fig. 5 (b)) and 20 mm (Fig. 5 (c)) generate similar output voltage for resonant sinusoidal input voltage, respectively. The output responses present similar peak-to-peak voltage and typical fix lag over time (input/output phase difference around

210°-220°). However, it can be noted that mass position 15mm (Fig. 5 (d)) create an output voltage clearly different behavior. The output response is on phase (input/output phase difference only 0.3°) and reduced peak-to-peak voltage compared with others mass positions.

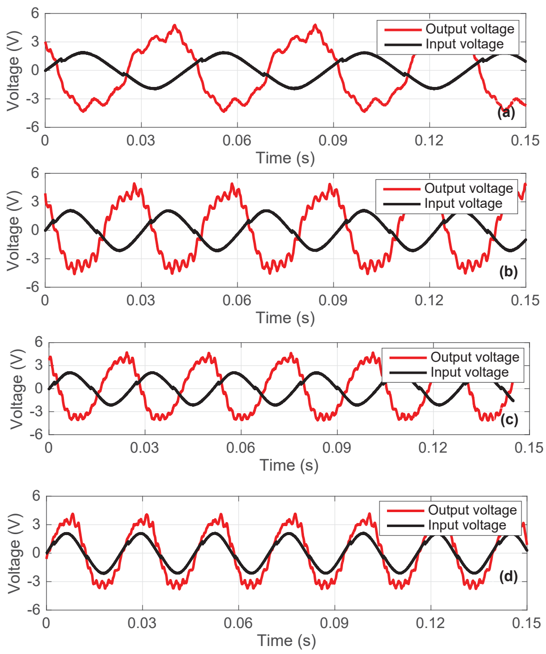


Fig. 5 Typical speaker input voltage and piezoelectric generator output voltage for linear mass distribution: (a) 30mm, (b) 25mm, (c) 20mm, and (d) 15mm

Measurement of voltage and current for a typical input impedance of an integrated circuit were obtained. Table I shows input/output phase shift, RMS voltage, RMS current and average power calculated for a shunt resistor of 19.74kΩ. The maximum harvested electrical power obtained was 432.4μW, when the mass position was installed at 25mm relative to the attachment point.

TABLE II
RMS Voltage, RMS Current and Average Power Calculated for a Shunt Resistor (Linear Mass Distribution)

Mass position	Phase Shift	RMS Voltage	RMS Current	Avg. Power
30mm	213.7°	2.00V	103μA	206.5μW
25mm	220.1°	2.92V	148μA	432.4μW
20mm	221.8°	2.74V	139μA	381.9μW
15mm	0.3°	2.28V	115μA	263.9μW

These values are significantly higher when compared to those of [17], called the piezoelectric parametric frequency increased generator (peak power 100μW and average power 3.25μW). However, the results presented here are similar to those obtained during normal walking (around 416.6μW) for a micro-generator that converts human movements to electrical energy [19]. These results, for linear mass distribution, seem promising for piezoelectric micro-generator in the context of energy harvesting applications.

B. Characterization of Angular Mass Distribution

Fig. 6 shows the typical peak-to-peak voltage of the piezoelectric generator for speaker excitation (type: sine wave, peak-to-peak voltage: 1V, offset voltage: 0V) at frequencies ranging from 10Hz to 160Hz for angular mass distribution. It can also be note that the voltage peak frequency is shifted forward (26Hz, 33Hz, 38Hz and 43Hz) when the angle of mass distribution relative to the attachment point is increased (10°, 25°, 35°, and 45°). However, the voltage peaks produced by angular mass distribution show a frequency widening of the peaks when compared to the linear mass distribution. In this case, the angular mass distribution is a more flexible configuration because it covers a frequency range greater than the linear mass distribution. This topology creates an extended operating range around the resonant frequency for each angular position.

