# Study on a Telemetric System that Works with an Inkjet-printed Resistive Strain Gauge

M. Bona, E. Sardini, M. Serpelloni
Department of Information Engineering
University of Brescia
25123 – Brescia – Italy
mauro.serpelloni@unibs.it

B. Andò, C. O. Lombardo
Dept. of Electric, Electronics and Computer Engineering
University of Catania
95127 – Catania – Italy
bruno.ando@dieei.unict.it

***Abstract*—Measuring strain is a task frequently required in many applications and, often, measurement devices have to adopt technologies that respect specific requirements, especially concerning power supply and transmission of information. In particular, the exploitation of wired solutions or batteries has several problems or it should be avoided in harsh environments. A valid answer to these issues is provided by telemetric systems, which consist of a reading unit that communicates with a passive sensor through the magnetic field established between two inductors connected to these components. The present work describes a study carried out on a telemetric system that has some elements of novelty with respect to the major part of those found in the literature. In fact, it operates with a resistive strain gauge realized through the innovative technology of inkjet printing on a flexible substrate. This permits to introduce advantages relating to design variability and low production cost of the components. Experimental tests were conducted in order to characterize the strain gauge and analyze overall system frequency behavior. Preliminary achieved results are satisfying, highlighting the possibility to measure telemetrically the strain from an inkjet-printed resistive sensor.**

***Keywords—impedance measurement; inkjet printing; strain gauge; telemetric system***

## I. INTRODUCTION

Strain measurement plays a crucial role in a great number of applications. Firstly, Structural Health Monitoring (SHM) can take advantage of it by gathering useful information about the conditions of different systems, in order to prevent possible damages that could lead to their failures [1]. Examples range from the assessment of structural integrity of buildings [2] to automotive area, measuring tire strain to enhance vehicle reliability [3]. In fact, avoiding failures by prevention becomes very important for individual safety issues and because of their increasing costs [4]. Then, cases in which strain is monitored are reported even in medical field. For instance, a wireless sensor for detecting the deformation of orthopedic implants is presented in [5]; a system designed to control bladder volume in patients who suffer from problems of urinary incontinence is described in [6], while an implanted device realized for detecting bone strain is illustrated in [7].

However, a device able to be effective in performing such tasks often has to satisfy specific requirements, especially dealing with power consumption and transmission of information. In fact, wired solutions are obviously unsuitable when measurement environment has to be kept isolated from the outside, or when measuring system has to be implanted. On the other hand, using wireless technologies implies the adoption of proper strategies to power the device in order to assure its long-term performance [8]. Furthermore, costs have to be maintained low enough to permit its wide exploitation.

A viable low power and cheap answer to all the above-mentioned aspects is represented by telemetric systems. They consist of a reading module connected to an inductor, and a sensing unit, simply a passive sensor, joined to a second inductor. The former supplies the latter by inducing a magnetic field that couples the two inductors. In the same way, it receives measurement data from the sensor wirelessly and treats the corresponding signals with a proper conditioning electronics. Therefore, neither batteries nor active circuits are requested inside the measurement environment for system operation. Most of the papers reported in the literature, like [8-9], describe devices that exploit the shift of the resonant frequency of a LC oscillator circuit, due to a strain variation. In this way, measuring such point allows to obtain the desired quantity, thanks to a relation between them. On the contrary, very limited works focus their attention on telemetric systems that operate with passive sensors relying on a resistive transduction principle. In [10-11], we started working on modeling such devices, aiming at extending measurement capabilities of telemetric systems, currently limited to the use of capacitive [8] and inductive [9] sensors.

Although the major part of electronic components is realized through silicon-based techniques, research is addressing many efforts in the innovative technology of inkjet printing [12]. Through its process, a suitable printer deposits droplets of a functional ink directly on a substrate of a proper material, according to a sequence, established by a digital image, which permits to create the printed electronics. Unlike traditional methods, several materials can be deposited in a unique process stage. Therefore, a number of additional steps can be cut [13]. This permits the rapid prototyping and batch production of devices characterized by high space resolution, good reproducibility and low manufacturing costs [14]. Another interesting aspect regards the possibility of printing on flexible substrates, leading to instruments that fit perfectly to working surfaces of various shapes. Examples cover different components, like Radio Frequency Identification (RFID) tags [15], antennas [16] and sensors [12,14,17-18].

