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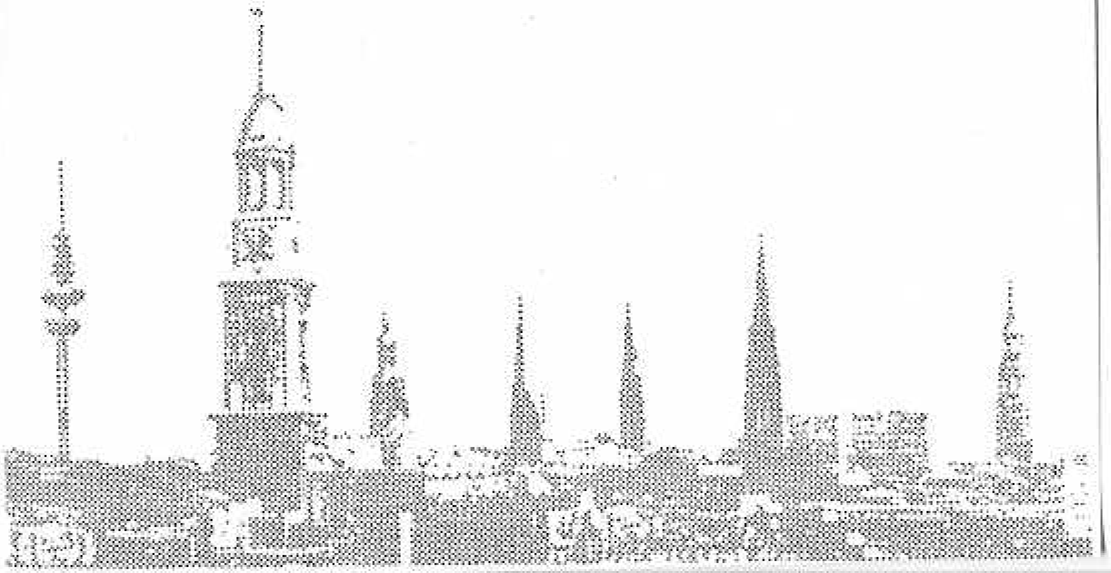
PROCEEDINGS



A THICK FILM INCLINOMETER

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SUMMARY

Taking advantage of thick film technology, a sophisticated device able to detect inclinations of a plane to which it is fixed has been developed. The device can measure inclinations up to ± 30° with a resolution better than 0.1° and has a very good linearity in a wide temperature range (- 20° C to + 70° C). The signal conditioning is integrated in thick film technology on one of the two plates of the sensing cell, resulting in a very compact design of the device.

INTRODUCTION

The measurement of inclination angles is a very common need in a variety of applications, ranging from scientific instrumentation and building engineering to automotive and navigation applications, just to quote a few.

There are several approaches useful to develop an inclinometer as an electrical sensor of the gravity force direction. Here, we restrict ourselves to the class of inclinometers based on the sensing of the horizontal surface which is developed by a liquid at the equilibrium under the gravity forces. Sensing of the horizontal can be accomplished by measuring, with properly arranged electrodes, a variety of electrical quantities such as resistance (for a conductive liquid), capacitance (for a dielectric liquid) or inductance (for a magnetic liquid). However, to be successful in a practical device, any proposed approach shall not only show adequate sensitivity, but also provide, by its inherent structure, more stringent requirements in terms, e.g. of dynamic range and linearity, temperature effects, supply range and power consumption, electromagnetic immunity, ambient-related stress, failure rate (or MTBF), etc. From this point of view, the resistance approach described below was selected as the best candidate to achieve high performances.

