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Automated Measurement Set-Up for the Electro-Mechanical Characterization of Piezoelectric Harvesters

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Abstract—This paper presents an automated measurement setup for the electro-mechanical characterization of piezoelectric energy harvesters in cantilever configuration. The setup provides a mechanical stimulus to the harvester and concurrently acquires mechanical and electrical quantities to characterize the electro-mechanical properties of the device under test in open-circuit conditions. The setup, composed by an electrodynamic shaker, a waveform analyzer, and two laser-based positioning sensors, is fully controlled via MATLAB. The use of two laser heads allows to measure the movement of the base, so to automatically consider artefacts due to the non-ideal response of the electrodynamic shaker. The proposed measurement system is compatible with any generic piezoelectric-cantilever harvesters, and it can be exploited for advanced modelling techniques that requires extensive experimental data. The proposed measurement setup was validated through the characterization of a commercial Piezo Protection Advantage (PPA) transducer up to 300 Hz.

Index Terms—Piezoelectric devices, energy harvester, measurement set-up, frequency response

I. INTRODUCTION

Power supplies for sensor nodes play an important role in highly sensorized environments, such as in automotive applications. Every additional sensor requires expensive wiring to be deployed, and battery replacement may not be a viable option due to difficulties in reaching the sensor sites or the need for specialized operators [1]. In this context, energy harvesting is an interesting solution to explore non-critical sensing applications.

Specific automotive applications, like the sensorization of the tyres and wheels, are envisaging energy harvesting as a way to replace or sustain classical power sources. In energy harvesting applications, energy in the form of light, radiation, thermal gradients, and vibrations is converted into electrical energy by means of specific energy transducers exploiting various physical effects. However, most of these energy sources

may not be a viable option in automotive applications, due to closed spaces with no light, or the need to reduce RF emissions for EMI reasons, thus restricting the options for energy transducers. Vibrations represent a viable solution to power wireless sensors [2], [3].

In the context of vibrational energy harvesting, piezoelectric transducers represent a popular choice. Correctly modeling this type of transducer, including the non-linearities induced by electronic power converter interface circuits, is an important task. Widely adopted approaches for resonant piezoelectric harvesters exploit well-known electromechanical analogies, which result in equivalent circuits that can jointly model mechanical and electrical quantities [4]. An accurate model can predict the power harvested from known input vibrations, thus allowing the proper interfacing with power converters at the design stage. In order to identify lumped parameters of equivalent electromechanical circuits, mechanical and electrical measurements should be performed to assess relevant quantities [5].

Conventional parameter identification approaches normally rely on a few selected measurements to be performed in specific operating conditions, such as short-circuit currents, frequency sweeps, various speed or displacement of the inertial mass, etc. These approaches reach their limitation when more complex models are adopted, e.g., those based on machine learning to predict power in complex conditions [6]. When non-conventional modeling techniques are adopted, extensive training datasets may be required, posing the problem of automating the measurement procedures.

There are many systems in the literature capable to characterize piezoelectric devices for performance evaluation [7]–[11]. In particular, an automated approach for obtaining piezo harvester parameters is presented in [7]. The system can determine the resonance frequency and calculates the harvester's total efficiency. The test bench in [8] can measure resonance frequency, impedance, ideal load, displacement, output power, and other parameters at a fixed frequency and acceleration. In [11], an accelerometer is used to monitor the vibration of the device under test (DUT), and a single laser displacement