In a telemetric system, passive components can be realized with such technology. For instance, a printed LC sensing circuit designed for this purpose is described in [19]. Considering all the previous aspects, this paper presents a telemetric device that has some peculiarities with respect to those cited in the past works. In fact, it combines the operation with a resistive strain gauge and the feature that such sensor is inkjet-printed on a flexible substrate, like those reported in [14,18]. First of all, its parts, i.e. coupled inductors and printed strain gauge, will be described. Afterwards, experimental tests carried out for sensor characterization and frequency analysis of the whole system will be illustrated, by showing the used real apparatuses and providing the achieved results.

## II. Telemetric System Description

The proposed telemetric device consists of a sensing circuit made of a printed strain gauge and an inductor (which will be called sensing's) magnetically coupled with the inductor connected to a readout unit (named readout's). Fig. 1 illustrates the conceptual scheme of the overall system.

### A. Coupled Inductors

Inductively coupled inductors are both planar and present a square shape. They were realized through printed circuit board (PCB) techniques. They are shown in Fig. 2. Readout inductor, on the left in this figure, has 28 windings, whose width is 150 µm and which are at a distance of 300 µm from each other. External side is 50 mm long, while the internal one has a length of 27 mm. Sensing inductor, on the right, has 27 windings. Width and distance are equal to 200 µm and 250 µm, respectively. Internal side is 5 mm long, while outer side matches readout inductor's inner one. In this way, if inductors are kept parallel and coaxial when telemetric device is operating, then parasitic capacitance generated when coupling their windings has a very low effect on the entire system [20].

Inductors can be represented by an equivalent circuit that consists of the series between an inductance $L_{ser}$ and a resistance $R_{ser}$, which is in parallel with a capacitance $C_{par}$ [20]. These parameters were measured with the aid of an HP4194A impedance analyzer. Table I lists their values. In addition, a commercial capacitor of about 560 pF was inserted in parallel to sensing inductor in order to reduce its resonant frequency, allowing the coupling with readout's.

### B. Inkjet-printed Resistive Strain Gauge

Used printed sensor is shown in Fig. 3. It was designed with the aid of a CAD software tool and it was realized with a low cost inkjet printer working with a silver nanoparticle-based ink, i.e. Metalon® JS-015, produced by NovaCentrix.

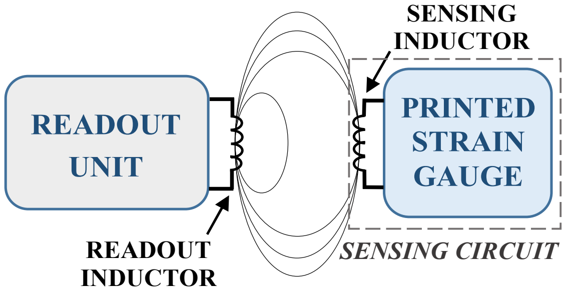


Fig. 1. Conceptual scheme of the proposed telemetric system.

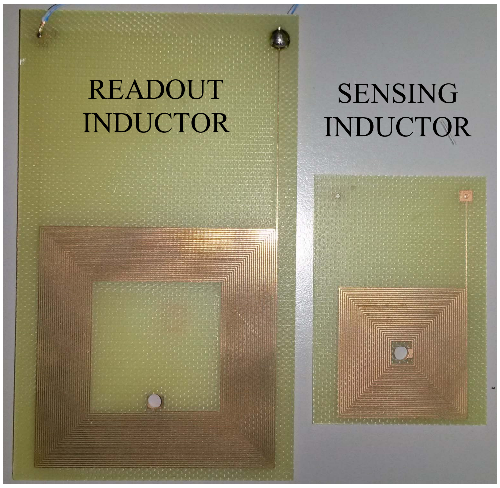


Fig. 2. Readout and sensing planar inductors.

