Thick-Film Tilt Sensors: Feasibility Study Example Using Free Convective Motion of An Heating Air Mass

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Abstract

In this application a feasibility study example of thick-film tilt sensor has been presented based on heat transfer by natural convection. The device measures internal changes in heat transfer due to the inclination. The device is functionally equivalent to traditional proof-mass accelerometer. The proof mass in the new thick-film sensor is a gas. The gaseous proof-mass provides great advantages over the use of the traditional solid proof mass. A conditioning electronics amplifies the signal variation induced by the inclination compensating the deviation due to the initial asymmetrical values of the bridge arms and their slow variations. Preliminary tests on the first prototypes show an accuracy of about 2% full scale output, repeatability of about 0.2° and resolution better than 0.1 ° over a ± 20° range.

1. Introduction

Many vehicles require the use of inclinometers to control their stability to prevent rolling over or flipping due to improper handling, especially in off-road environment. Moreover inclination sensors with reduced power supply and minor cost/performances ratio expand their use in applications such as security, computer peripherals and so on. The use of screen-printing thick-film technology in the field of sensors started about 20 years ago [1],[2],[3],[4]. The advantages of this technology in electronics are also apply to the sensor field, as for example:

- low investment for equipment
- versatility in the sensor design (size of the substrate, size, shape and nature of the metallic contacts, of the heating elements etc.)
- mass production of customized sensors at low cost

Should be noted however, that the technology is also widely used for the fabrication of chemical and mechanical sensors and many commercial devices exist [5,6]. The integrability of the technology also allows combination with other enabling technologies, such as silicon, to provide powerful and economically viable solid-state sensors.

2. The operating principles and the fabrication method in thick-film technology

The principle of operation of the TFT inclinometer is based on heat transfer by natural convection. The device measures internal changes in heat transfer due to the inclination caused by the gravity force. The device is functionally equivalent to traditional proof-mass accelerometers. The proof mass in the new thick-film sensor is a gas. The gaseous proof-mass provides great advantages over the use of the traditional solid proof mass. The device does not show striction and particle contamination problems associated with competitive devices and provides a high shock survival leading to significantly lower failure rates and lower loss due to handling during assembly. The arrangement necessary for measuring the inclination effects on heat transfer is described next. A double structure heat source, centered in the ceramic substrate is suspended across a cavity. Equally spaced temperature sensors are located equidistantly on all two sides of the heat source. Under zero inclination, a temperature gradient is symmetrical to the heat source, so that the temperature is the same at all two temperature sensors, causing them to output the same voltage (reference Figure 1 (A)). Inclination in the sensing direction will disturb the temperature profile, due to free convection heat transfer, causing it to be asymmetrical (reference Figure 1 (B)). The temperature, and hence voltage

