



ALMA MATER STUDIORUM  
UNIVERSITÀ DI BOLOGNA

ARCHIVIO ISTITUZIONALE  
DELLA RICERCA

Alma Mater Studiorum Università di Bologna  
Archivio istituzionale della ricerca

Wireless Telemetry for Characterization of Piezoelectric Energy Harvesters in Tires

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

*Published Version:*

*Availability:*

This version is available at: <https://hdl.handle.net/11585/950586.2> since: 2023-12-13

*Published:*

DOI: <http://doi.org/10.1109/SENSORS56945.2023.10325316>

*Terms of use:*

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).  
When citing, please refer to the published version.

(Article begins on next page)

# Wireless Telemetry for Characterization of Piezoelectric Energy Harvesters in Tires

Cinzia Tamburini <sup>1</sup>, Matteo Pizzotti <sup>1</sup>, Leena Ryyänen <sup>2</sup>, Mika Penttilä <sup>2</sup>, and Aldo Romani <sup>1</sup>

<sup>1</sup>Advanced Research Center on Electronic Systems, University of Bologna, Cesena, Italy

<sup>2</sup>Nokian Tyres Plc, Department of Products and Innovations, Nokia, Finland

aldo.romani@unibo.it

**Abstract**—In order to design electronic systems and circuits powered by mechanical energy harvesting in novel applications, it is essential to obtain information about electrical quantities related to the transducer like voltages, currents, and power in realistic operating conditions. However, in some cases, e.g. in tires, transducers and circuits are not accessible, and it is difficult to predict theoretically or numerically the exact values of the above mentioned quantities. To overcome this limitation, this paper presents the design of a wireless telemetry circuit capable of measuring and acquiring open-circuit voltage, short-circuit currents, and static power transfer characteristics from piezoelectric transducers. The circuit was tested in a commercial tire on a drum test machine at different speeds and axial loads. The characterization under these conditions of a commercial piezoelectric harvester suitable for use in tires is reported.

**Keywords**—telemetry; piezoelectric transducers; energy harvesting; tires.

## I. INTRODUCTION

Characterizing energy harvesting transducers in realistic conditions is of utmost importance in view of the design of successful energy autonomous applications. A careful estimation of the involved power levels, the developed voltages and currents is in general among the first and most important steps to accomplish in system design. Since energy budgets are often limited, it is essential to understand the actual operation and performance of a selected energy transducer in realistic conditions [1] [2]. When energy budgets are constrained, a precise sizing of power conversion and management electronics based on realistic data is priority. Among the potential applications of energy harvesting for self-supplied sensors, we can include the development of smart tires [3], which can host inside the pressurized area a plethora of sensors (e.g. tire pressure monitoring systems (TPMS), temperature, motion, etc.) to acquire relevant information during driving and contribute to safety and energy savings. Normally, this type of sensors are battery-powered, which implies the progressive discharge and aging of the battery, due to the intrinsically harsh environment. Tires are tough environments to host electronics, characterized by high pressures, intense forces and deformations, variable temperatures. Moreover, such systems are sealed inside the tire, and electrical connections outside the tire are not viable.

Then, wireless links are required to extract any type of information, either from sensors or for on-field testing purposes.

This paper presents a wireless telemetry system including a series of measurement circuits for real-time monitoring of piezoelectric transducers placed inside tires. The telemetry system acquires in realistic operating conditions different relevant quantities to assess power budgets and to aid the design of associated electronics.

## II. METHODOLOGY

In the envisaged operation, a flexible piezoelectric transducer (PT) [4] is attached to the inner liner of a tyre and is subject to all the associated deformations during motion. Then, it becomes important to acquire relevant quantities during the motion. For this purpose, the wireless telemetry system is designed to perform the following types of measurements, which provide significant data, not retrievable otherwise:

- 1) acquisition of voltage waveforms, e.g. the open-circuit voltages;
- 2) acquisition of short-circuit current waveforms, e.g. the charge displacement caused by deformations;
- 3) construction of the static power transfer characteristics in association with an electronic power extraction interface.

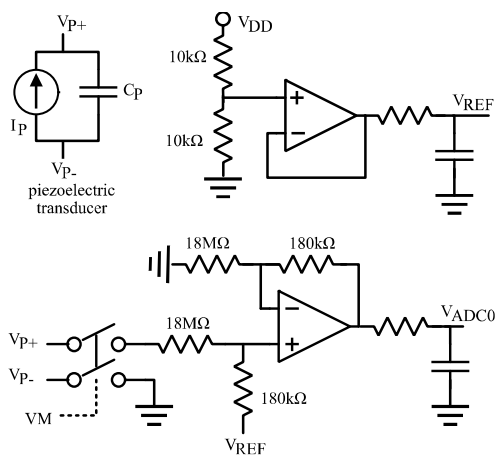


Fig. 1. Equivalent circuit of the piezoelectric transducer and schematic of the analog conditioning circuit for voltage acquisition.

