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EXPERIMENTAL TESTS WITH PIEZOELECTRIC HARVESTER FOR TUNING RESONANT FREQUENCY TO VIBRATING SOURCE

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The paper deals with experimental testing of a cantilever piezoelectric harvester, aiming to obtain a preliminary assessment of the behavior that should be expected when harnessing the vibrations of a compressor. For this purpose, to exploit the resonant structure to the fullest and obtain the maximum electric response, its fundamental frequency ought to be adjusted to enter resonance at the frequency of the vibrating source. Since the natural frequency of the piezoelectric cantilever is higher than the compressor's male rotor frequency targeted, an inertial mass was attached at the tip of the cantilever. Passive frequency control is preferred because it does not consume any energy. However, suppose the source does not have a stable frequency in a quasi-static regime. In that case, semi-active control solutions should be adopted, changing frequency from the components of an external electric circuitry connected.

1. INTRODUCTION

Piezoelectric transduction for energy harvesting has received significant attention regarding electric energy conversion from vibration from the beginning of the 21st century, a research field that is being thoroughly researched now [1–3], considering the large number of papers being published worldwide. Assessing and optimizing the power output by any possible means and widening the resonance bandwidth or maximum power point tracking are continuously exploited topics and trending research in almost every micro energy harvesting technology [1,4].

When dealing with resonant piezoelectric structures, it is a must to tune the piezoelectric harvester (PEH) to the source's vibrating frequency in the mounting spot to achieve a maximum electrical response. The most common practice is to excite the harvester at its fundamental resonance frequency [5–7]. Since the primary vibrations harvested are ambient or produced by vibrating machines, other higher-order bending modes are not easily achievable in practice. Still, they can be addressed only in simulations or laboratory tests, as they occur at too high of natural frequencies to be able to tune to the harvested vibrations without exceeding the maximum yield strength of the piezoelectric structure.

The foremost requirement for PEH devices is to operate at resonance with the excitation frequency, as a small force driving the structure can produce a significant vibration response [1], which reflects into a peak electric response as well. It is noteworthy that even a slight deviation (±1 Hz) from the resonance matching condition will result in a significant drop in generated electric response in the case of lightly damped systems. Using a higher damping or other methods for widening the frequency response near resonance [8,9] is also a good practice that does not require a semi-active or active tuning with power consumption.

The paper studies the electric response to forced vibrations of a piezoelectric resonant multilayer structure in cantilever construction with four active PZT-5H layers [5]. The paper herein aims to tune the structure's resonance to match the vibration source, an industrial screw compressor available on a test bench. In a previously published work, the vibrations were measured regarding their frequency, amplitude, and stability of the specific spectral components [10].

The targeted frequency is found at ~83 Hz and is generated by the male rotor of the twin-screw compressor running at the normal quasi-static speed of 2500 rpm. The male and female rotors' speeds are the only spectral components not affected by the discharge pressure. The female rotor frequency and vibration amplitudes are much lower [10]. Hence, the paper aims to obtain the piezoelectric frequency response before and after attaching a tip mass for tuning the PEH to 83 Hz.

Few published papers in the literature address a real source to harvest vibration from [5,6,11,12], the great majority only focusing on simulations and laboratory tests that excite the structures at their resonant frequency. In in-situ or test bench operation, it is impossible to drive industrial machinery to match harvesters' natural frequencies, as the purpose of those machines with inherent vibrations is not to work as shaker tables.

2. PIEZOELECTRIC HARVESTER AND INERTIAL MASS ANALYTICAL CALCULATION

The piezoelectric harvester (PEH) (Fig. 1) employed is a quadmorph cantilever beam comprising four piezoceramic wafers of lead zirconate titanate, PZT-5H. The beam consists of 17 very thin layers, its overall dimensions being 71.0 mm x 25.4 mm x 1.32 mm (L x W x H) [13].

Fig. 1 – Midé PPA-4011 multilayer piezoelectric harvester

To assess what value of the inertial mass we will need in the experiment, we can obtain a rough estimation, relying on the well-known equation describing the natural frequency of cantilever beams fixed constrained at one end [6, 14-18]. The

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terms used in the mathematical model are measured quantities (frequency, mass), data taken from product specifications [13], and calculated parameters relying on both measured and given quantities, introduced in (1):

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{\frac{3EI}{L^3}}{m}}, \quad (1)$$

where: f_n [Hz] – natural frequency; k [N/m] – bending stiffness constant; m [kg] – beam total mass; E [N/m^2] – Young's modulus; I [kg·m^2] – the moment of inertia of beam cross-section; L [m] – beam length.

