Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **70**, *1*, pp. 9–14, Bucarest, 2025

EXPERIMENTAL STUDY OF A PIEZOELECTRIC HARVESTER VIBRATING ON AN INDUSTRIAL SCREW COMPRESSOR

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Keywords: Piezoelectric harvester; Forced vibrations; Resonance frequency; Electromechanical conversion; Test bench; Industrial compressor.

The paper presents preliminary experimental works on a twin-screw compressor to validate and demonstrate piezoelectric energy harvesting. The experiments target an industrially relevant environment: a test bench for industrial air and gas compressors. This work was only possible after previous studies assessing the piezoelectric harvester's behavior, considering essential factors. In our case, a high working temperature may negatively influence the piezoelectric response and even damage the material; hence, it should be avoided as much as possible. The piezoelectric harvester's resonant frequency ought to be adjusted in real-time to match as closely as possible the target vibration frequency of the male rotor, of ~83 Hz. We obtained a voltage peak response of ~4 VAC and a maximum measured RMS current of ~515 µA. The RMS power, calculated at about 1.5 mW, was deemed very satisfactory for a piezoelectric device.

1. INTRODUCTION

The present study deals with a preliminary experimental prospection of the practical application of piezoelectric energy harvesting from industrial machinery vibration, namely a twin-screw compressor. Piezoelectricity as an alternative renewable energy source offers broad perspectives for low-power applications [1].

Piezoelectric energy harvesting is presently an intensely researched topic; however, it has not reached technological maturity, and it seems to be stuck at the simulations and laboratory testing phase, proven by the large number of papers that are still dealing with ideal working conditions. Most researchers are still seeking ways to optimize the piezoelectric response by any means [2–6], along with designing the energy harvesting circuitry [7–10]

Wireless sensor networks (WSN) together with structural health monitoring (SHM), have been vehiculated for the last two decades as an ultimate application for piezoelectric harvesters (PEH) [11–16].

Before considering any practical implementation, some important issues should be considered. The working conditions and environmental factors must be assessed not only in terms of vibration spectra and frequencies, but special attention must be paid to any parameter that may influence or damage the piezoelectric device.

The output power of a vibration energy harvester is dependent on a wide range of factors (such as temperature, humidity, electromagnetic interferences, etc.) and varies if operating at resonance or outside resonance [17].

One of the most critical parameters for the PEH that ought to be assessed when dealing with industrial machinery is the temperature, unlike when installed on a much smaller air conditioning unit [18].

It is well-known from the literature that piezoelectric properties can degrade much faster when subjected to higher temperatures, and reaching Curie point causes total depolarization of the piezoelectric material.

The experimental validations presented herein rely on numerous previous works involving numerical simulations, analytical approaches and laboratory tests in ideal conditions [19–22], as well as studies assessing the compressor as source and how the parameters in an industrial environment could affect the piezoelectric material and hence a harvester's response [23–26]. The present study makes a step forward towards the practical implementation, proposing a Midé PPA-4011 piezoelectric harvester [27] operating on an industrial twin-screw compressor chosen as vibrating source. Thus, a technology readiness level TRL 6 is achieved, demonstrating the technology in an industrially relevant environment [28–30]. The PEH is part of a multisource energy harvesting system, together with thermoelectric generators (TEG).

2. EXPERIMENTAL SETUP ON COMPRESSOR

The compressor test bench is presented in Fig. 1. The compressor was driven at 2500 rpm, operating in quasi-stationary mode, with a ±20 rpm speed variation during operation. The compressor is driven by a DC motor whose speed is varied via a variable speed drive.