Outline of the sensor structure

The measuring cell (Fig. 1) is a cylindrical cavity obtained by bonding together two alumina plates spaced by an alumina ring a few millimiter thick. On the two plates, tow opposite pairs of semicircular electrodes faced each other, which are obtained by screen printing of conductive paste are located. The paste is cofired with a glass frit to cement the ring and the plates. A small hole is punched in one plate by a CO_2 laser, to feed the conductive liquid into the cell, and the hole is then sealed by SnPb solder. An exact quantity of liquid is fed so as to half-fill the cell. Thus, two resistances are found between the opposite electrode pairs, which are nominally equal when the cell is horizontal. By varying the inclination of an angle α, one electrode pair has a change of conductance $\Delta G_1 = G_1 (\alpha/90°)$ (α in deg.) while the other pair has a change $\Delta G_2 = -G_1(\alpha/90°)$. Therefore, in a voltage divider made by the series of resistors R_1 and R_2 fed by a supply V_o, the output voltage V is given by $V_o R_2/(R_1 + R_2) = V_o G_1/(G_1 + G_2)$ and its variation ΔV with α (i.e. the useful signal) is given by $\Delta V = V_o (\alpha/90°) G_1/(G_1 + G_2)$. This shows that the output signal is inherently a linear function of α, which for semicircular electrodes is allowed to span a dynamic range from $\alpha = -90°$ to $\alpha = +90°$. The residual linearity error found in a practical device is only due to small inaccuracies such as:

. geometrical errors in the semicircular electrode contours and in plates centering

. error in liquid height

. finite electrodes sheet resistance.

With the tolerances commonly employed in the thick film process, the typical integral linearity error of fabricated devices is ± 0.1% in the range of inclinations $-30° < \alpha < +30°$. Also, the zero bias error α_o of the sensor output respect to the mechanical reference offered by the bottom edge of the square plates is less than 0.5°, and such a small value allows an easy correction by in-circuit trimming. Because of its construction, the sensor of Fig. 1 is a 1-axis inclinometer sensitive to the rotation

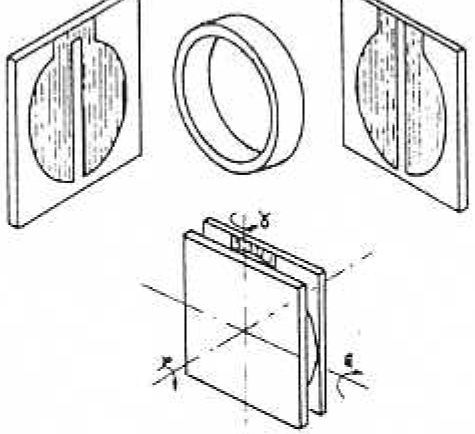
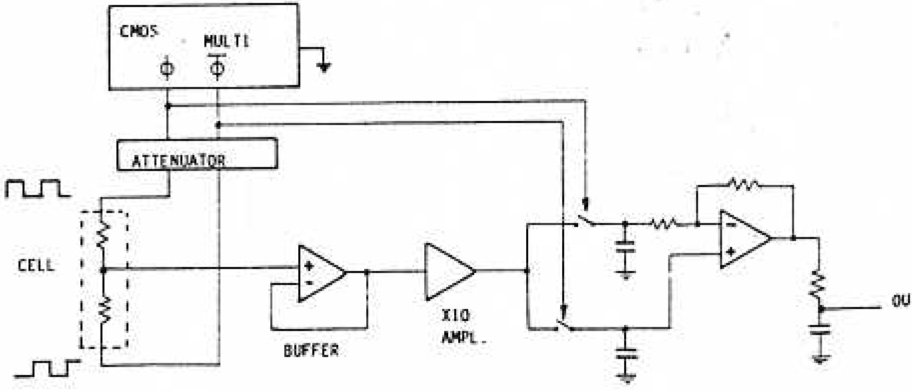


Fig. 1 - THE INCLINOMETER SENSING CELL IN ITS PARTS (TOP) AND ASSEMBLY (BOTTOM)



SYNCHRONOUS RECTIFIER

Fig. 2 - SCHEMATIC OF A ONE-AXIS INCLINOMETER CIRCUIT

α around one axis perpendicular to the plate surfaces. The cross sensitivity to rotations β (Fig. 1) is very little, typically below 0.01% of the main axis sensitivity, while respect to γ it is obviously zero.