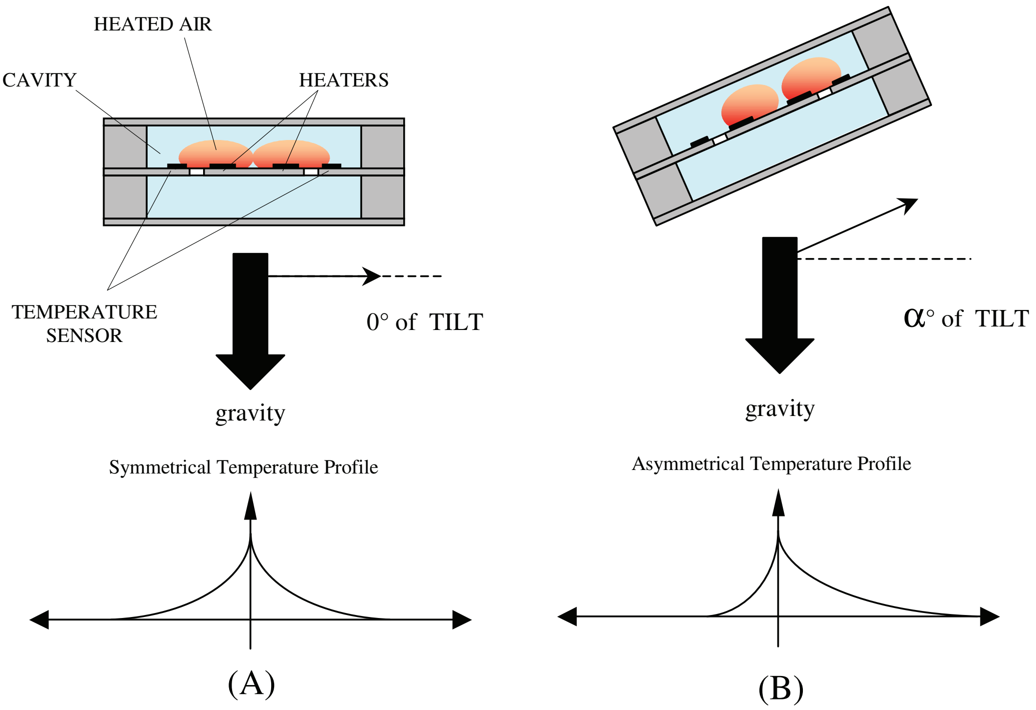

Fig.1. Vertical cross-section showing the sensing sequence (a) 0° TILT angle (b) α° TILT angle.

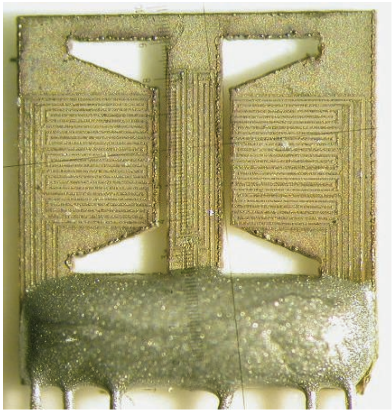

Fig. 2. Photograph of the TFT substrate.

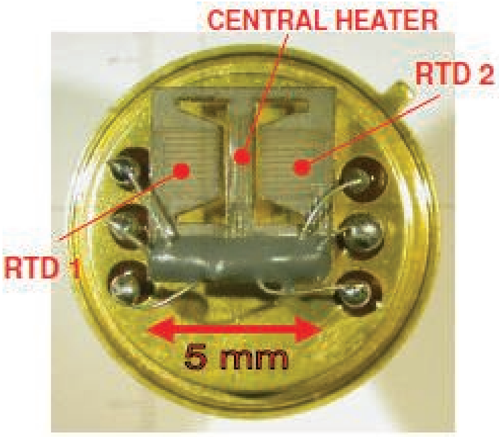

Fig. 3 – Photograph of the tilt sensor prototype in thick-film technology

output of the two temperature sensors will then be different. The differential voltage at the temperature sensor outputs is directly proportional to the inclination. The TFT tilt sensor is most sensitive to changes in angular position, or tilt, when the sensitive axis is perpendicular to the force of gravity, or parallel to the Earth's surface. Similarly, when the sensitive axis is parallel to the force of gravity (perpendicular to the Earth's surface), it is least sensitive to changes in tilt. The fabrication method involves the standard thick-film procedures on 96% alumina substrate. The planar resistors adopted for the heating processes and the thermal sensors are based on a Pt/Au ink. In order to achieve adequate electrical characteristics, a firing process has been adopted at a peak temperature of about 950°C. After the screen-printing and firing processes the ceramic substrate, covered by the conductive layer (thickness of about 25 µm) is cut by laser to obtain central heater's support and the double bridge structure for the thermal sensors. The final configuration of the heater and the thermoresistors are then obtained by laser scribing. In Figure 2 a photograph of the TFT sensor substrate is reported. The central vertical bar hosts the resistance track of the heater while the two vertical lines equidistant and close to the bar are the two termoresistances

Figure 3 shows a photograph of the TFT inclinometer sensor into a TO package. The dimension of the sensor is 4 mm X 6 mm.