The data provided in the product specifications [13] is summarized in Table 1. The piezoelectric cantilever is clamped in the rear clamp position on the support [6], ensuring maximum effective length and higher amplitude. This position is also beneficial for the lower working frequencies of the vibrating rotary machine targeted because the mass required for tuning is smaller, and the risk of damaging the brittle piezoceramic material is reduced significantly.

Table 1

Stiffness and effective mass of PPA-4011

Clamping location	Effective stiffness k_{eff} [N/m]	Effective mass m_{eff} [g]
Rear clamp	1934.93	1.457
Middle clamp	4125.55	1.480
Front clamp	5534.45	1.936

However, the specifications are unreliable since the resonant frequency corresponding to these parameters is 183.41 Hz in the rear clamp, rounded as 183 Hz in the datasheet [13]. There is a quite significant difference from the resonant frequency $f_r \cong 208.62$ Hz that we obtained in real, which is furthermore damped by an intermediate elastic layer. Hence, assuming the correctness of the effective mass and using relation (1), we recalculated the real effective stiffness, k_{real}, corresponding to the real resonant frequency

$$k_{real} = m_{eff} \cdot (2\pi f_r)^2 \Rightarrow k_{real} = 2503.4\ \frac{\text{kg}}{\text{s}^2}. \quad (2)$$

The piezoelectric cantilever was aimed to resonate at a tuned frequency of ≅ 83 Hz, measured in [10] and afferent to the vibrations of compressor's male rotor. Using relations (3) and (4), we calculated the necessary tip mass, m_{tip}

$$f_t = \frac{1}{2\pi}\sqrt{\frac{k_{real}}{m_{eff} + m_{tip}}}, \quad (3)$$

$$m_{tip} = \frac{k_{real}}{(2\pi f_t)^2} - m_{eff} \Rightarrow m_{tip} \cong 7.7\ \text{g}, \quad (4)$$

where: f_t [Hz] – tuned frequency; k_{real} [N/m] – real effective stiffness; m_{eff} [kg] – effective mass, and m_{tip} [kg] – tip mass.

3. EXPERIMENTAL TESTS

Most often, simulations can spare much time and material costs for experimental testing. Moreover, we can also derive the safe or optimum working conditions and warnings about conditions that a piezoelectric element should rather not be exposed to (such as temperature, stress, electric and mechanical loads, *etc.*). The most important parameters influencing the actual behavior should be well-known to obtain reliable results before proceeding to experimental testing on an industrial compressor.

In other cases, however, it is simpler, faster, and much more helpful to carry out experimental tests if physical components are available, especially if a practical application is sought. The source, precisely the location targeted for placing the PEH, should also be evaluated to see if it fits within the supported ranges of the critical environmental parameters, which can negatively influence or damage the piezoelectric material.

The experimental setup presented in Fig. 2 is typical for laboratory evaluation of piezoelectric devices [19].

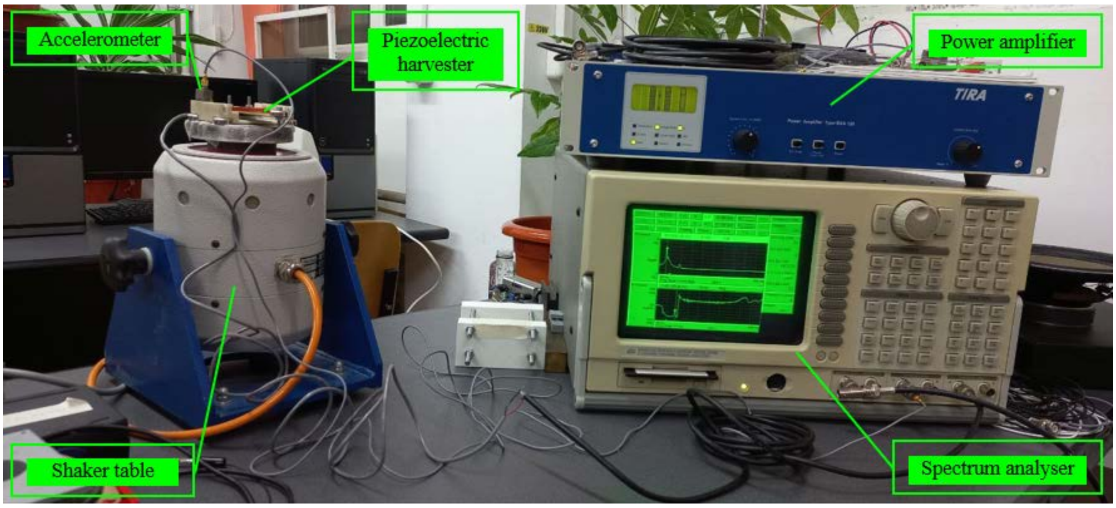

Fig. 2 – Experimental setup

The experimental setup consists of the following main components:

- **Dynamic spectrum analyzer** with integrated functions generating capabilities and automatic fast Fourier transform (FFT);
- **Power amplifier** with high signal-to-noise ratio, sinusoidal output power (120 VA RMS), and signal amplification in a direct current of up to 20 kHz;
- **Electrodynamic shaker table**, driven by a swept sine signal generated from spectrum analyzer via the power amplifier and connected to analyzer output channel;
- **Piezoelectric energy harvesting system**, with the piezoelectric harvester, clamped on the support, which is attached to the shaker table with double-sided adhesive

tape. The terminal output is connected through a cable with a BNC jack to the input channel 2 of the analyzer;

- **A triaxial accelerometer**, placed on the shaker table, is used as a reference input signal for the vibration amplitude, which is connected to input channel 1 of the analyzer. The sensitivity of the Brüel&Kjær 4508-001 accelerometer used is 1 mV/m/s^{-2}.

It must be mentioned that no experimental measurements on a piezoelectric harvester can maintain the same conditions. Introducing an intermediate elastic layer between the support and the mobile platform of the shaker table renders an unknown and variably increasing elasticity through the reuse of the double-sided adhesive tape. This alone can introduce frequency variations of several Hz or a few tens of Hz.

In previous research [5], it was observed that tightening the two screws, holding the beam onto the support through the clamp bars, with a quarter of a turn (90°), would manifest in an increase of the resonant frequency with 15-20 Hz.

Before placing the PEH on the compressor targeted as the source for vibration energy harvesting, laboratory tests must be conducted. The mounting on the compressor unit will be more rigid, employing the four magnets already provided and screwed onto the corners of the support. The compressor unit housing is made of cast iron, hence a ferromagnetic material, unlike the aluminum mobile platform of the shaker table. Therefore, magnetic clamping is possible and shall be exploited due to higher clamping stability compared to the adhesive tape, as well as because a screw mount cannot be used, as holes cannot be drilled in the compressor housing.

3.1. EXPERIMENTAL TESTS WITHOUT TIP MASS

The accelerometer is an Integrated Circuit Piezoelectric (ICP) type, having a built-in preamplifier. Hence an ICP power supply type was activated for channel 1 of the spectrum analyzer which is the input from the accelerometer. The shaker table is driven with a swept-sine excitation signal generated from the spectrum analyzer.

The output voltage is measured considering the input R||C impedance of 1 MΩ || 50 pF of the signal analyzer. Since the resonant frequency is low, the capacitance influence is negligible.

The first set of PEH experiments without inertial mass (Fig. 3) sought to obtain the frequency response, focusing on the resonant frequency and the corresponding peak voltage output. Knowing the resonant frequency is an essential first step for deriving the value of the tuning mass.

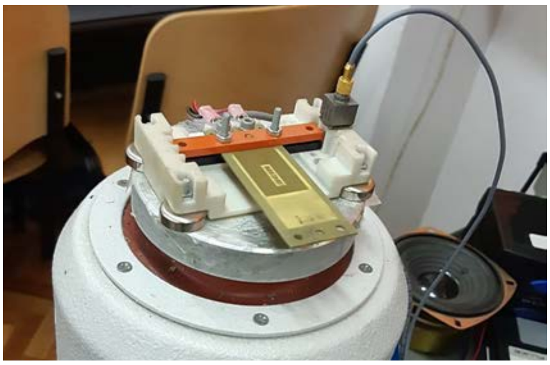

Fig. 3 – Piezoelectric cantilever with free tip

A resonant frequency of 208.62 Hz was measured (Fig. 4), recording a 135.9 V/(m/s^2) peak voltage output, *i.e.*, 1.333 V/g. Channels A and B display the frequency and voltage response and, respectively, the phase of the piezoelectric transducer. The visualization channel of importance in this work is the upper channel A.