TABLE I. Inductors' Equivalent Circuit Elements

| Element | Measured Value | |
|---|---|---|
| | *Readout inductor* | *Sensing inductor* |
| $L_{ser}$ [µH] | 47.73 | 11.64 |
| $R_{ser}$ [Ω] | 35.33 | 9.35 |
| $C_{par}$ [pF] | 3.31 | 2.08 |

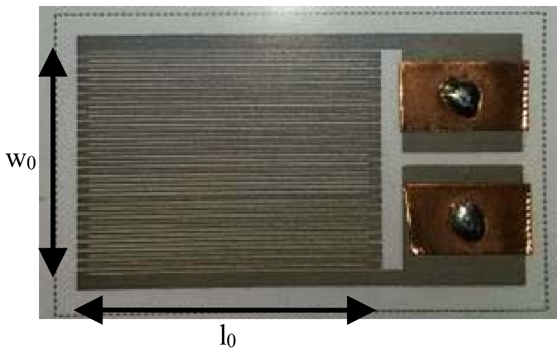


Fig. 3. Resistive strain gauge realized through inkjet printing technologies on a flexible substrate.

Its patterns were reproduced on a flexible 200 µm-thick substrate made of Polyethylene terephthalate (PET). Characteristics of considered ink and PET are reported in [14]. Referring to Fig. 3, resistive strain gauge has a set of tracks of length at rest $l_0$ of 27 mm, while its total width $w_0$ is equal to 20 mm. Furthermore, specific areas for electric contacts were made on the other edge, on the right in Fig. 3. Output resistance at rest, measured with an Agilent 34401A digital multimeter, is equal to about 2.3 kΩ.

## III. Strain Gauge Characterization

Printed strain gauge, separated from the planar inductors, was characterized in the first step of the presented study, in order to obtain some indications about its behavior when deformed and the corresponding gage factor.

## A. Experimental Setup and Folllowed Measurement Protocol

Characterization was performed through traction tests along strain gauge's longitudinal axis. Sensor edge with the electric contacts was kept fixed, while the other one was attached to a support driven by a micrometric screw having a resolution of 10 µm and exerting a pulling force. Fig. 4 provides an image of the fixing apparatus. In addition, a digital microscope, having a resolution of 2 Megapixel and communicating directly with a Personal Computer (PC), was positioned perpendicularly to the plane of strain gauge's PET substrate as an aid for evaluating the occurring actual deformation. Finally, sensor's terminals were attached to the probes of 34401A multimeter, connected to the same PC acquiring the output signal thanks to a LabVIEW program.

Tests were conducted as follows. Micrometric screw acted on the mobile support, elongating the sensor at regular strain intervals of about 0.25% of its length at rest, until a deformation equal to about $0.01l_0$ was reached. Actual strain was assessed through virtual markers placed on the images provided by the microscope. An example of such a view is given in Fig. 5. At the same time, output resistance value was detected by 34401A multimeter, with a period of 3 s, and saved by the PC.

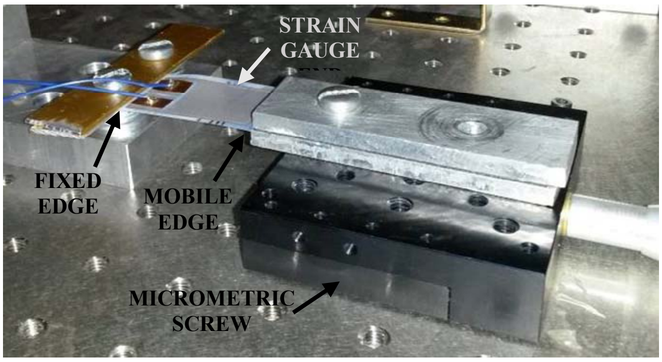


Fig. 4. Fixing apparatus adopted for strain tests.

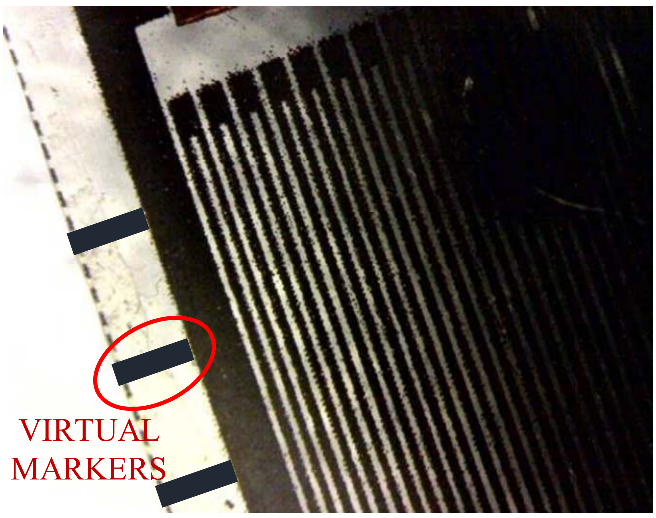


Fig. 5. Example of an image obtained with the digital microscope.