3. Signal conditioning electronics

A block scheme of the conditioning electronics is reported in Figure 4. H is the heater resistance driven by a generator whose current is modulated by an α(t) factor equal to A sin (2πf$_c$ t). T_1 and T_2 are the two thermoresistances: both have one common terminal linked to the input of a trans resistance amplifier. The other two terminals of T_1 and T_2 are respectively tied to a positive voltage reference and to the output of an integrator. The amplifier, the integrator and T_2 are a negative feedback system whose function is to compensate slow frequency variations. The output of the feedback system is multiplied by α(t) and low pass filtered. These last two blocks function as a synchronous demodulator and the output V_O is the sensor output. Into the common node, T_1 and T_2 currents are subtracted. The positive integrator regulates its output voltage until the low-frequency current flowing into T_2 is equal and opposite to the lo- frequency current of T_1, zeroing, in this way, the voltage output of the trans resistance amplifier. The detailed scheme of the feedback system is shown in Figure 5: R1 e R2 represent the resistances of the thermoresistances T_1 and T_2, R3 and the A1 amplifier constitutes the negative trans resistance amplifier, and the other four elements (marked as R and C) together with A2 constitute the positive integrator. The transfer function between the current ΔI injected into the negative terminal of A1 amplifier and the V_1 is:

$$\frac{V_1}{\Delta I} = -\frac{sCRR_2R_3}{sCRR_2 + R_3} \qquad (1)$$

corresponding to an high pass filter having a cut off frequency of :

$$f_t = \frac{R_3}{2\pi CRR_2} \qquad (2)$$

Since R1 ≅ 50 Ω, R2 ≅ 50 Ω, R3 = 10 kΩ, R = 3.3 M Ω and C = 10 μF, f_t is equal to 1 Hz. In this case slow drift and initial mismatching of the two thermoresistances are compensated and do not influence the sensor output. Because α(t) is a sinusoid with a frequency f_c (30Hz) greater than f_t the cut-off frequency, the heating mass induces a ΔR1 and ΔR2 changes, modulated again at f_c, into R1 and R2 respectively. Choosing f_c greater than f_t, the difference between ΔR1 and ΔR2 comes directly to the syncrounous demodulator. When the sensor is parallel to the horizontal line, ΔR1 is equal to ΔR2 and because R1 and R2 are driven by voltages of opposite signs, the current induced, namely ΔI1 and ΔI2, are equal and opposite producing a zero output voltage Vo. Applying an inclination to the sensor, due to the asymmetric profile of temperature, ΔR1 and ΔR2 have opposite signs and their corresponding currents ΔI1 and ΔI2 have same signs; they are summed and amplified of a -10^4 factor and through the synchronous demodulator generates a signal (V_O) proportional to the inclination.

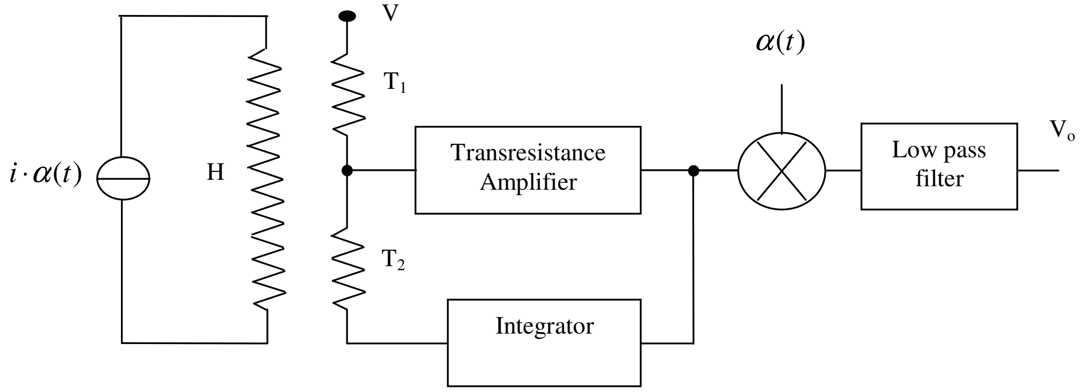

Fig. 4. Block scheme of the conditioning electronics, T_1 e T_2 are the two thermoresistances while H is the heater.