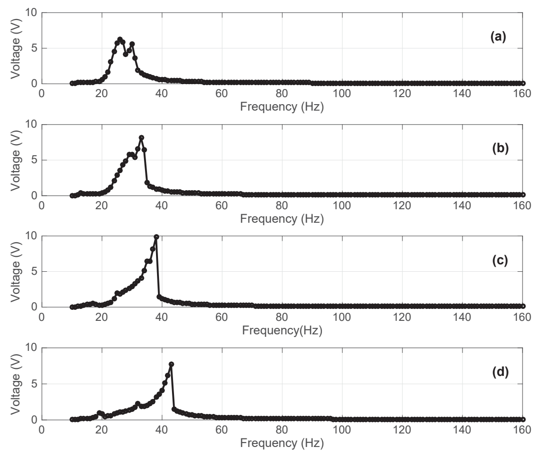


Fig. 6 Typical piezoelectric generator response for speaker signal at frequencies ranging from 10Hz to 160Hz and angular mass distribution at: (a) 10°, (b) 25°, (c) 35°, and (d) 45°

Fig. 7 shows the piezoelectric generator behavior when the speaker is submitted to resonant sinusoidal excitation to maximum peak-to-peak voltage of each angular mass position. We observed a behavior similar to the linear mass distribution for small mass position angles (10°and 25°). Figs. 7 (a) and (b) show similar peak-to-peak voltage and typical phase shift around 180°. Fig. 7 (c) presents a phase shift around -5.9° and the maximum peak-to-peak voltage compared with all others mass distribution configurations. Finally, Fig. 7 (d) illustrates a phase shift of only 1.4° and reduced peak-to-peak output voltage.

Measurements of voltage and current for a typical input impedance of an integrated circuit (19.74KΩ) were obtained. Table III shows the input/output phase shift, RMS voltage, RMS current and average power calculated for shunt resistor.

One can note that the values obtained are similar to those of the linear mass distribution. However, the higher average

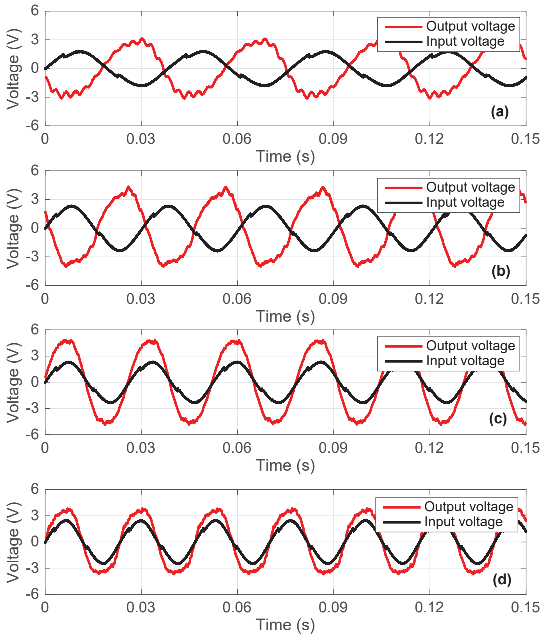


Fig. 7 Typical speaker input voltage and piezoelectric generator output voltage for angular mass distribution: (a) 10°, (b) 25°, (c) 35°, and (d) 45°

TABLE III
RMS VOLTAGE, RMS CURRENT AND AVERAGE POWER CALCULATED FOR A SHUNT RESISTOR (ANGULAR MASS DISTRIBUTION)

Mass position	Phase Shift	RMS Voltage	RMS Currrent	Avg. Power
10°	165.9°	2.14V	108μA	230.8μW
25°	193.8°	2.70V	137μA	369.3μW
35°	-5.9°	3.27V	166μA	543.3μW
45°	1.4°	2.59V	131μA	339.3μW

power result (543.3μW) is obtained for the mass position at 35°and presents the output voltage in phase with the input. This is the best choice among all tested mass distribution configurations to be used as a piezoelectric micro-generator prototype for energy harvesting applications.

V. CONCLUSION

In this paper, we examined a low-cost alternative piezoelectric micro-generator for energy harvesting application. The maximum average power output produced was 543.3μW, when the generator was excited with a sinusoidal acceleration of 9.8m/s^2 at 38Hz and an angular mass distribution of 35°. The prototype can operate over a frequency range of 23-43Hz. In this way, we can easily make adjustment to prototype for energy harvesting applications such as electrical machines and/or electrical generators that have the typical dominant frequency around the 30Hz.

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