## B. Results and Discussion

Fig. 6 and Fig. 7 show the results obtained from the described analysis. They are sensor response over time and its characterization curve, respectively. Fig. 6 clearly highlights how output resistance changed when applying a load through the micrometric screw. Average detected variation is about 20 Ω for each strain step. Furthermore, sensor response is fast. Slight decreases in trend are probably due to PET relaxation. Fig. 7 represents these values as function of strain data found from reading the screw scale and verified through the visual markers on microscope images. It allows to appreciate sensor linear behavior within the considered interval of deformation; in fact, a straight line fits well the measured points (coefficient of determination $R^2$ is more than 0.99). Deviation from mean points is satisfying, being equal to about 4 Ω at most (considering that only stretching cycle was included). Derived gage factor was estimated to be 3.63, which is in accordance with values obtained in previous works [18]. For the specific purposes of the present analysis, we focused only on elongation phase, to find an immediate relation between resistance and applied strain. Nevertheless, we are currently carrying out additional tests, which include release cycle too, with the aim of investigating possible hysteretic effects and the presence of residual stresses, in order to obtain more information for a complete study on sensor behavior.

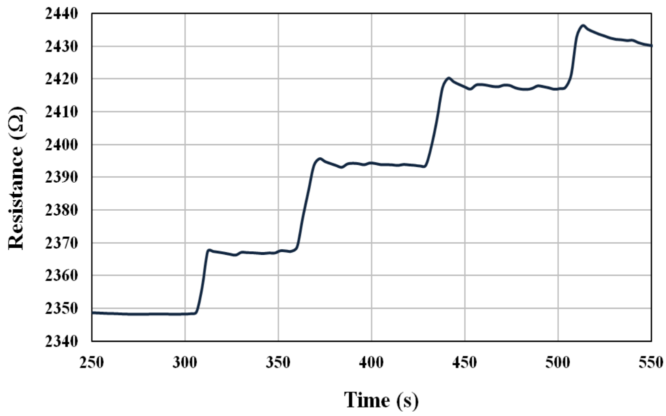


Fig. 6. Resistive sensor response over time.

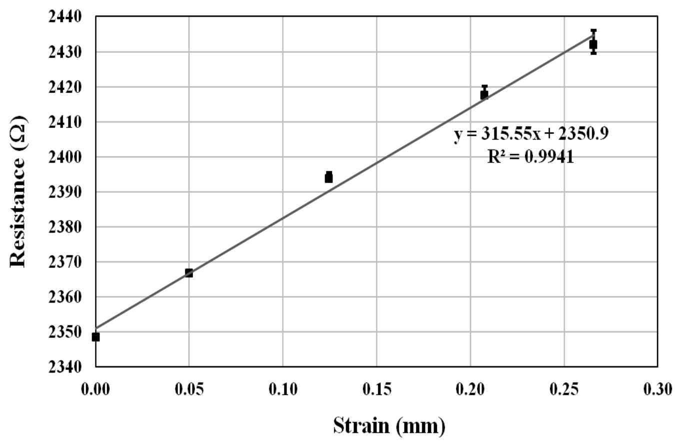


Fig. 7. Sensor characterization curve: resistance vs. applied strain.

## IV. Frequency Analysis of the System

Behavior of the overall system, as reported in Fig. 1, was studied, in order to assess if the described telemetric device is able to detect indirectly a strain variation. A frequency analysis was performed, by evaluating electrical impedance at readout inductor's terminals. Impedance depends on system elements, i.e. inductors' equivalent parameters (which have been listed in Table I), capacitance in parallel to sensing inductor and sensor resistance [11].

### *A. Experimental Setup and Performed Test*

The experimental apparatus used in this phase combines the one described in section III with an additional part. As before, printed strain gauge was maintained in the correct position through the fixing system of Fig. 4. Furthermore, it was joined to sensing inductor, which was kept parallel and coaxial to readout inductor thanks to a mechanical structure whose supports are moved by micrometric screws. Readout inductor's terminals were connected to HP4194A impedance analyzer, driven by the PC for signals acquisition through a LabVIEW program (these components form system's readout unit). Fig. 8 provides a view of the setup, whereas Fig. 9 presents its block scheme.