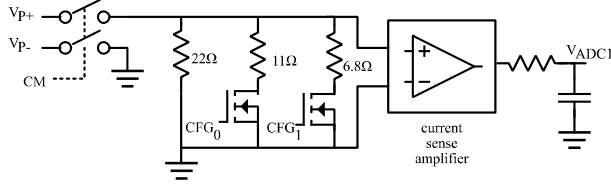


Fig. 2. Analog conditioning circuits for short-circuit current waveforms acquisition

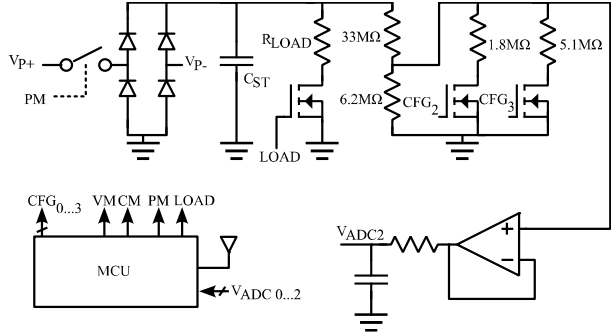


Fig. 3. Microcontroller unit and conditioning circuits to determine static power transfer characteristics.

In order to drive acquisition and enable wireless remote control and data transfer, a microcontroller unit (MCU) equipped with a radio module was adopted. Solid-state relays were used to connect and isolate specific dedicated measurement sub-circuits, to prevent interactions affecting the accuracy of the measurement.

### III. MEASUREMENT CIRCUITS

#### A. Open-circuit voltage waveforms

PTs in tires can generate alternating voltages in the order of tens to hundreds of V. For this reason, the voltage measurement circuit (Fig. 1) is designed to acquire time waveforms with voltages up to  $\pm 160$  V. Two solid-state relays (SSRs) are used to connect the terminals  $V_{P^+}$  and  $V_{P^-}$  of the PT to  $V_{IN}$  and ground, respectively. A  $V_{DD}/2$  reference voltage is generated with precision resistors and an analog buffer based on the OPA342UA opamp. An amplifier stage based on the OPA342UA scales the  $\pm 160$  V signals down to a 0 to  $V_{DD}$  range compatible with the analog-to-digital converter (ADC) of the MCU. An RC filter reduces high frequency noise.

#### B. Short-circuit currents

A PT operated in forced displacement mode can be modelled as a current source  $I_P(t)$  with a parallel capacitance  $C_P$  (Fig. 1). Shorting the transducer and measuring the corresponding current determines  $I_P(t)$ . As shown in Fig. 2, This is accomplished by connecting  $V_{P^+}$  and  $V_{P^-}$  with two SSRs to a grounded shunt resistor. Two parallel PMV15UNEA MOSFET switches with proportionally scaled series resistors allow to set multiple measuring ranges. A bidirectional ultra-precise INA190 current sense amplifier converts the current signal into a single-ended voltage fed into the MCU ADC. The measured current range is programmable from  $\pm 3$  mA up to  $\pm 18$  mA.

#### C. Static Power Transfer Characteristic

In this measurement (Fig. 3) a SSR connects the PT to a storage capacitor  $C_{ST}$  through a full bridge rectifier, which generates the rectified voltage  $V_R(t)$ . A PMV15UNEA load switch is controlled by the MCU, which also samples the voltage on  $C_{ST}$  through a programmable high-impedance resistive divider and an analog buffer based on the OPA342UA: when the switch is open, the rectifier charges  $C_{ST}$ , when the switch is closed the load discharges  $C_{ST}$ . The MCU can apply a user-programmable output bias voltage  $V_{BIAS}$  by determining two switching thresholds  $V_H = V_{BIAS} + \Delta V$ , and  $V_L = V_{BIAS} - \Delta V$ , at which the load is connected and disconnected, respectively. The hysteresis amplitude  $\Delta V$  is user-programmable and should be sufficiently small. The MCU then records the switching times  $t_{H,i}$  and  $t_{L,i}$  at which the two above thresholds are reached along with the corresponding actual voltages  $V_{H,i}$  and  $V_{L,i}$ , where  $i = 0, 1, \dots, N-1$ , and  $N$  is the number of performed switching cycles. Then, for every bias point, the average extracted power through the  $N$  cycles is computed as:

$$P(V_{BIAS}) = \frac{1}{2} C_{ST} \frac{\sum_{i=0}^{N-1} (V_{H,i}^2 - V_{L,i}^2)}{\sum_{i=0}^{N-1} (t_{H,i} - t_{L,i})} \quad (1)$$

This measurement is repeated for different values of  $V_{BIAS}$ . The user can configure the spanning range for  $V_{BIAS}$  up to 100V, the amplitude of hysteresis  $\Delta V$ , and the number of switching cycles  $N$ .