Several issues shall be considered in order to select the conductive liquid used in the sensor. It shall firstly offer an adequate conductance to allow an easy interfacing with the circuits, shall be chemically compatible with the electrode paste and have a 90° contact angle, have a wide temperature range of liquid phase and, lastly, do not decompose under applied voltage for a long lifetime. We have selected an antifrost liquid for cars as a very cheap and viable solution. It offers ≈ 1 KΩ resistance between the cell plates, and has a wide (- 30° to + 100°C) temperature range. At small voltages, the conduction is ohmic and the temperature dependence of conductance shows an activation energy of about E_a = 1 V. Therefore, we use the liquid cell with a low (100 mV) supply voltage, with square waveform at a frequency of some KHz, so as to avoid any possible electrolysation of the liquid. Accelerated life test have demonstrated that no measurable degradation in resistance occurrs in a 2000 h period.

Finally, the liquid has a temperature range (-30° to + 100° C) suitable for most applications.

Circuit and measurements

The sensor cell provides two resistances in series, the one decreasing and the other increasing linearly with the angle α, and both being affected by the same strong (typ. - 5%/°C) temperature dependence.

Thus, the first stage of the electronic circuit (Fig. 2) is a high-impedance voltage follower with a FET input giving $\Delta V/V_0 = (\alpha/90°)G_1/(G_1 + G_2)$ independent from the cell conductance. The two cell resistors are fed by opposite-sign square waves obtained by a standard CMOS multivibrator, properly attenuated to a level V_e = 100 mV peak-to-peak. The residual DC component across the cell is less than 0.2 mV. After a suitable amplification, the signal is rectified by a synchronous rectifier comprising two CMOS switches on the inputs of an operational amplifier, operated on and off by the same square ware going to the cell.

For a two axis sensor (with two cells placed orthogonally to each other) the full circuit occupies an area of 4x2 cm² using three SSI ICs (Fig. 3).

Several units of the inclinometer have been used for a through test of performances. The integral linearity error is within ± 0.1% in the range - 30° $<\alpha<$ + 30° and within 1% up to ± 60°. Hysteresis effects are negligibly small. The noise equivalent angle, defined as the output noise divided by the responsivity of the device, was 0.005 deg/$\sqrt{\text{Hz}}$, what amounts to resolve 0.005 deg = 18 seconds of arc in a 1-Hz bandwidth with signal/noise = 1.

In the temperature range - 10 ÷ + 70° C, the output drift amounts to an angle error less than ± 0.25°; no systematic drifts were noted after several cycles from - 10° C to + 70° C and back.

Lastly, a 3-dB bandwidth of a few Hz was measured, which is adequate for most application requirements.

Conclusions

In conclusion, we have demonstrated the practical feasibility of a new concept for the measurement of inclination angle. The sensor has been fabricated in thick film technology and exhibits very good performances and projected low cost.

References

S. Donati, R. Dell'Acqua, G. Brunetti, G. Dell'Orto: Italian Patent deposited 27th January 1988.

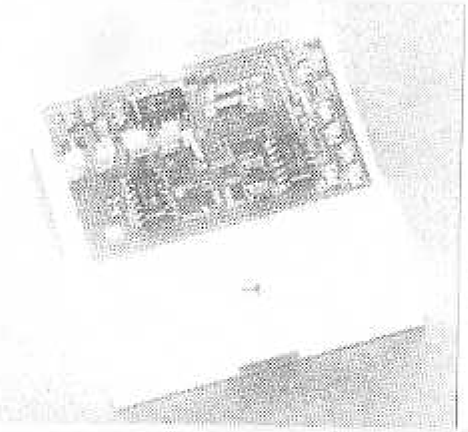


Fig. 3 - THE HYBRID CIRCUIT FOR SIGNAL CONDITIONING OF A TWO-AXIS INCLINOMETE