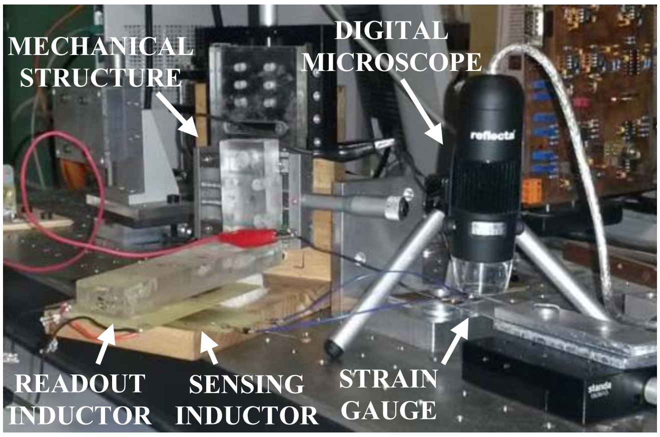


Fig. 8. View of the experimental apparatus for system frequency analysis.

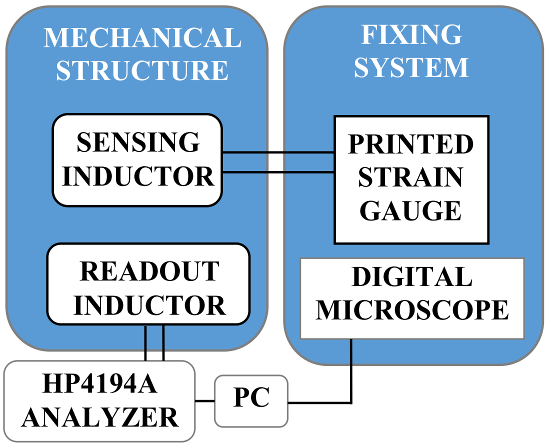


Fig. 9. Block scheme of the experimental apparatus.

Performed test consisted in evaluating system impedance variation corresponding to a change in sensor output. Inductors were kept at a fixed distance of about 12 mm between each other thanks to the mechanical structure. Then, the micrometric screw in fixing apparatus induced a series of deformation steps on the strain gauge, equal to about 0.25% of its length at rest, until 1% of $l_0$. At the same time, the PC drove HP4194A analyzer to continuously detect impedance at readout inductor's terminals. A sweep in frequency was executed, from 1.6 MHz to 2.2 MHz, to obtain the corresponding curves in the range of interest. All data were saved for successive elaboration and visualization.

### *B. Results and Discussion*

Fig. 10 shows the results obtained from this experimental test. It reports the curves of impedance magnitude (above) and phase (below) within the frequency range of interest, for all conditions (i.e. no strain and applied deformations of 0.25%, 0.5%, 0.75% and 1% of $l_0$, respectively). Since scales are wide and impedance variations are limited, there are three insets focusing on the intervals close to magnitude resonance peaks and phase minimum (i.e. the most sensitive points), respectively. They highlight how impedance increasingly changes when sensor undergoes a growing deformation.

