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SOLID-CERAMIC LOAD CELLS IN THICK-FILM-TECHNOLOGY

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Abstract:
Load cells are usually applied in industry where high quality materials and reliability in a wide range of environments are paramount. Differences exist in performances, accuracy, fabrication technologies, intended application, and cost; notwithstanding this, repeatability, hysteresis, creep and dynamic response can be a prevalent cause of errors in standard strain gauge elements. This contribution presents an innovative architecture based on piezoresistive sensing elements in Thick-Film Technology (TFT). The proposed force sensor, of various measure-ranges from 1 N to 10 N, is screen printed and fired on 96 % alumina substrate showing low creep effect and high figure of merit.

Keywords: force sensor; thick-film technology; piezoresistors; creep.

1. INTRODUCTION

Many force-sensitive structures base their transduction principle on resistance change. In strain gauge elements the piezoresistors are usually configured in a bridge circuit to improve linearity and maximize sensitivity. In recent years, several type of piezoresistive elements have been developed and applied to realize force sensors using various materials and fabrication technologies, e.g diffused or implanted semiconductors resistors, thin- and thick-film elements. Piezoresistive load cells have been made using thick-film technology for more than one decade [1,2,3,4]. In thick film technology, three large industrial families of piezoresistive inks or pastes have been developed. Those based on ruthenium oxide and ruthenate of lead (or Bi) have gathered considerable momentum. The piezoresistive character of these formulations is more pronounced than that of metals (5 to 10 times greater), and their thermal behavior is often better than that of semiconductors. This field, which is of considerable importance in its application, must remain confidential in nature, due to certain work done in the sectors of both armaments and industrial research. The literature discussing the properties of thick layer resistances (thickness deposition of 10 µm to 40 µm) is relatively sparse. Analytical methods and Finite Element Analysis (FEM), can be used in order to predict stress profile and optimize the figure-of-merit (the product of the sensitivity and the square of the resonant frequency). The device presented in this paper has been designed and then realized in Thick Film Technology (TFT) on ceramic. This sensor types have several advantageous properties such as low cost, good reproducibility, low creep, compatibility with signal amplifier and converter units, etc.

2. MANUFACTURING PROCESS IN THICK-FILM TECHNOLOGY ON CERAMIC

Load cell is basically a mechanical system consisting of a flexural beam(s). When the substrate is loaded by the external force, the measurand causes strain on beam(s) which is, in turn, sensed by piezoresistors previously located in tailored position. The solution proposed, uses a cantilever beam with an opportune shape with the aim to impose a constant strain where the piezoresitors are printed. The analytic model has been verified by using simulation of the finite element method (FEM), resulting in satisfactory agreement. In Figure 1 an example of the FEM model is reported. "Thick Film" technology consists in screen printing insulating, conductive, or resistive inks on a ceramic substrate (usually alumina), and then sintering them at high temperature. These inks are powders incorporated in a liquid containing binders and organic solvents. For resistive inks, the powders are mixtures of conductive oxides (types $RuO2$, Pb or $Bi2Ru2O7-x$ at concentrations varying between 5 and 60 %) and insulators. When subjected to mechanical strain, they show great variation in their resistivity. The described structure was implemented in TFT on 96 % alumina substrate, 450 µm thick that was previously laser cut alongside of the correct final shape (the width and length of the beam were 4.5 mm and 16 mm respectively). The fabrication process included several steps involving the screen-printing of conductive paths and the piezoresistors and final firing at high temperature (850°C) [5]. The conductor paths were printed with platinum-gold ink. (ESL5867) to a thickness of 15 µm. Whilst the strain gauges were printed with 10 kΩ/□ resistor ink