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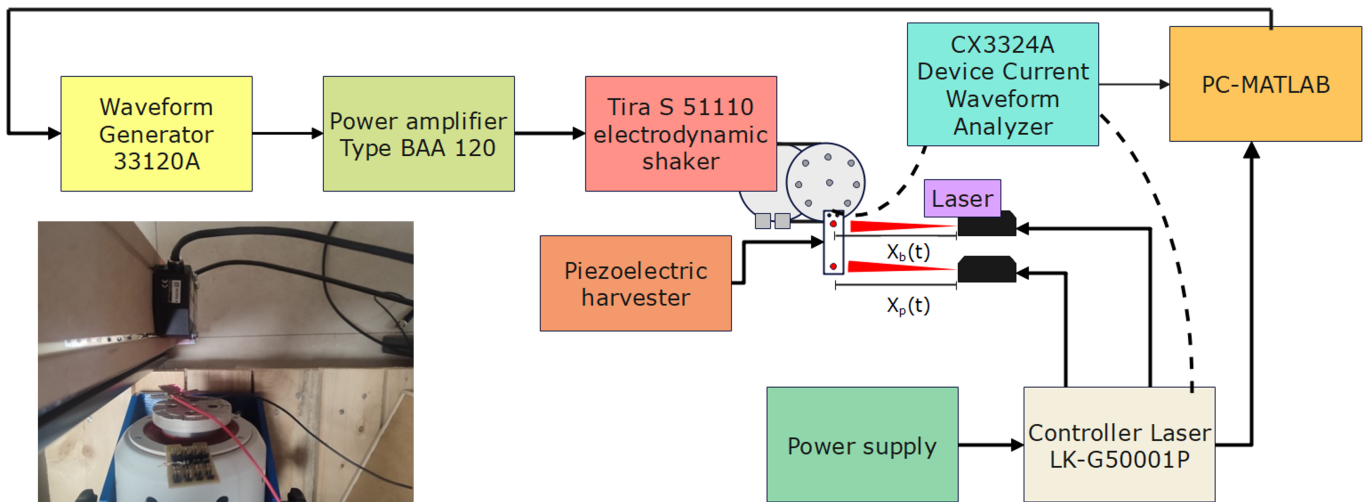


Fig. 1. Block diagram and photo (inset) of the electro-mechanical measurement set-up tailored to piezoelectric harvesters.

meter is used to measure the beam movement.

This paper presents a fully automated measurement system for the characterization of the mechanical and electrical properties of a piezoelectric harvesting devices in the frequency domain. The measurement system automatically synchronizes the acquisitions from the different instruments and takes into account the effects of the non-ideal response of the shaker. The article is organized as follows. Section II describes the proposed setup configuration and its operation, while Section III reports the experimental results obtained in the characterization of a commercial piezoelectric harvester. Conclusions are drawn in Section IV.

II. MEASUREMENT SETUP

A. Setup Configuration

The proposed measurement set-up is based on i) an electrodynamic shaker, which mechanically excites the device-under-test (DUT); ii) two laser-based sensors, for the measurement of the mechanical quantities; iii) a device current waveform analyzer, which acquires the electrical quantities. The block diagram of the system is shown in Fig. 1.

The excitation signal is generated by an arbitrary waveform generator (Agilent 33120A). Different excitation signals may be synthesized, depending on the target characterization required. In this work, however, only sinusoidal excitations will be implemented, as it is commonly done for piezoharvester characterization. The electrical excitation signal is amplified by the amplifier (Tira BAA 120) to realize a current signal suitable to drive the electrodynamic shaker (Tira S 51110), which converts the electrical signal into a mechanical vibration signal. The shaker is horizontally placed to apply a mechanical force in the perpendicular direction with respect to the force of gravity, allowing to neglect the effect of the latter on the measurement results. One edge of the piezoelectric DUT (the base) is fastened on the shaker by means of a custom 3D-printed support and fixing screws, so to transfer the mechanical

excitation unaltered from the shaker to the DUT. The other edge of the piezoelectric DUT (the tip) is left free to move. Two laser-based position sensors are used to acquire the mechanical quantities (mainly movement, displacement, and acceleration) at the base and at the tip of the DUT. The outputs of the laser heads are acquired by a controller (Keyence LK-G50001P) that communicates with the main PC via Ethernet. The lasers used (Keyence LK-H050) perform measurements with a linearity deviation of 0.02% of the full-scale (20 mm). In addition, the laser controller also synthesizes analog output voltages proportional to the vibration movement of the base and tip, and one of these voltage signals is acquired by the Keysight CX3324A Device Current Waveform Analyzer. Finally, the CX3324A is connected to the electrical port of the DUT and can perform current and voltage measurements. In the present configuration, only the output voltage signal v is acquired. The Keysight CX3324A Device Current Waveform Analyzer is equipped with 14-bit ADCs featuring an rms noise of 120 μV_{rms} (± 0.5 V range, full bandwidth).