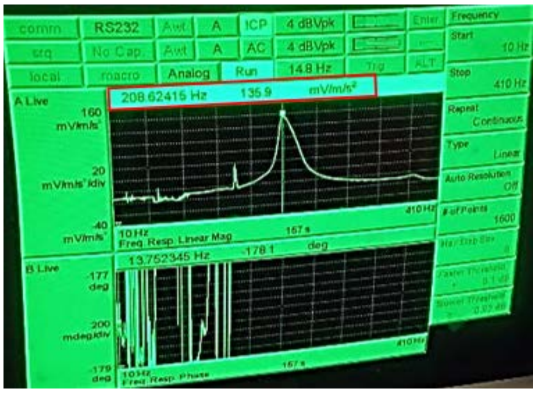

Fig. 4 – Voltage response of the piezoelectric harvester with free tip

The sinusoidal vibration input signal and the alternating voltage response of the PEH can be visualized in Fig. 5 on channels A and B, respectively. The input sinusoidal displacement applied to the shaker table and measured with the accelerometer is shown on upper channel A. The time response of the PEH is displayed on channel B (lower display window).

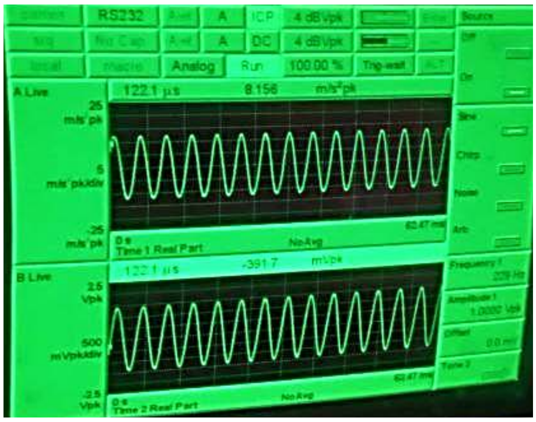

Fig. 5 –Time response of the PEH with free tip

3.2. EXPERIMENTAL TESTS WITH TUNING MASS

The tip mass used consisted of a magnet fastened with an M3 screw and nut, as in Fig. 6. The overall value of the elements forming the tip mass was weighted with a precision scale of 7.4 g.

Fig. 6 – Piezoelectric harvester and detail showing tip mass mounted

The resonant frequency obtained matched the desired f_t of 83 Hz, as shown in Fig. 7 below. A peak voltage output of 5.345 V/g from the piezoelectric harvester was recorded.

Fig. 7 – Voltage response of the piezoelectric harvester with free tip

4. **RESULTS AND DISCUSSION**

Evaluating the bare resonant frequency and the tuned lower frequency with a 7.4 g mass, a significantly improved electrical response is observed, summarized in Table 2. Adding the inertial mass results in an approximately 4 times increase in output peak voltage.

An important aspect that needs to be mentioned is that even though there is a remarkable improvement between the two peak voltages obtained, all three piezoelectric cantilevers purchased in 2018 have started to lose their piezoelectric properties. Comparing to the experimental tests conducted in 2018, when ~4.4 V/g was obtained with no tip mass [5], and to the tests in early 2020, when 3.280 V/g was observed in the same conditions with no mass [14], a descending trend is more than evident in the electric response.

Table 2

Experimental results

Tip mass	Resonant frequency f_r [Hz]	Voltage peak V_{pk} [V/g]
No tip mass	208.62	1.333
With 7.4 g mass	83.06	5.345

The tuned frequency is adapted to the electrical impedance of the analyzer. When turning on the compressor, we will consider the electrical circuit to be powered and an adequate ac-dc rectifying circuit and dc-dc converter [20,21] for multiple PEHs. This complicates the problem regarding both frequency shifting due to the electric components and voltage drops.

5. **CONCLUSIONS**

The working frequencies of the vibration source, a twin-screw compressor, have previously been measured experimentally, noticing the stability of the spectral component of the male rotor at around 83 Hz (± 5 Hz). The inertial mass that downshifts the piezoelectric harvester's fundamental frequency, measured at 208.62 Hz, to ~83 Hz is 7.4 g, provided with an elastic layer between the shaker table and the piezoelectric support.

Finer measurements of compressor vibrations need to be carried out. However, the laboratory experiments aim to form an idea about the tip mass required.

Fine-tuning to the source's frequency can only be realized on the test bench since the clamping method will be magnetic, therefore, less elastic than double-adhesive tape. A method to increase the resonance bandwidth shall also be implemented.

This study will be continued with a mathematical model and numerical simulations that aim to unveil the piezoelectric conversion's physics insights and the harvester's optimal adaption to its presumable electric load.

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