(ESL 3414B). The nominal thickness was 20 μm giving a gauge factor of 16. In Figure 2 details of the printed piezoresistors are reported in TFT on ceramic. The strain gauge geometry tested were a 0.3 mm X 0.3 mm square. In order to determine the gauge factor (GF) tests were performed in a homemade apparatus, which consists of the ceramic bar fixed by one side, and the thick film resistors screen printed over the bar. On the free side of the bar were applied loads ranging from 0 N to 1 N with a step of 0.1 N. In order to achieve the best process condition a study using the serigraphic paste that resulted in the best gauge factor was conducted. The influence of sintering process on the electrical resistance of the thick film resistors was studied then five resistors were fabricated and submitted to sequential sintering cycles ranging from one to five. Between each sintering cycle the electrical resistance were measured. A final value of 16 for the gauge factor has been obtained. In Figure 3 an example of the new TFT load cell layout is reported. The application of the new load cell can be found in the field of wire tension measurement in textile and wire winding of transformer and/or inductor. Dynamic responses with 3 dB band up to 500 Hz are required.

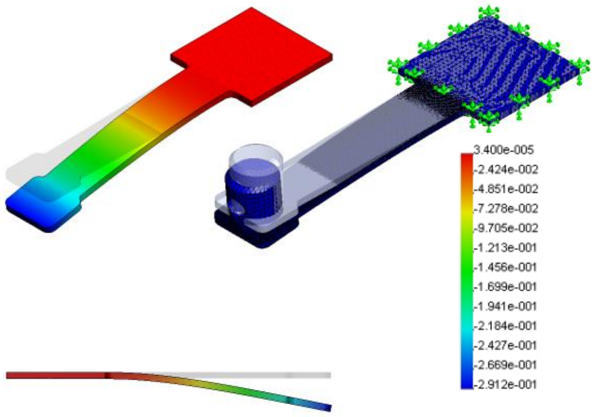

Figure 1: FEM for strain and resonance frequency analysis

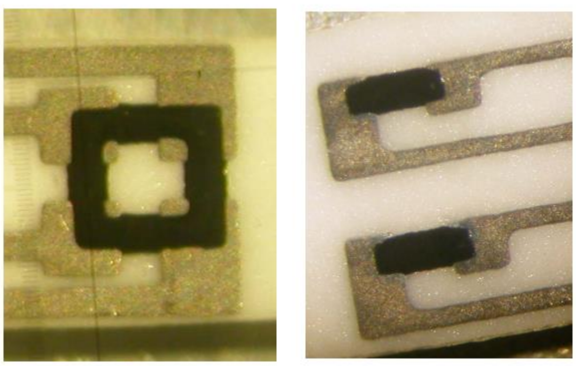

Figure 2: Details of the TFT piezoresistors screen printed and fired

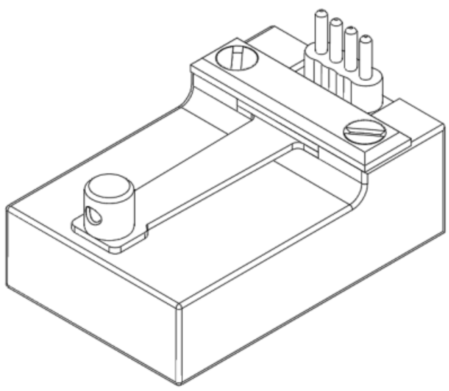

Figure 3: Schematic layout of the new TFT load cell

3. SIGNAL CONDITIONING ELECTRONICS

In Figure 4 a block scheme of the signal conditioning electronics dedicated to the load cell signals ADC conversion and CAN communication is reported. In the proposed approach a dc-excitation has been chosen. Connections between the AD7730 (signal amplifier and 18 bits ADC) and the bridge are very straightforward in this type of application. The bridge configuration shown is a six-lead configuration with separate return leads for the reference lines. This allows a force/sense effect on drops caused by the excitation current flowing through the lead resistances. Illustrating a major advantage of the proposed approach, the 5 V excitation voltage for the bridge can be used directly as the reference voltage for the AD7730, eliminating the need for precision matched resistors in generating a scaled-down reference. The application is a ratiometric one with variations in the excitation voltage being reflected in variations in the analog input voltage and reference voltage of the AD7730. Because the AD7730 is a truly ratiometric part, with the reference voltage and excitation voltages equal, it is possible to evaluate its total excitation voltage rejection. This is unlike other converters which give a separate indication of the rejection of reference, analog inputs and power supply. The combined (total) rejection for the proposed solution when moving the excitation voltage (which was also the power supply voltage) was better than 115 dB when evaluated with a load cell simulator. Drift considerations are a primary concern for load cell applications. For the ADC functionality has been chosen a CHOP mode operation to accrue the benefits of the excellent drift performance. The AD7730 also boasts excellent common mode and normal mode rejection of mains frequency on both the analog and reference inputs. The input offset current is 10 nA maximum which results in a maximum, dc offset voltage of 2 mV using the TFT piezoresistors. The AD7730 signal amplifier and ADC converter is directly connected to a 8-bits microcontroller (PIC18F2580) via SPI line for linearization, zero and sensitivity thermal drift compensation and digital communication. As digital field bus a CANBUS approach has been proposed. In fact, the CAN network architecture has many advantages in comparison with a standard design using a central microprocessor to carry out the control work:

• *Fewer wires in the system make the wiring cheap and easy. In many cases the wiring can be reduced by 90% or more;*

• *Short connections to electrical noise sensitive analog sensors before the signals are converted into digital noise insensitive messages;*

• *A flexible system. Functional Units can be added or removed in a simple way;*

• *Simple maintenance. The electronics in many Functional Units can be identical and fully interchangeable;*

• *Each Functional Unit can be developed and tested individually according to a specification given from the system demand;*

• *The network architecture is very well suited for project oriented development work.*

4. EXPERIMENTAL RESULTS

The TFT load cell for static and dynamic force measurement was evaluated by securing the cantilever structure to a purpose built test aluminium enclosure and loading the free edge with masses up to a total of 1 N in 0.1 N increments whilst measuring the change in bridge output voltage. In Figure 5 the TFT load cell and the fixing frame is reported together with the quotes. The full dimensions of the load cell with the aluminium housing are 5 mm x 20 mm x 5 mm. The average change in the output computed from a number of samples is shown graphically in figures 6 a) and 6 b). The data have been normalized with respect to the bridge excitation voltage and offset values have been removed. The figure 6 b) shows that the force sensor exhibits a reasonably linear relationship over the range investigated, with an average sensitivity of 7500 µV/VN ± 200 µV/VN (a statistical variation of 3%). This is nearly a factor of two times lower than the force sensitivity predicted using FEM and classic modelization. Hysteresis effects in the response of the static force sensor have been investigated by recording the sensor bridge output voltage as the tip of the cantilever beam is first deflected by a graduated micrometer and then as it is relaxed back as the micrometer is unwound. Figures 7a) and 7b) show a typical set of responses over two successive trials of beam deflection and relaxation