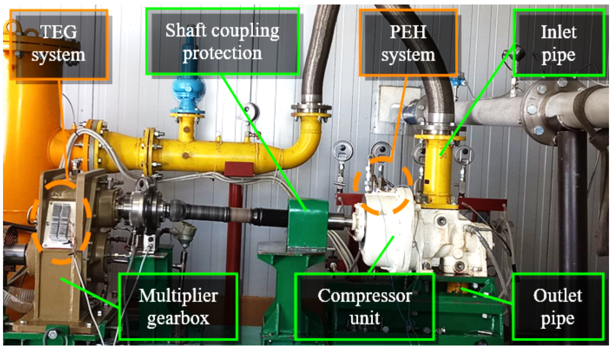

Fig. 1 – Compressor skid, at the headquarters of the Romanian Research and Development Institute for Gas Turbines COMOTI.

The male rotor frequency of ~83 Hz was targeted from the previously extracted compressor's spectral components, due to its stability and higher amplitudes.

The compressor's vibration spectra have been investigated in prior research [22, 25]. Due to the slight instability of the DC motor's speed driven by a frequency inverter, slight oscillations appear in compressor's speed, varying between 2488 rpm and 2519 rpm (Fig. 2). The parameters acquired by the test bench PLC, displayed on the screen are: **DPGA** [mbar] – Differential pressure of inlet gas; **Qm** [kg/h] – Mass flow rate; **Qv** [Nm^3/h] – Volumetric flow rate; **T0** [°C] –

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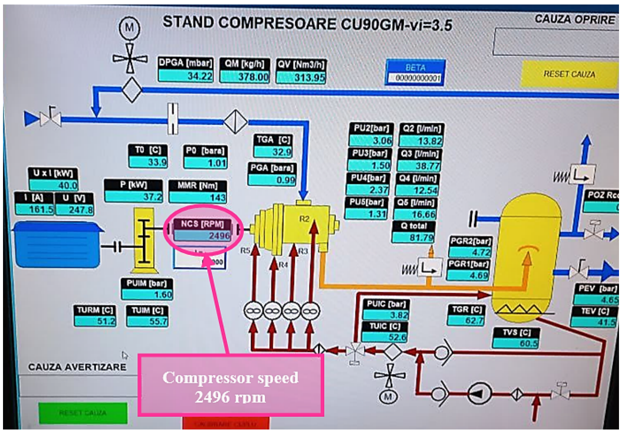
DOI: 10.59277/RRST-EE.2025.1.2

Ambient air temperature; **P0** [bara] – Ambient air pressure; **I** [A] – Motor current; **U** [V] – Motor voltage; **U x I** [kW] – Motor power; **P** [kW] – Compressor power; **MMR** [Nm] – Driving shaft torque; **NCS** [rpm] – Screw compressor speed; **PUIM** [bar] – Multiplier inlet oil pressure; **TUIM/TURM** [°C] – Multiplier inlet/outlet oil temperature; **TGA** [°C] – Inlet gas temperature; **PGA** [bara] – Inlet gas pressure; **PUIC** [bar] – Compressor inlet oil pressure; **TUIC** [°C] – Compressor inlet oil temperature; **PU2÷PU5** [bar] – Oil pressures measured on fittings R2÷R5; **Q2÷Q5** [l/min] – Flows measured on fittings R2÷R5; **PGR1, PGR2** [bara] – Discharge gas pressure; **TGR** [°C] – Discharge gas temperature; **TVS** [°C] – Temperature in separator vessel; **POZ Rcos** [%] – Discharge valve position; **PEV** [bar] – Separator vessel outlet pressure; **TEV** [°C] – Separator vessel outlet temperature.

The parameter that interests us the most for the purpose of this work is the compressor speed, captured at 2496 rpm and highlighted in Fig. 2.



