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Piezoresistive Accelerometers for Vehicle Dynamics: A New Solution in Thick-Film Technology on AISI430 Metal Substrate

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The phenomenal growth of automotive electronics in the 1980's has been paced by the development of low-cost and reliable microprocessors. Automotive sensors have closely followed the microprocessor in becoming low-cost, reliable components. Among the various sensor technologies, thick-film technology (TFT) on insulated metal substrates offers several appreciable capabilities, *e.g.*, flexibility in choice of material and design, high shock resistance, ease of integration into electronic circuits and packaging. In this application, strain gauges, based on the piezoresistive effect in TF resistors, are particularly interesting, not only for their immunity to contamination and mechanical roughness, but also for their compromise between sensitivity and temperature coefficient of resistance (TCR). The theory of operation of the proposed accelerometer is presented with a description of its implementation in TFT on stainless steel AISI430 substrate, and experimental results of its characterization. It is shown that, by proper control of screen printing and firing processes, good linearity and high sensitivity can be achieved.

1. Introduction

The advent of air-bags and "smart" suspension systems in the automotive industry has created a need for high-performance, low-cost accelerometers.(1) Automotive requirements include: self-diagnostic features, high sensitivity, long-term environmental stability, excellent linearity and low cost.(2–4) Until recently, the majority of interest in accelerometers focused on piezoresistive, micromachined silicon devices.(5–7) Because of their low cost, deficiencies in their performance such as low resonance, temperature compensation requirements, and shock resistance problems, are often overlooked.(8–9) Now, however, new technologies are emerging that show great promise for satisfying the needs of the automotive industry both in terms of cost and performance. This paper discusses one of these new technologies: TFT on insulated metal substrate. The technology lends itself to the fabrication of inexpensive, robust and miniaturized devices on planar substrates. The fabrication process itself involves depositing inks via a screen-printing method and firing at high temperatures (> 900°C) to form a fixed composite material. If a metal substrate is chosen as the elastic deformable base, then an insulating ink is required to isolate the gauges from the metal. The choice of a metal-insulated layer combination will play an important part in the overall system performance, and the effects of the high temperature required for processing should be considered carefully. In this article we will present the development of a new cantilever-type accelerometer, describing manufacturing processes and experimental results of its characterization.

2. Description of the Structure

A piezoresistive accelerometer is basically a mechanical system consisting of a seismic mass supported by flexural beam(s). When the substrate is under acceleration, the inertial force on the mass causes strain on the beam(s) which is, in turn, sensed by piezoresistors previously fixed in appropriate positions (usually in the form of a full active Wheatstone bridge configuration).(10) The solution proposed uses a conventional cantilever beam to support a seismic mass. This type of accelerometer has the following well-known features:(11)

— *high sensitivity*
— *low resonance frequency*
— *center of mass moving on an arc*
— *nearly uniform stress on the surface of the beam under constant acceleration.*

For automotive applications, in which high sensitivity and accuracy without a large bandwidth are required (from DC to 50 Hz maximum for horizontal vehicle motion), this could be one of the best solutions.(12) The accelerometer transducer shown in Fig. 1 comprises a metal-sensor element such as a TF strain gauge, a hybrid IC instrumentation amplifier which has low temperature drift and the metallic package. A schematic view is shown in Fig. 2. We adopted a stainless steel AISI430 substrate in order to convert the inertial force caused by acceleration into a strain sensed by the resistance in the screen-printed thick film. The thickness of the elastic element was 600 μm and a metallic mass was mounted on the single-ended lever because of its effect of increasing the sensitivity of the device. Four piezoresistors were connected so as to form a bridge circuit.