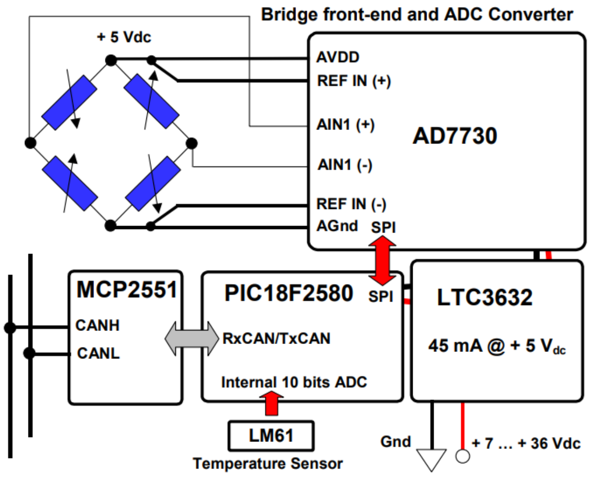

Figure 4: Block scheme of the signal conditioning electronics

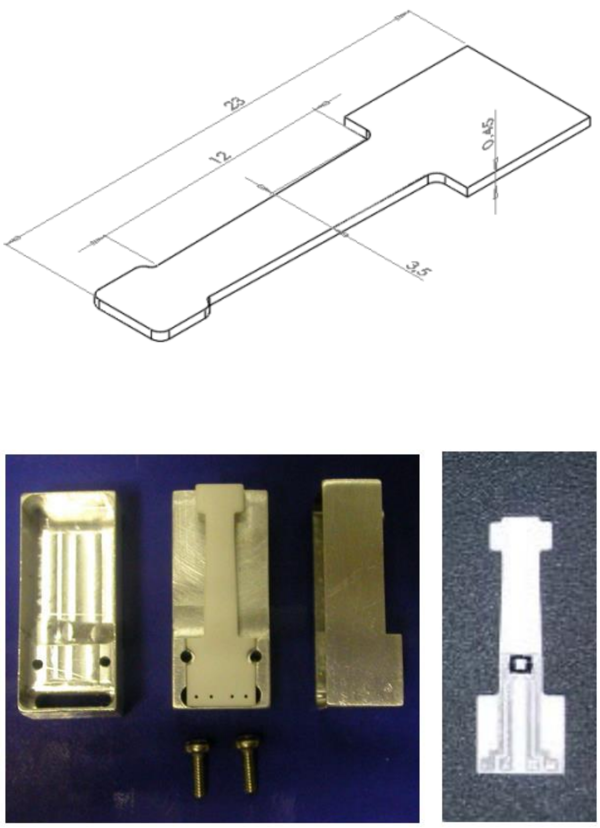

Figure 5: The TFT cell with the housing and quotes (in mm)

The results shown have been obtained by taking the difference in the sensor response between the undeflected reading of the first deflection trial (i.e. the initial unstrained value) and all subsequent measurements, and then normalizing these values with respect to the bridge excitation voltage.

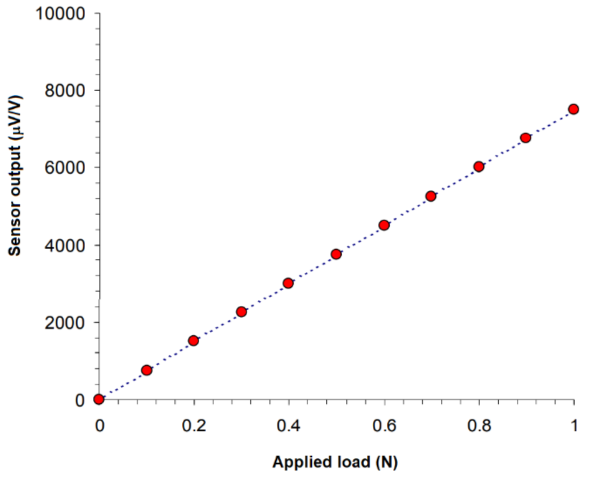

Figure 6.a: Calibration curve

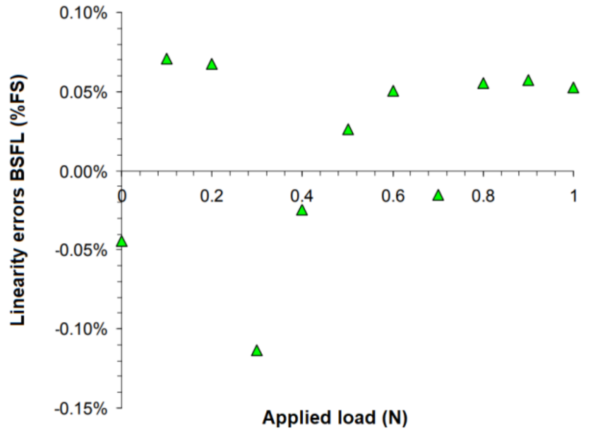

Figure 6.b: Linearity errors

Values for the force measurement sensitivity, bridge offset voltage and maximum hysteresis levels have been calculated from the slopes and intercepts of the curves. Here, and throughout this section, the maximum hysteresis level is calculated as the largest difference recorded between the sensor responses for the same micrometer setting, expressed as a percentage of the average response range recorded during both deflection and relaxation of the beam in the same experiment trial. In the case of the measurement sensitivity figures, these have been converted from a deflection based value to a force equivalent figure using the theoretically derived association that a 100 µm deflection at the tip of an ideal cantilever of similar dimensions is equivalent to a beam tip force of 1N [6]. Figures show that there is no significant change in the sensor response between the very first set of deflection data and any subsequent measurement.