Both the laser controller and the CX3324A operate at the sampling rate of 10 kSa/s. The whole setup is remotely controlled via MATLAB, so that the characterization is fully automated by a MATLAB script imposing the input sinusoidal excitation through the AWG and reading out the time-domain data from both the laser controller (at the mechanical port) and the CX3324A input channel (at the electrical port). The proposed measurement setup and methodologies are general and compatible with most piezoelectric harvesters in cantilever configuration. To validate the system, a rectangle-shaped Piezo Protection Advantage (PPA) transducer from Mide Technology in cantilever configuration (PPA-1014 [12]) has been used as the device under test (DUT).

B. Setup Operation

The spatial deflection of the piezoelectric cantilever, that is the measurement of the bending of the tip with respect

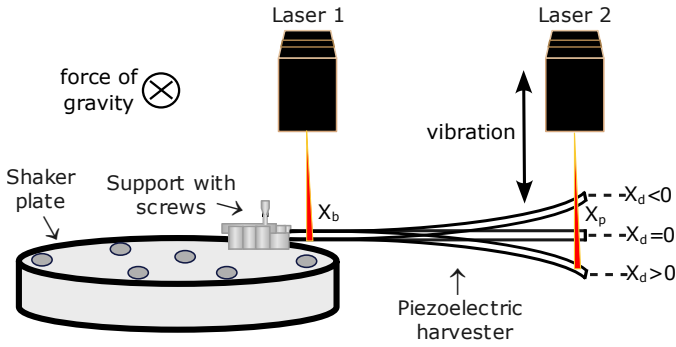


Fig. 2. Graphical representation depicting the shaker along with the positions assumed by the piezoelectric harvester when subject to a mechanical vibration.

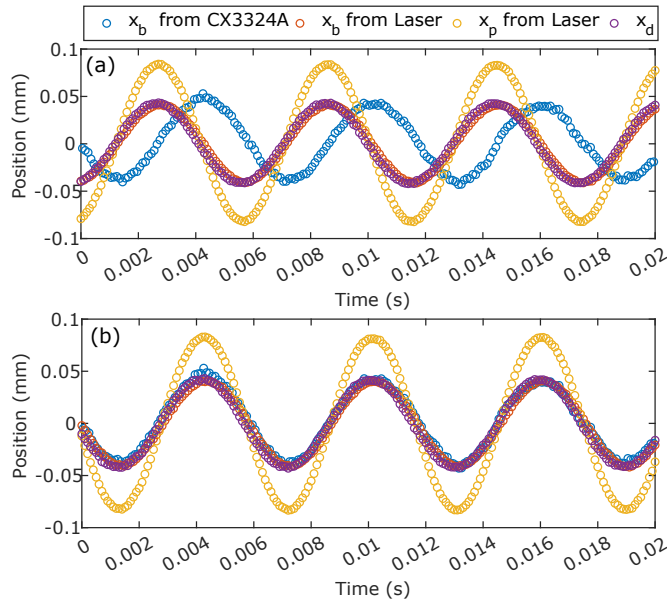


Fig. 3. Time-domain waveforms at the excitation frequency of 170 Hz from both the Keysight CX3324A and Laser controller before (a) and after (b) time-alignment.

to the base position, is indicated by $x_d(t) = x_p(t) - x_b(t)$, where $x_p(t)$ is the position of tip and $x_b(t)$ is the position of the base (see Fig. 2). Without any electrical input signal applied, the shaker stands still without any vibration. This position is taken as the reference one, for which $x_b(t) = 0$. As a consequence, also the piezoelectric DUT does not vibrate ($x_p(t) = 0$), resulting in the absence of deflection, namely $x_d(t) = 0$.