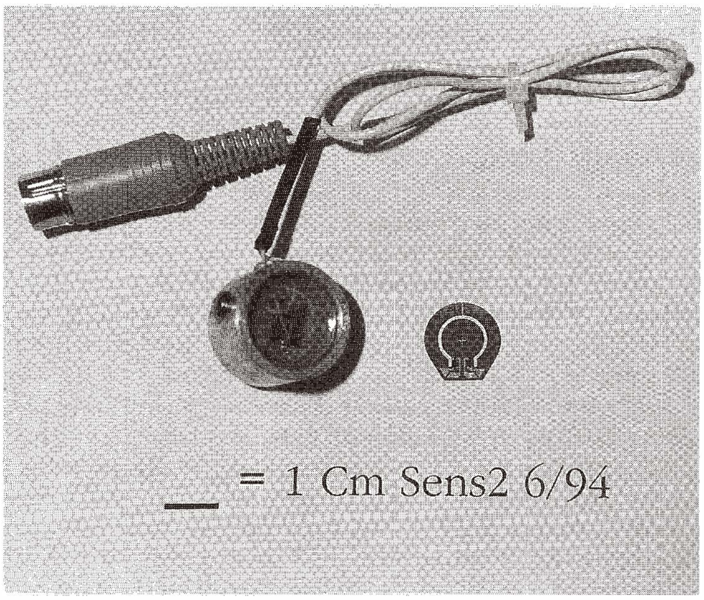

Fig. 1. Photograph of the TFT accelerometer prototype and the support base.

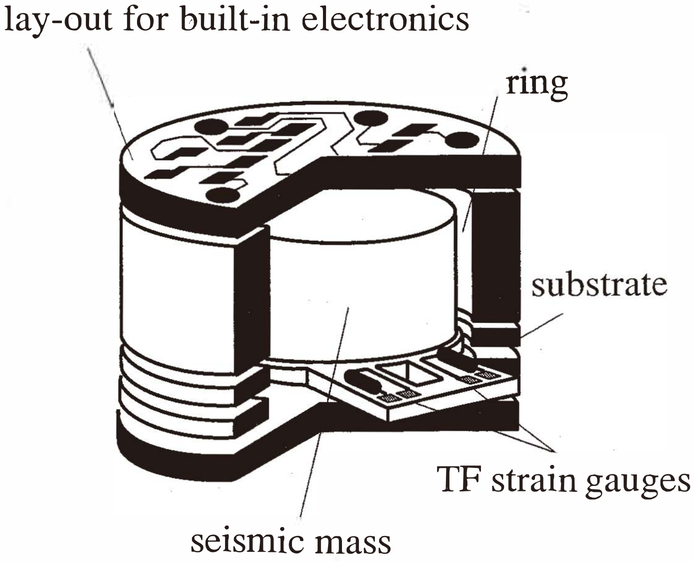

Fig. 2. Schematic drawing of the acceleration sensor.

3. Realization of the Accelerometer in TFT

TFT possesses many attractive properties for the realization of sensors; several results have recently been reported.(13–16) The use of piezoresistive pastes allows the realization of strain-sensing structures with high sensitivity at a low cost.(17–20) The described accelerometer was developed using TFT on a ferritic AISI430 stainless steel substrate, that was previously cut using a laser along the sides of the beams to obtain the correct shape and the final design. The choice of AISI430 is based on the following advantages:

- low temperature expansion coefficient [TCE = 10 ppm/°C]
- good anticorrosion characteristics in terms of both ambient and high temperature conditions
- easily cold-working
- low work hardening compared to austenitic stainless steels
- good chemical compatibility with many TF dielectric inks
- as a ferritic steel, it is not susceptible to considerable change of its mechanical characteristics after thermal treatment
- easily available at low cost (it is a common material in the automotive industry)

Care must be taken to adopt the correct cooling profile during the sintering processes requiring high temperatures (from 930°C to 980°C). Under these conditions, a low cooling rate is important in order to avoid a reduction in resistance to intergranular corrosion and an excessive decrease in tenacity.

The flexural beams of the cantilever-type accelerometer sensor are 2 mm wide and 2 mm long. The four resistors have, in this case, planar dimensions of about 0.75 mm × 0.30 mm giving a total resistance of approximately 12 kΩ. Two sequentially fired layers of Hereaus IP211 are first deposited onto the metal to give a total thickness of around 40 μm. The manufacturers of this ink report a breakdown voltage of greater than 1 kV at this thickness. The conductor pads and tracks (Du Pont 9596 Pt/Au) are then screen printed and fired (to a final thickness of 20 μm). The resistor is the final layer to be deposited and the choice of Du Pont D1441 originated from the results of our previous research.(21–22) Great care was thus devoted to the screen-printing step in order to minimize tolerances; this, in addition to careful control of the firing profiles (i.e. peak temperature of 935°C for 10 min in the case of IP211 sintering processes), ensured good adhesion and reproducibility in resistance and gauge factor values.(23) By means of glassy dielectric, the sensing cantilever-type element was bonded to a double ceramic circular frame, producing a constant action at the clamped end of the two beams. An interdistance metal ring was also adopted, to produce an oil-proof chamber for eventual damping control.