Over the deflection range investigated this equates to a maximum hysteresis value equivalent to approximately 0.12 % of the full scale response.

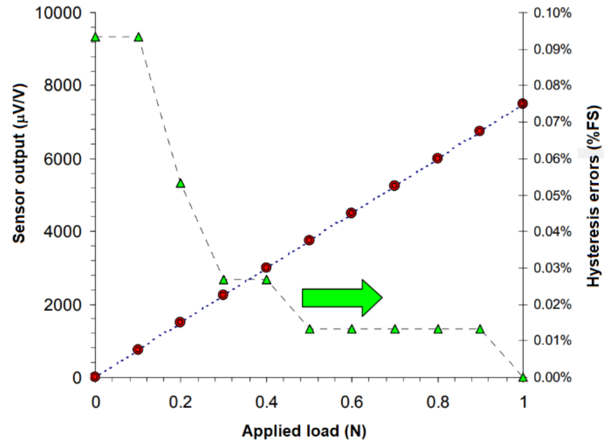

Figure 7.a: Normalized sensor response over a succession of cantilever deflection/relaxation and hysteresis errors trial n°1

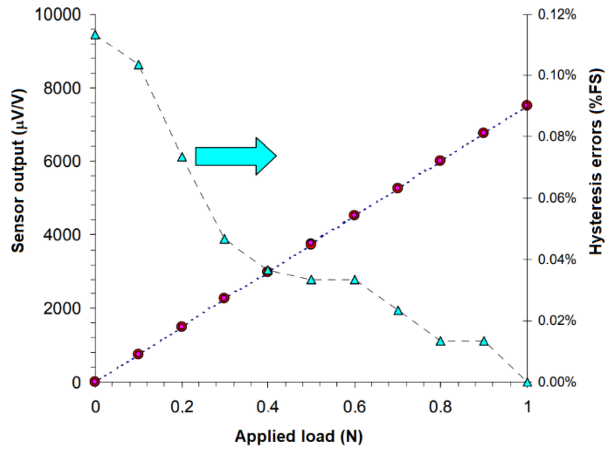

Figure 7.b: Normalized sensor response over a succession of cantilever deflection/relaxation and hysteresis errors trial n°2

In Figure 8 an example of response to creep curve at 30 minute is reported together at room temperature. A maximum value of 0.025% of the full scale output has been obtained. Considering the TFT load cell morphology, if it is assumed that the temperature coefficients of resistance of the four individual resistors are closely matched then, in theory, the output of the bridge circuit should be temperature independent since strain induced ratiometric changes in resistances are maintained with temperature. However, it has been demonstrated that the piezoresistors were not closely matched so a zero drift will be expected. Regarding the gauge factor of the thick-film resistors, it exhibits a temperature dependency [7] and therefore we would expect the force measurement sensitivity to exhibit some variation with temperature.

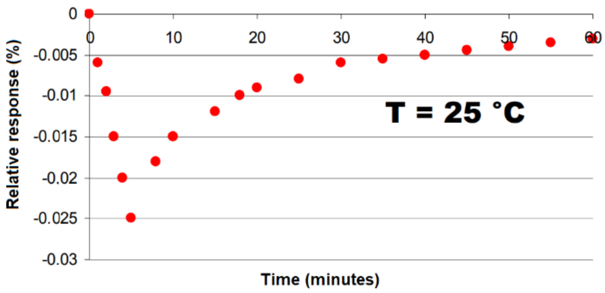

Figure 8: Creep response and creep recovery response in 30 min

The room temperature resistance of the post processed piezoresitors was nearly twice as large as expected, with an average value of 10 kΩ +/- 50 Ω at 25 °C. This was attributed to a thinner printed film than recommended for this material, but was not considered a problem. In fact a higher nominal resistance is advantageous since it permits an easier and potentially more accurate measurement of resistance changes. To characterize the temperature dependence of the thick film load cell, the Wheatstone bridge output with and without loads, of a number of samples were measured in a PERANI UC 150 environmental chamber between −10 °C and +50 °C. The local temperature experienced by each load cell was determined by measuring the resistance of a calibrated commercial thin-film Pt100 temperature sensor glued to the load cell surface. The average measured zero and sensitivity variation due to temperature is reported in Figure 9 a) and 9 b).