### IV. CONTROL CIRCUITS

The core of the telemetry system (Fig. 3) is an Arduino Nano RP2040 Connect MCU, which implements a Wi-Fi access point with its embedded wireless transceiver, to allow laptops and smart phones to connect. A web server running on the MCU hosts the main control panel that allows to select the type of measurements and their configuration parameters. Acquired data can be viewed or downloaded locally. Omron G3VM-201DR SSRs are used to connect and disconnect the individual measurement sub-circuits.

### V. EXPERIMENTAL VALIDATION

The implemented telemetry circuit is shown in Fig. 4. Experimental tests were conducted on a Nokian Tyres Hakka Green 3 205/55-R16 tyre. A rubber foot with a M6 thread was glued to the inner liner of the tyre with cyanoacrylate to mount the telemetry circuit. A 9V battery and an ultra-low leakage high-voltage polypropylene capacitor were attached on the inner liner of the tyre (Fig. 4). A thin double-sided adhesive tape was used to attach different Smart Material MFC flexible 300  $\mu$ m thick piezoelectric transducers [4]. Tyres were then mounted on their rims, inflated to a pressure of 3 bar, and mounted on a drum test machine (Fig. 4) applying an axial load and different rotation speeds.

In a first set of experiments, the Wi-Fi telemetry system acquired open-circuit voltage waveforms from a

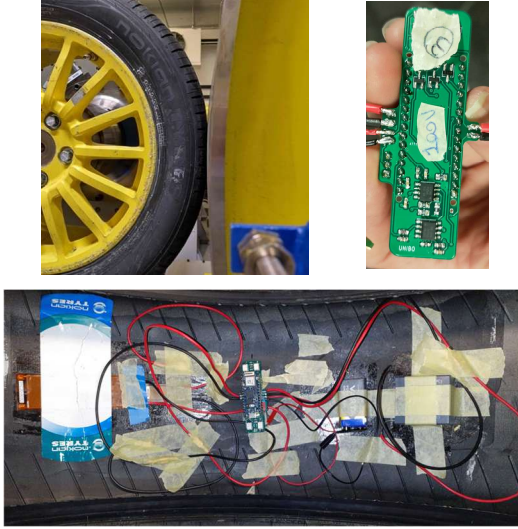


Fig. 6. The drum test machine used for experiments (top left); a picture of the PCB of the telemetry system (top right); an example of experimental setup.

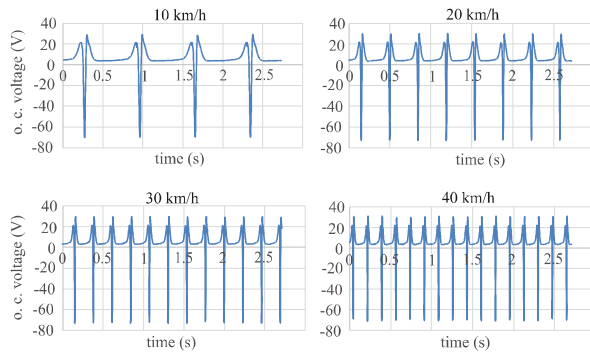


Fig. 7. Acquisition of open-circuit voltages from a Smart Material MFC 8514-P2, with 3 kN axial load, at different speeds. Units are V and s, respectively for y and x axes.

Smart Material MFC 8514-P2 at different speeds, with a 3 kN axial load (Fig. 5). Starting from 10 km/h, the peak amplitude of voltage reaches steadily 70V with faster waveform development as speed increases. Tire deformation depends only on rotation angle and preserve almost the same intensity at different speeds, confirming operation of the PT in forced displacement mode. It can also be observed that voltage waveforms are coherent with tire stress distributions shown in [5] [6]. Moreover, the regularity of voltage waveforms paves the way towards the adoption of highly effective synchronized-switch interfaces [7].