When the amplifier is turned on, the shaker vibrates and forces a sinusoidal oscillation to both the base and the tip of the piezoelectric DUT. The time-domain acquisitions in Fig. 3 show an excitation frequency of 170 Hz. Obviously, the tip shows a wider movement, as it is further away from the clamping point.

The acquisition from the laser position sensors can only be triggered by the user, therefore the time alignment between the laser-based measurements and the electrical measurements

acquired by the CX3324A cannot be directly imposed in hardware. As shown in Fig. 3a, the base position signal acquired by the laser controller and the base voltage signal acquired by the CX3324A are out of phase. To solve this issue, the base voltage signal is used to estimate the random delay between the two instrument and compensate for it at each operating regimes, as shown in Fig. 3b. The time-aligned waveforms can then be used in order to properly characterize the electro-mechanical response across frequency in terms of both amplitude and phase of the piezoelectric DUT.

III. EXPERIMENTAL RESULTS

The shaker was driven by a sine-wave, sweeping its frequency from 110 to 300 Hz. The main common characterization figures are reported in Fig. 4. Figure 4a shows the vibrational movement of the base that corresponds to the mechanical input given by the shaker. As known from the literature, the shaker cannot typically enforce a constant vibration at all frequencies, and may also suffer from the loading effect of the piezoelectric harvester, especially at its resonant frequency. This generally translates into a non-constant acceleration/mechanical force, as can be drawn from Fig. 4b, and has a spurious impact on the absolute movement of the tip.

The mechanical properties of the DUT are usually characterized by considering only the movement of the tip (Fig. 4c) while assuming the movement of the base as ideal. In this case, instead, we account for the movement of the base and calculate the actual displacement as $x_d(t) = x_p(t) - x_b(t)$ (see Fig. 4d). This technique allows to remove the non-idealities originated by the mechanical source, as can be seen in Fig. 4d, where the low-frequency behavior displayed in Fig. 4a-b is compensated for. Fig. 4e finally reports the open-circuit differential voltage measured at the electrical port.

Beyond the standard characterization, the proposed measurement setup allows to extract transfer functions, both in magnitude and phase. Fig. 5 reports the mechanical response $H_{db}(f_i) = x_d(f_i)/x_b(f_i)$ of the piezoelectric harvester evaluated as the transduction transfer function of the deflection x_d due to the input mechanical vibration of the base x_b . Fig. 6 shows the global transfer function $H_{vb}(f_i) = x_v(f_i)/x_b(f_i)$ of the system in open-circuit condition computed as the output voltage divided by the movement of the base. This characterization treats the measurement system as a whole, thus the non-ideal behavior of the shaker is mainly reflected as a distortion in the phase response.

The last transfer function, shown in Fig. 7, describes how a deflection x_d is transduced into a differential voltage across the piezoelectric DUT. The amplitude response $|H_{vd}(f_i)| = |x_v(f_i)|/|x_d(f_i)|$ is approximately constant before 220 Hz. The phase response of $H_{vd}(f_i)$ is approximately a straight line with a positive slope.

IV. CONCLUSION

In this work, we have proposed an automated measurement setup for the electro-mechanical characterization of piezoelec-