4. Static and Dynamic Characterization

4.1 *Measurement principle*

All the measurements were conducted on the sensitive elements, encapsulated in a stainless steel case. The resonance frequencies were measured electrically using a vibrating table (Bruel & Kjær exciter-body-type 4290). For dynamic characterization in a range above 200 Hz we adopted a rotating calibration structure designed specifically for low-frequency measurement.(24) Despite rather large errors (±10%), the predicted values were confirmed. For dynamic measurement on the vibrating table, the housing box was screwed onto the head of the table. The sensitivity was measured both statically by turning the accelerometer in the gravitational field, and dynamically on the vibrating table.

4.2 *Results*

The calculated and measured data of the TFT accelerometer are summarized in Table 1. The analytical formulae and FEM are extended in order to optimize the dimensions of the beam and mass with respect to the desired sensitivity and bandwidth and to the technological constraints imposed by the industrial fabrication process.(25) The main feature of the data presented here is that the values of the sensitivity calculated using FEM analysis are in better agreement with the observed values than those obtained using the classic analysis. This is because we can best reproduce the clamped condition at the beam free ends, a term which corresponds rather closely to the experimental setup. Shown in Fig. 3 is the transfer function (gain-phase trend with the marker positioned at the resonance frequency), in the tested range from 200 Hz to 900 Hz, measured against a laboratory-grade piezoelectric accelerometer (R), at room temperature. In contrast, Fig. 4 shows the fairly constant frequency response of the sensor from DC to 3.5 Hz at a fixed acceleration value $a_{cc} = 5$ g; the ordinate axis on the right represents the variation in sensitivity as a percentage of full-scale output. The frequency range investigated covers most of the mechanical vibrations on the wheels and in the driver's cabin of a vehicle in motion, such as those due to unevenness of the road surface. Finally, the device exhibits a linearity of better than ± 0.3% F.S. in a low-range test from DC to 5 Hz. Figure 5 illustrates, in the case of constant frequency excitation $F = 2$ Hz, the percentage deviation of the experimental data from the regression line. Lifetime testing at room temperature is still in progress for evaluating the long-term adhesion between TF inks and metal substrate.

Table 1
Performance of the tested transducer.

	Classic formulae	FEM analysis	Measured data
Acceleration range	50 g	50 g	50 g
Resonance frequency	892 Hz	713 Hz	653 Hz
Frequency range	–	–	from DC to 200 Hz
Sensitivity	174 mV/g	191 mV/g	203 mV/g
Output linearity	–	–	better than 0.3% F.S. (in the tested range from DC to 5 Hz)
Temperature offset drift	–	–	0.05% F.S./°C
Operating temperature range	–	–	–30°C – +85°C
Voltage supply	–	–	–12 V – +12 V
Built-in electronic gain	–	–	40 dB
Resolution	–	–	0.07 g (at room temperature)

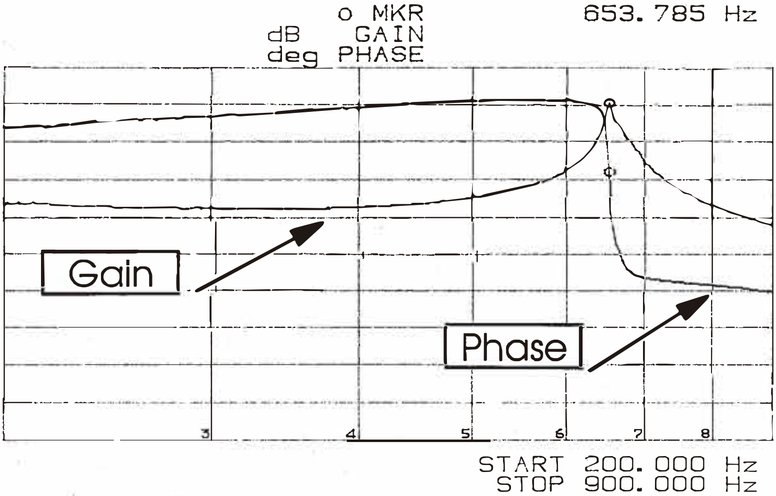

Fig. 3. Transfer function in the measured field from 200 Hz to 900 Hz (gain and phase are reported in terms of tested/reference (T/R) acceleration ratios).