In a second set of experiments, current waveforms in a short circuit configuration of the PT were acquired. Fig. 6 reports the results obtained with a Smart Material MFC 8514-P2 transducer with an axial load of 3 kN. Once again, the shape of the waveform is preserved at different speeds, with observable increases in amplitude and faster development over time. Peak currents range from 1.2 mA at 10 km/h to approximately 6 mA at 40

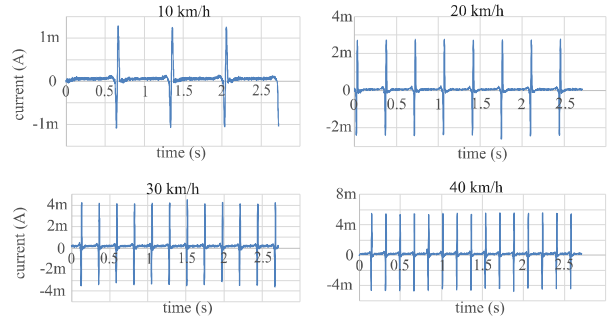


Fig. 4. Acquisition of short-circuit current waveform from a Smart Material MFC 8514-P2, with 3 kN axial load, at different speeds.

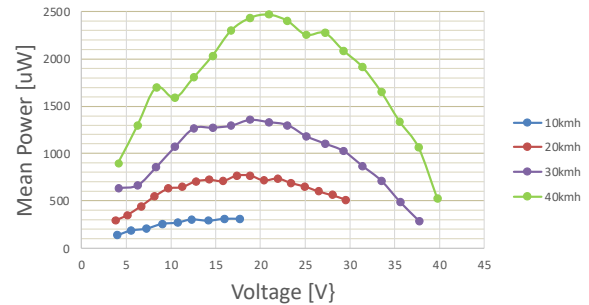


Fig. 5. Power transfer characteristics of a Smart Material MFC 8514-P2 connected to a rectifier, at different speeds, with 3 kN axial load

km/h. It can also be observed that waveforms are coherent with open-circuit voltage waveforms of Fig. 7, since current reaches 0A in correspondence of voltage peaks.

In a third set of experiments, a set of power transfer characteristics of a Smart Material MFC 8514-P2 was extracted by the telemetry system (Fig. 7) with an axial load of 3 kN, at different speeds, and for output bias voltages up to 40V. The test circuit includes rectifier and storage capacitor. The maximum power ranges from approximately 300  $\mu$ W at 10 km/h, up to almost 2.5 mW at 40 km/h. The maximum power point is located in a relatively flat region of the power curve, between 15 V and 25 V, which should be the bias applied by any effective power converter.

## VI. CONCLUSION

Data acquisition in realistic conditions provides precious information to design electronic power conversion interfaces and support system design. The operating range of Wi-Fi makes the system suitable for on-field characterizations, e.g. on test cars, and in all applications where wired connections to instrumentations are unfeasible.

## ACKNOWLEDGMENT

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No 101007247. The JU receives support from the European Union's Horizon 2020 research and innovation programme and Finland, Germany, Ireland, Sweden, Italy, Austria, Iceland, Switzerland.

## REFERENCES

- [1] R. Rantz and S. Roundy, "Characterization of Real-world Vibration Sources and Application to Nonlinear Vibration Energy Harvesters," *Energy Harvesting and Systems*, vol. 4, no. 2, pp. 67-76, 2017.
- [2] X. Ma, S. Bader and B. Oelmann, "Characterization of Indoor Light Conditions by Light Source Classification," *IEEE Sensors Journal*, vol. 17, no. 12, pp. 3884-3891, 2021.
- [3] Nokian Tyres. [Online]. Available: <https://www.nokiantyres.com/heavy/innovation/nokian-tyres-intuitu/>. [Accessed 16 06 2023].
- [4] Smart Material GmbH. [Online]. Available: <https://www.smart-material.com/EH-product-mainV2.html>. [Accessed 16 06 2023].
- [5] M. Germer, U. Marschner and A. Richter, "Energy Harvesting for Tire Pressure Monitoring Systems from a Mechanical Energy Point of View," *IEEE Internet of Things Journal*, vol. 9, no. 10, pp. 7700-7714, 2022.
- [6] C. R. Bowen and M. H. Arafa, "Energy Harvesting Technologies for Tire Pressure Monitoring," *Advanced Energy Materials*, vol. 5, no. 7, p. 1401787, 2015.
- [7] Y. C. Lo and Y. C. Shu, "Self-powered SECE piezoelectric energy harvesting induced by shock excitations for sensor supply," *Mechanical Systems and Signal Processing*, vol. 177, p. 109123, 2022.