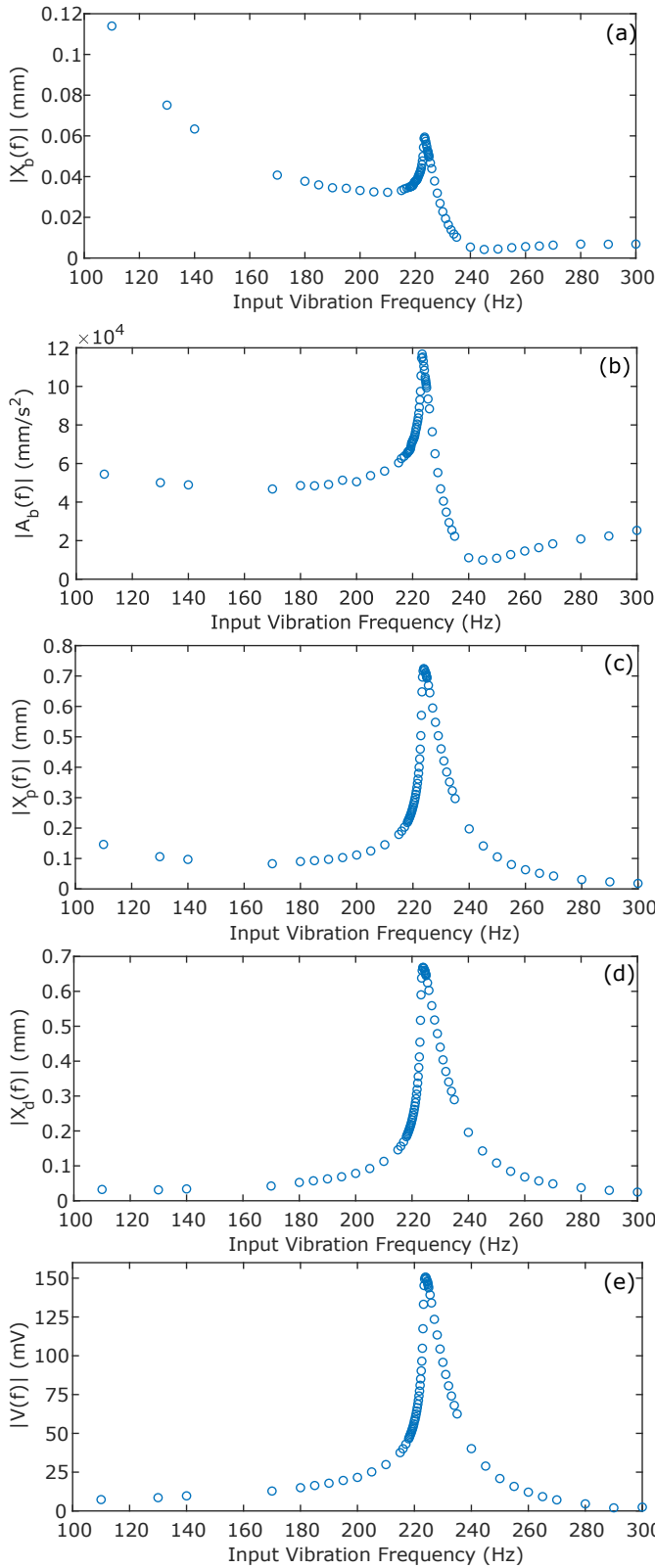


Fig. 4. Absolute amplitude response over frequency of the various quantities of interest. (a) DUT base position x_b ; (b) DUT base acceleration a_b ; (c) DUT tip position x_p ; (d) DUT deflection x_d ; (e) DUT output differential voltage v .

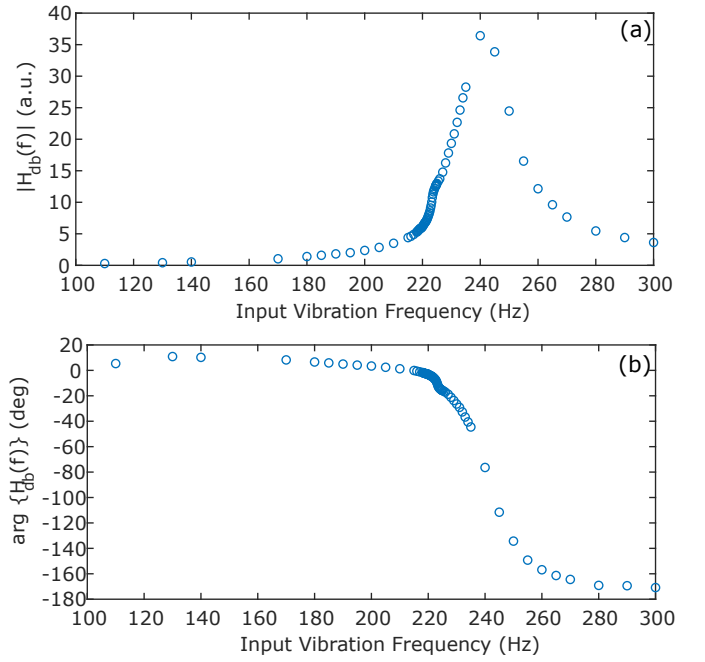


Fig. 5. Frequency response in both amplitude (a) and phase (b) calculated as the ratio between the DUT deflection x_d and the base vibration x_b .