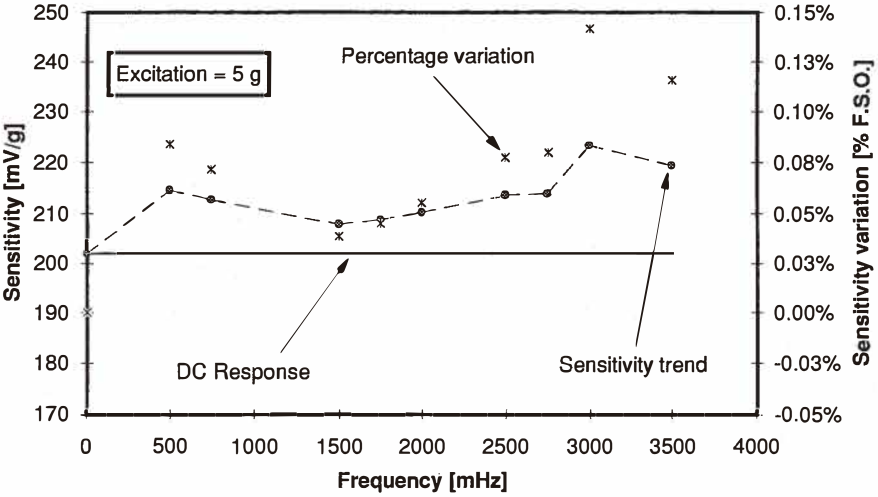

Fig. 4. Sensor response at fixed acceleration in a dynamic range from DC to 3.5 Hz.

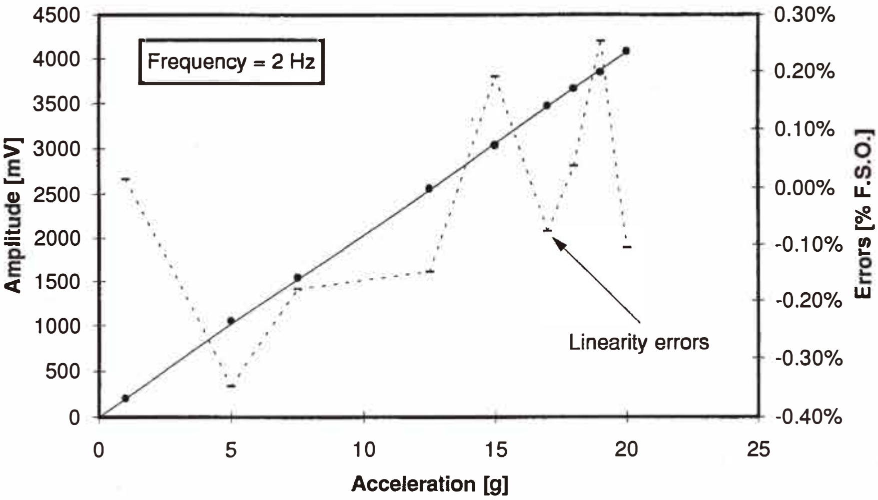

Fig. 5. Output nonlinearities observed under 2 Hz dynamic excitation with respect to different forced accelerations.

5. Conclusion

This paper describes the design and development of a low-cost planar TFT accelerometer on stainless steel substrate with integrated preprocessing electronics. Through careful control of the screen printing and firing processes, linearity better than ± 1% over the range ± 50 g is achieved, with a sensitivity near 200 mV/g. TFT allows the strain gauges to be deposited easily onto the structure in a cost-effective manner. The TF resistors screen-printed on a ceramic substrate (*e.g.*, Al_2O_3) have piezoresistive properties whose applicability in the transducer field is well known. This solution is certainly appealing, although it has some drawbacks with regard to automotive applications. These are mainly due to the mechanical properties of the ceramic substrate and its chemical compatibility with the processes involved in both sensor manufacture and its final utilization. The compressive strength of alumina is very good, over 200 MPa, but its flexural strength is about 8 times less. Therefore, the maximum applicable strain is limited to 500–600 $\mu\varepsilon$. In addition, alumina is brittle (necessitating great accuracy in substrate design to avoid microcracking) and the circuits require damping control against excessive stress and shock. Another drawback of alumina is its poor machinability after sintering. On the other hand, if the thermal treatment chosen and the chemical compatibility between TF inks are appropriate, metal substrates are a promising material for overcoming the limitations of ceramics.

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