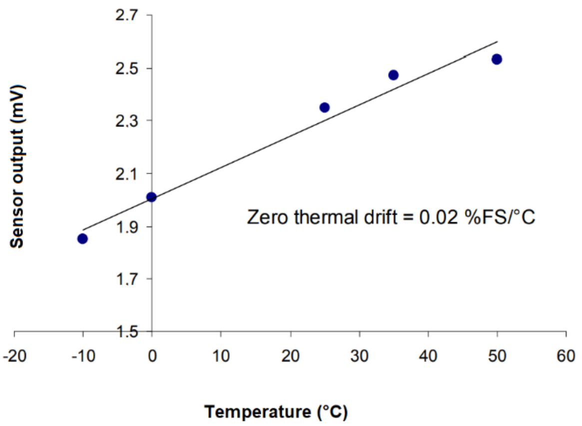

Figure 9.a: Zero drift of the TFT load cell from –10 °C up to 50 °C

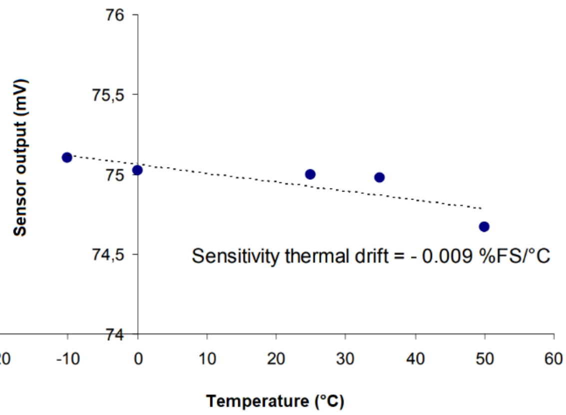

Figure 9.b: Sensitivity drift of the TFT load cell from -10 °C up to 50 °C

The resonance frequencies have been measured electrically using a vibrating table (B&K 4808 exciter-body). In Figure 10 a photograph of the developed TFT sensor during the thermal zero and sensitivity shift analysis is reported.

Figure 10: Photograph of the sensor during the zero and sensitivity shift in the PARANI UC 150climatic chamber

During the dynamic characterization a first resonance frequency of about 1 kHz has been found (the resonance frequency decrease up to 610 Hz when a load button is applied at the end of the load cell in the case of tensile force measurements). In Figure 11 an example of the dynamic response has been reported in the range 10 Hz … 1 kHz.

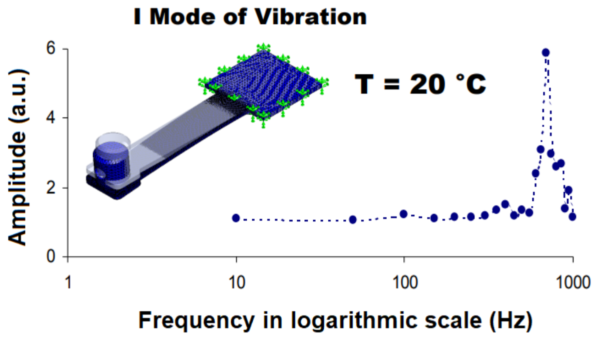

Figure 11: Amplitude of the output signal vs frequency

5. SUMMARY

In this paper a small structure based on piezoresistive effect, implemented in Thick-Film Technology (TFT) on 96 % Al_2O_3 substrate, working as load cell with high sensitivity and low creep effects, has been presented. The analytic model has been verified by using simulation of the finite element method (FEM), resulting in satisfactory agreement. The overall performance of the prototypes suggest that many applications in advanced industrial requirements will be possible specially in the field of yarn feeders tension controls in textile and wire winding of transformer and/or inductor.

6. REFERENCES

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