STAND COMPRESOARE CU90GM-vi=3.5

CAUZA OPRIRE

DPGA [mbar] 34.22
QM [kg/h] 378.00
QV [Nm3/h] 313.95
BETA 00000000001
T0 [C] 33.9
P0 [bara] 1.01
TGA [C] 32.9
PGA [bara] 0.99
U x I [kW] 40.0
I [A] 161.5
U [V] 247.8
P [kW] 37.2
MMR [Nm] 143
NCS [RPM] 2496
PU2[bar] 3.06
PU3[bar] 1.50
PU4[bar] 2.37
PU5[bar] 1.31
Q2 [l/min] 13.82
Q3 [l/min] 38.77
Q4 [l/min] 12.54
Q5 [l/min] 16.66
Q total 81.79
PGR2[bar] 4.72
PGR1[bar] 4.69
PUIM [bar] 1.60
TURM [C] 51.2
TUIM [C] 55.7
PUIC [bar] 3.82
TUIC [C] 52.6
TGR [C] 62.7
TVS [C] 60.5
PEV [bar] 4.65
TEV [C] 41.5

CAUZA AVERTIZARE

Compressor speed
2496 rpm

Fig. 2 – Compressor parameters displayed on the monitoring screen.

The cantilever’s resonant frequency was then adjusted in laboratory (Fig. 3), from ~210 Hz to 83 Hz using an inertial tip mass of 7.3 g [26].

The laboratory setup and testing, however, has its limitations compared to testing in a relevant industrial environment:

- The vibration exciter can generate vibrations in a single direction (vertical), whereas the compressor vibrates in all three directions.
- The attaching method of piezoelectric support onto the shaker’s aluminum mobile platform is made with double-sided adhesive tape, which could never be a reliable solution in real applications involving high temperatures.
- In laboratory, the resonance of the piezoelectric harvester is found by sweeping the vibration frequency via the spectrum analyzer, so the source’s vibration is adjusted to match the natural frequency of the PEH. This is a backward practice, since in a real practical application, the harvester’s frequency must be adjusted to match the source’s, not the other way around.
- The ambient temperature in the laboratory is maintained around room temperature (20-30 °C). On the compressor unit, the higher housing temperatures rising to more than 65 °C can cause a faster ageing of the piezoelectric material and make adhesive tape and wax-mounted accelerometers unusable.

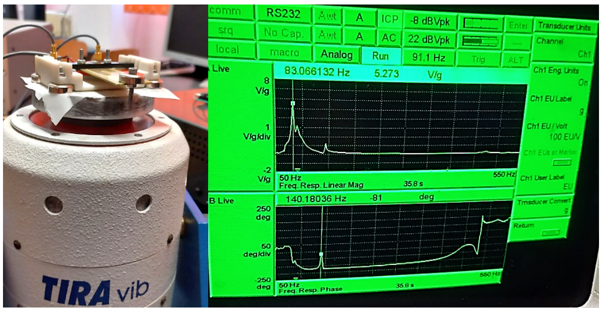


Fig. 3 – Laboratory tests and voltage response displayed on the spectrum analyser.

A magnetic mounting method was employed on the compressor. Since the magnetic mount is more rigid than the adhesive tape used in laboratory, increasing the tip mass for tuning the PEH to the male rotor’s frequency was required, according to:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}}, \tag{1}$$

where: f_n [Hz] is the natural frequency; k [N/m] is the stiffness constant; m [kg] is the total mass.

3. TESTING CONDITIONS FOR THE PIEZOELECTRIC DEVICE

The vibrations have previously been measured in [25], choosing five points on the compressor unit known for higher amplitudes. The compressor unit is the same CU90G, having a red coating in Fig. 4 and currently being painted in white.

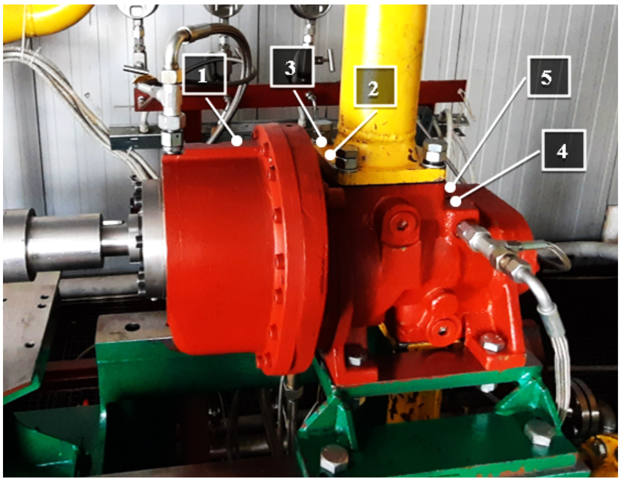


Fig. 4 – Vibration measurement points considered [25].