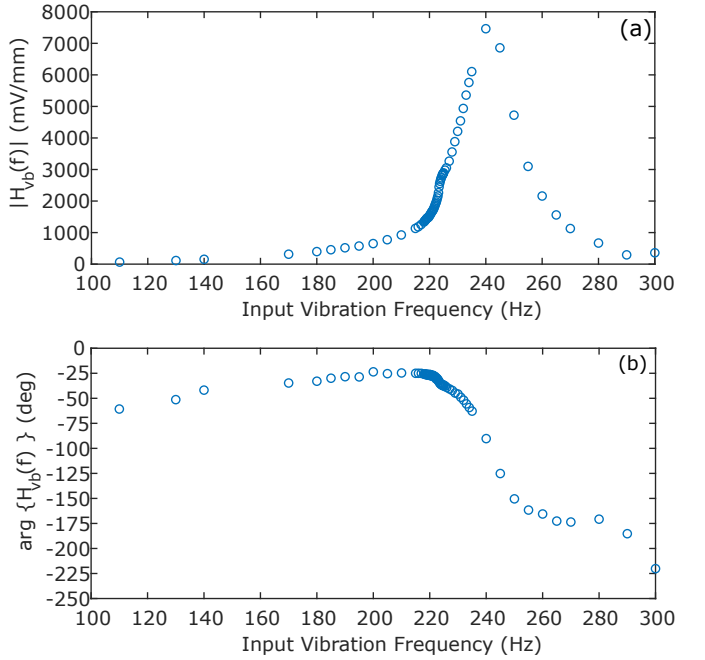


Fig. 6. Frequency response in both amplitude (a) and phase (b) calculated as the ratio between the output differential voltage v and the base vibration x_b .

tric harvesters. Such a setup allows to characterize, in a fully automatic way, the dynamic behavior of both electrical and mechanical quantities of interest. The frequency responses in both amplitude and phase can be extracted, providing the basis for fast and efficient measurement-based modeling of piezoelectric harvesters in cantilever configuration. The results shown are limited to open-circuit configuration but the setup

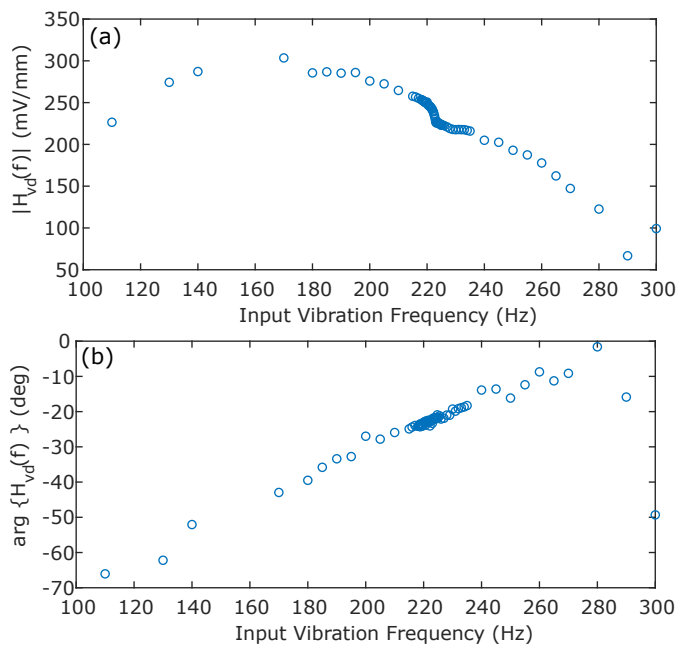


Fig. 7. Frequency response in both amplitude (a) and phase (b) calculated as the ratio between the output differential voltage v and the DUT deflection x_d .

can be easily extended to short-circuit configuration or specific loading conditions.

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