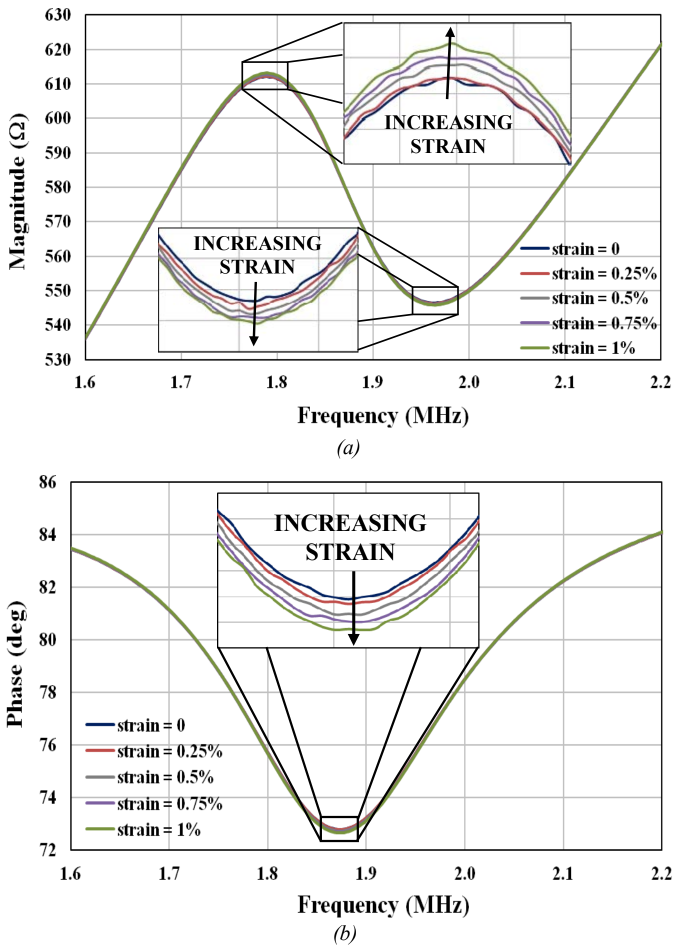


Fig. 10. Impedance curves as function of frequency for different applied strains. Distance between the inductors is fixed: (a) magnitude; (b) phase.

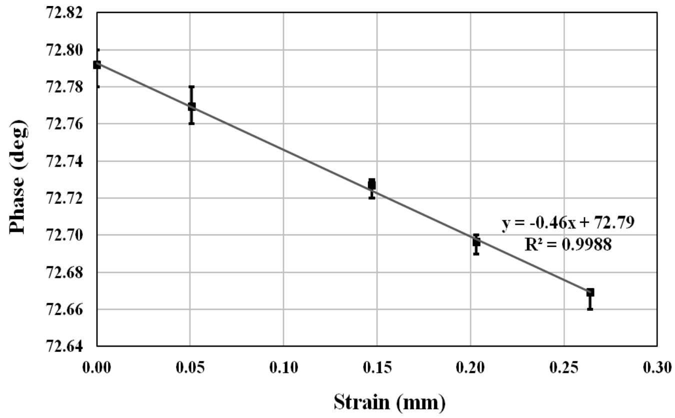


Fig. 11. Impedance phase minimum vs. applied strain. Distance between the inductors is fixed.

In particular, Fig. 11 focuses on phase minimum trend as a function of actual strain, since this is a convenient point to be detected. It shows that, given a fixed distance between the inductors, minimum decreases when applied strain augments, because sensor resistance grows and affects whole system impedance. This agrees with what is found in the literature [11]. For a strain variation of about 0.27 mm, we measured an average phase decrease of about 0.12 degrees, which lies in the same order of magnitude than results found from previous analyses [11]. In addition, such trend presents a very good linearity, as a straight line is effective in fitting suitably the measures. In fact, the derived coefficient of determination is almost 0.999. Furthermore, phase deviation from mean values is satisfying, since it does not lead to incorrect interpretations if considering the entity of total impedance variation consequent to occurring strains. For the considered strain range, maximum deviation is about 0.01 degrees. Thus, the presented achievements permit to conclude that there is a relationship between deformation applied to the sensor (and therefore its resistive output) and read system impedance (e.g. phase minimum).

Given the entity of impedance variation, highlighted in the above figures, keeping fixed the distance between the inductors was fundamental. In fact, a change in this variable modifies the inductive coupling between them [20], affecting the shape of impedance curves and, consequently, the values of magnitude resonance peaks and phase minimum. Furthermore, a too high distance would not allow to detect a variation on system behavior due to sensor output, leading to not reliable results. Anyway, the chosen value of 12 mm is sufficient to appreciate this change, making effective the described analysis.

## V. Conclusions

The proposed work has presented a telemetric device, composed of PCB planar inductors, which operates with a resistive strain gauge realized through the innovative technology of inkjet-printing on a flexible substrate. We carried out either an analysis for characterizing the sensor or a study of device frequency behavior by applying a deformation on the inkjet-printed component and evaluating system response. For each test, realized setups have been illustrated, followed protocols have been explained and obtained results have been reported. They highlight, on one hand, sensor capability of detecting occurring strains, demonstrating once again that inkjet printing technology is a valid way to produce effective devices. On the other hand, the feasibility of finding strain value through a remote impedance measurement at readout inductor's terminals has been assessed, proving that the proposed telemetric system holds promise to be exploited in applications in which solutions like cabled connections and batteries must be avoided.

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