Point 1 was chosen as mounting spot for the tests with the piezoelectric harvesting system. Points 2 and 3 were discarded for this preliminary study due to space constraints, even though the 10 °C lower temperature recorded in Point 2 (35.8 °C) compared to Point 1 (45.9 °C) [25] is worth considering the future use of a custom-made uplifting support. Points 4 and 5 are close to the compressor’s discharge port, where the highest pressure is naturally accompanied by high temperatures. The temperatures in these points are about 10 °C higher than in Point 1, 55 °C in Point 4 and 53.3 °C in Point 5 respectively. These points were discarded as well due to very high temperature that would cause an important thermal hysteresis, resulting in a decreased electric output. It is worthwhile to specify that these measurements were taken on 30.05.2022, when the maximum temperature in Bucharest was 24 °C.

Subjecting the piezoelectric transducer to high temperatures would furthermore cause accelerating material ageing and decreasing its Curie point, where the loss of piezoelectric properties occurs. The specified Curie point of the PZT-5H material employed by Midé PPA-4011 is T_C = 225 °C [27]. The maximum recommended operating temperature is up to half of the Curie point, above which the material gets depolarized when subjected to several operation cycles.

A real-time frequency tuning of the piezoelectric transducer was necessary to match the compressor's frequency component as closely as possible, for maximum piezoelectric output. The resonance frequency of the PEH is unknown, as we cannot possibly sweep the source's vibration frequency like in laboratory. For the real-time tuning, we started from the mass used in laboratory, adding supplementary weights of ~0.3 g each, and observing a gradual increase in voltage response. The maximum response recorded was with five weights, a voltage decrease being observed when adding the sixth piece, indicating that we have increased the frequency past the resonance peak. The mass elements were overall weighted at 9.0 g (Fig. 5).

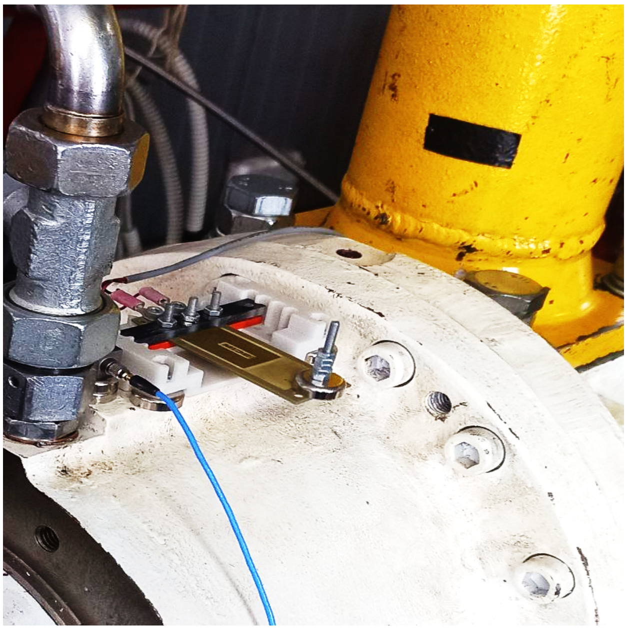


Fig. 5 – Piezoelectric harvester with tuning mass, mounted on the compressor.

A thermographic image was taken with a thermal imaging camera, adding temperature markers in Fig. 6. A maximum of 65.2 °C is marked on the compressor housing near the mounting spot of the PEH. It can also be observed that the magnets are cooler, inferring a poor thermal transfer of the magnetic material. This is advantageous for our experiments since it ensures less heating of the piezoelectric element.