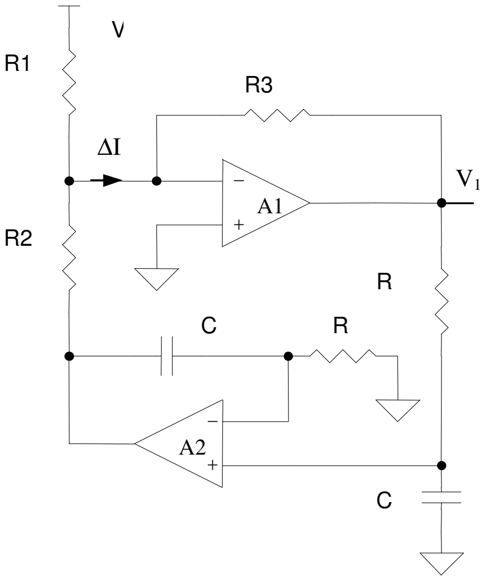

Fig. 5. Circuit details of the transresistance and integrator blocks.

4. Experimental results

Preliminary tests on the first prototypes show a sensitivity of about 8 mV/° from + 50° to 0. Figure 6 illustrates, in the case of a constant room temperature, the inclinometer output at different inclination angles. Figure 7 reports, the percentage deviation of the experimental data from the regression line.

A maximum error of about 3° can be found in the case of ± 50° full scale output. Differently, a lower nonlinearity errors The repeatability has been evaluated and a value less than 0.2 ° has been observed. Thermal tests will be performed in the near future. The total supply current is less than 20 mA.

Note that the voltage output change for a small inclination angle is relatively small (8mV for 1°), so careful consideration to noise must be applied in the TFT inclinometer design. Reducing the low pass filter of the synchronous demodulator to 1 Hz, a noise level in the order of 0.1mVrms has been measured. With such value a resolution better than 0.1° should be obtained.

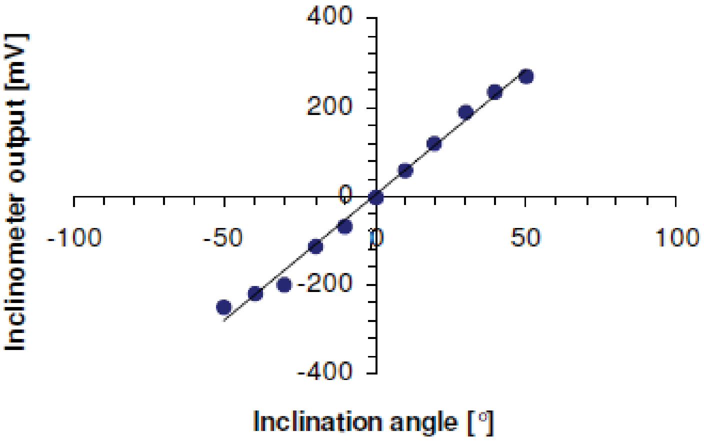

Fig. 6. Gravity component vs. Inclination angle.

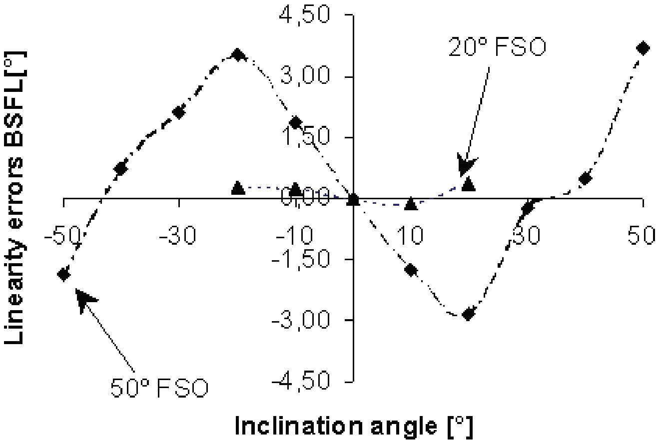

Fig. 7. Gravity component vs. Inclination angle.

5. Conclusions

Using thick-film technology on a ceramic substrate, a new tilt sensor based on the heat transfer principle has been developed. The sensor is fabricated from ceramic materials and thick-film technology. From the preliminary test the accuracy has been evaluated of about 2 % full scale output while the repeatability of about 0.2° over a ±20° range. The TFT tilt sensor is capable of resolving less 0.1°. Due to the compensation of the conditioning electronics , no trimming operation on the thick film resistors is necessary, contributing to the reduction of the overall fabrication costs.Finally, the sensor is inexpensive enough to be, in the near future, competitive with other types of commercial tilt transducer.

References

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