The beam temperature of 49 °C is rather high for a longer operation period, due to thermal hysteresis and decreased performance parameters in terms of electric output and resonant frequency, furthermore, occurring at a higher mechanical stress compared to the ideal operation at room temperature. Even though the operating temperature range for the Midé harvester is -40 ÷ 120 °C due to the epoxy layers used [27], piezoelectric harvesters exhibit best performances and prolonged lifespan if kept at room temperature.

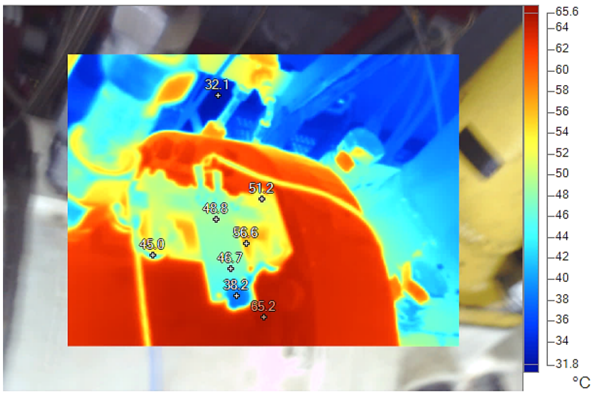


Fig. 6 – Thermographic image of the piezoelectric harvester.

The maximum recommended temperature for a piezoelectric material is typically half of its Curie point, T_C, in our case for the PZT-5H, T_C = 225 °C [27]. Therefore, the harvester should be kept below 110 °C for safe operation, without leading to depolarization and faster material ageing.

4. RESULTS AND DISCUSSION

For the experimental setup and measuring, the following equipment was used:

- Piezoelectric harvesting system comprising Midé PPA-4011 transducer mounted on Midé PPA-9001 clamping kit [27]. The support is attached using a magnetic mount on compressor's cast iron housing.
- Fluke 190-504 scopemeter with four channels (BNC inputs), and input impedance of 1 MΩ + 15 pF. The embedded waveform mathematics functions allow the extraction of the real-time frequency spectrum using FFT analysis. The maximum record length is 30,000 points per channel in ScopeRecord ™ Roll mode.
- Fluke 117 true RMS multimeter for voltage measurement. For Volts AC function used in our experiments, the nominal input impedance given in the specifications is > 5 MΩ < 100 pF.
- Fluke 87V true RMS industrial multimeter, for microamperes current measurement. The input impedance for Ṽ is 10 MΩ < 100 pF.

Since compressor vibrations occur on all three axes, a triaxial accelerometer should be employed within future experiments. For this purpose, a measuring device supporting ICP (Integrated Circuit Piezoelectric) input must be used. The scopemeter does not support inputs from ICP accelerometers that incorporate built-in microelectronics, hence we did not have information about the compressor's real-time working frequencies and amplitudes, other than the prior spectral measurement conducted in [24, 25].

The piezoelectric voltage response was recorded over a short period of 48 s due to the high sampling rate of the scopemeter, and a limited number of points recording (Fig. 7).

Even though the carrier signal, observed in the time response in Fig. 7 above, appears to be amplitude modulated, the FFT (Fast Fourier Transform) mathematical operation applied from the scopemeter to the piezoelectric harvester's time response reveals a single frequency peak, the targeted one at ~83 Hz, as shown in Fig. 9.

This is explained by the fact that the modulating signal's period is about 8 seconds, which infers a very low frequency (0.125 Hz), possibly indicating to the compressor frame or the floor, whereas the spectrum displayed on logarithmic scale starts from a value of 1 Hz.

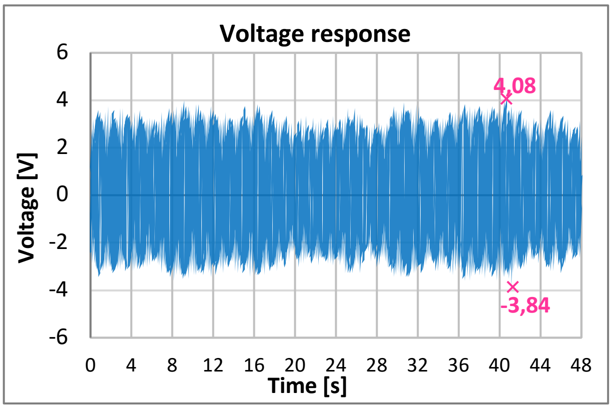


Fig. 7 – Piezoelectric voltage response recorded.

A zoom-in on the range with the maximum and minimum voltage recorded is presented in Fig. 8, also providing an insight on the quasi-sinusoidal piezoelectric output, due to the quasi-stationary mode of the compressor.

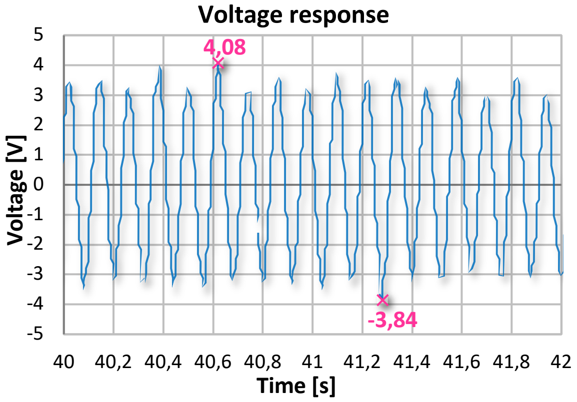


Fig. 8 – Zoom on the quasi-sinusoidal piezoelectric voltage response.

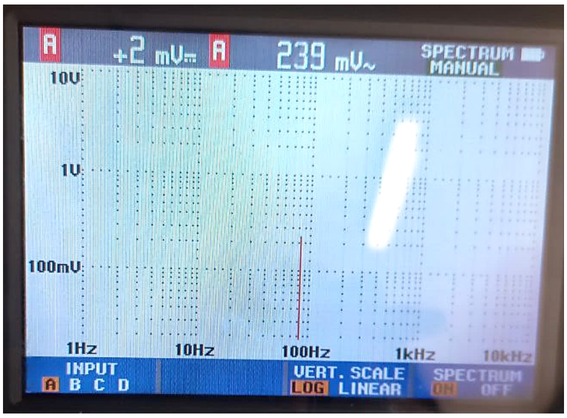


Fig. 9 – Frequency response of the piezoelectric cantilever.

Fig. 10 presents the harvester's time response captured at a frequency of 82.35 Hz on the scopemeter and the AC voltage read on multimeter (left), as well as the measured RMS current (right).

A piezoelectric material has an extremely high internal resistance, of the order 10^{12} to 10^{14} Ω, which basically makes it an insulator. Hence, the current is typically very low, of the order of tens or, at most, hundreds of microamperes. The maximum current obtained was about 515 μA RMS.

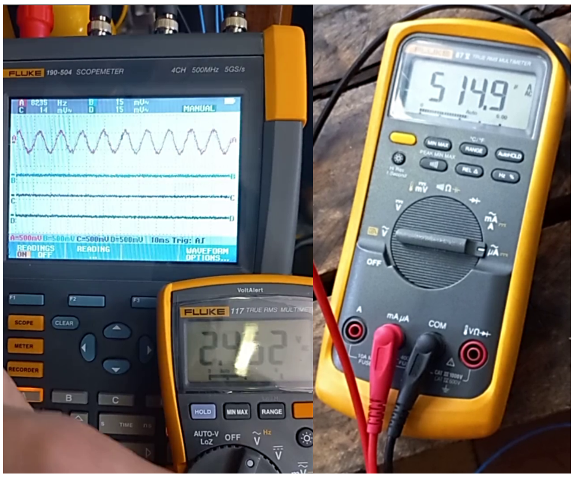


Fig. 10 – Time response recorded around 83 Hz on the scopemeter and AC voltage read on multimeter (left); measured RMS current (right).

The maximum RMS power was calculated. Since the multimeter is not made for dynamic measurements, the maximum current value could be slightly higher than the one displayed. The maximum voltage, $V_{\max} = 4.08$ V, and the RMS current, $I_{RMS} = 514.9$ μA, were introduced in (2):

$$P_{RMS} = I_{RMS} \cdot V_{RMS} = I_{RMS} \frac{V_{\max}}{\sqrt{2}} \cong I_{RMS} (0.707 \cdot V_{\max}) . \quad (2)$$

where: P_{RMS} [W] is the RMS power; I_{RMS} [A] is the RMS current; V_{RMS} [V] is the RMS voltage; $I_{\max}$ [A] is the maximum current amplitude; $V_{\max}$ [V] is the maximum voltage amplitude.

The maximum measured output parameters are summarized in Table 1 below.

Table 1

Measured piezoelectric output parameters

Symbol	Quantity	Value	U.M.
1.	Maximum AC voltage	4.08	V
2.	Maximum RMS current	514.9	μA
3.	Maximum RMS power	1.485	mW
5.	Frequency	83 ± 1	Hz

5. CONCLUSIONS

The paper herein demonstrates a piezoelectric energy harvesting system, harnessing the vibrations of an industrial twin-screw compressor that operates in quasi-stationary mode. The electric response obtained from these preliminary assessments is satisfactory and promising for the further upcoming experimental works. The ultimate purpose of these works is to be able to harvest enough power to supply some low-power wireless sensors nodes, as well as to use the harvesters themselves as sensors for the structural monitoring of the machine, and for ensuring the predictive maintenance of the equipment. Besides the piezoelectric harvesters, we also have a thermoelectric harvesting part that we have experimentally validated. An energy harvesting circuitry shall be designed and developed, as well as the wireless transmission part that is envisaged to be powered with the harvested energy.

Proper measurements will be pursued using single-axis accelerometers. Acquiring a data acquisition module with embedded ICP on the BNC input channels would be preferable for measuring the three-axial vibration in the same spot. It is worth noting that the experimental work presented herein was carried out on the 3rd and 4th of July 2023, when the ambient temperature in Bucharest, Romania, reached 33-35 °C. Another set of experiments will be pursued in the cold season when temperatures will be much lower. A cooling method or distancing from the hot compressor surface shall be considered, especially for summer ambient temperatures.

To our knowledge, there is no reported literature on piezoelectric energy harvesting implemented on an industrial compressor. Before taking this technology in situ in an industrial environment, many aspects must be studied and understood. The paper is a first step for taking this piezoelectric energy harvesting technology from the laboratory towards real in-situ applications. To get there, we need to identify the issues and the influencing environmental factors that we are dealing with, try to overcome them, mitigate the risks of damaging the harvesters, and only then think of a possible industrial implementation, which is still going to be concerning due to the high costs involved. Hence, prolonging the piezoelectric harvesters' lifespan is the priority.

ACKNOWLEDGEMENT

This paper was realized as part of "Nucleu" Program within the Romanian Research, Development and Innovation Plan 2022-2027, conducted with the support of the Romanian Ministry of Research, Innovation and Digitalization, as part of contract 31N/2023, project number PN 23.12.09.01.

CREDIT AUTHORSHIP CONTRIBUTION

Author_1: Conceptualization, Data curation, Investigation, Methodology, Project administration, Validation, Visualization, Writing (draft, review and editing).
Author_2: Conceptualization, Formal analysis, Supervision, Validation.
Author_3: Investigation (experiment, measurements), Methodology, Writing (draft).
Author_4: Investigation (experimental setup, measurements), Software.
Author_5: Investigation (experimental setup, measurements).
Author_6: Investigation (experiment – compressor start-up and operation), Writing (review and editing).
Author_7: Formal analysis, Investigation, Funding acquisition.
Author_8: Formal analysis, Funding acquisition, Resources.

Received on April 16, 2024

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