THE ABSOLUTE STRAIN GAUGE

W.Chr. Heerens, S.D. Tarasenko

Introduction.

The gauge factor of common strain gauges cannot be completely pre-calculated and needs calibration. Common resistive strain gauges are integrated on a dielectric carrier, which is then glued to the object under test. The deformations are transmitted via the glue and the carrier to the resistive material of the resistance and one should be directly proportional to the other. But due to non-linear creep and hysteresis effects on the resistance of the strain gauge, it turns out to be non-proportional to the strain to be measured.

Making resistive and semiconductor strain gauges with thin-film techniques provides for stable sticking of conductive gauges material to the carrier and overcomes the gluing problems. But the resistivity and resistance of every strain gauge vary more or less in different ways and cannot be completely predicted [1]. Gauges therefore have to be trimmed and calibrated before measurements are taken.

The class of flat capacitive strain gauges, developed by the authors, can also be made by the same thin-film techniques. But it will be proved that putting a pattern of rather good conductive material directly on top of an insulating layer on the surface of the object under test will provide for reliable strain gauges without any practical influences of thickness and remaining resistance of the conductive layer. It's possible to see, that the variation of capacitance is in a pre-calculable way linearly dependent only on the length variation of the sensor and is almost completely independent of its perpendicular contraction.

Methods of Investigations and Theoretical Background.

Using the uniplanar three-terminal capacitance concept [2,3], a capacitive sensor that meets all of the demands necessary for making precision strain gauges was designed and optimized.

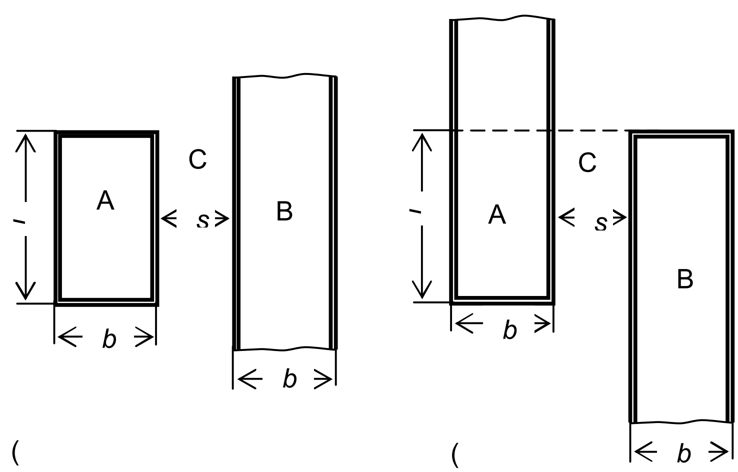

Fig. 1. Basic uniplanar capacitive configuration.

The absolute capacitive strain gauge is based on the uniplanar capacitance principle given by Tarasenko [3,4] and Heerens [5]. For the configuration of Fig. l (a), the capacitance between electrodes A and B, where C, the rest of the surface, acts as a guard electrode, is given by

$$\mathrm{C_{AB}} = \frac{\varepsilon_0 \varepsilon_r l}{\pi} \ln\left[\frac{(s+b_1)(s+b_2)}{s(s+b_1+b_2)}\right] \tag{1}$$

This is in the case that the strip electrode B is much longer than length s, b_1 and b_2 respectively. In practice much longer means > $5(s+b_1+b_2)$.

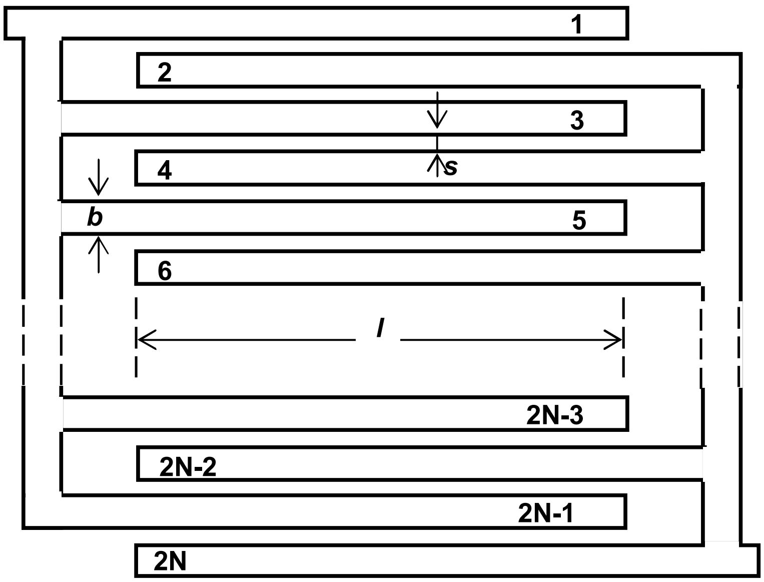

Fig. 2. Inserted comb structure.

If we take the configuration of Fig.1 (b), where both strip electrodes A and B end father away than $5(s+b_1+b_2)$, the capacitance between both strip is also given by eqn. (1). For a given s and total width $W = s + b_1 + b_2$, we can find a maximal capacitance value if $b_1 = b_2 = b$ in egn. (1).

To increase the total capacitance of a capacitive configuration, based on the principle of Fig.1 (b), we can use inserted comb structures like those shown in Fig.2. If we substitute the strip-width guard-width radio $r = b/s$, the partial capacitance between tooth 1 and tooth 2 will given as

$$\mathrm{C_{12}} = \frac{\varepsilon_0 \varepsilon_r l}{\pi} \ln\left[\frac{(1+r)^2}{(1+2r)}\right] \tag{2}$$

But there exist partial capacitance contributions between each tooth of comb electrode A and B each tooth of comb electrode B, and it can be proved that the total capacitance of the whole comb structure is given by

$$\mathrm{C_{TOT}} = \sum_{i=1}^{n} (2N-2i+1) \frac{\varepsilon_0 \varepsilon_r l}{\pi} \ln\left(\frac{(2i-1)^2 (r+1)^2}{[(2i-1)(r+1)]^2 - r^2}\right) \tag{3}$$

The total width of the comb structure can be defined as $W_{TOT} = (2N(r+1)-1)s$. We can define a "capacitive density" as $D_C = C_{TOT} / W_{TOT}$, while for maximum C_{TOT} we will have to maximize D_C by optimizing the value of r in

$$D_C = \frac{\varepsilon_0 \varepsilon_r}{\pi} \frac{l}{s} \sum_{i=1}^{n} \frac{(2N-2i+1)}{2N(r+1)-1} \ln\left(\frac{(2i-1)^2 (r+1)^2}{[(2i-1)(r+1)]^2 - r^2}\right) \tag{4}$$

These calculations show that for almost any value of N the optimal radio r is so close to three that for easy fabrication the value $r = 3$ is the best choice. The worst care for $r = 3$ instead of its optimal value gives a capacitance less then 4% lower than the maximum possible one.

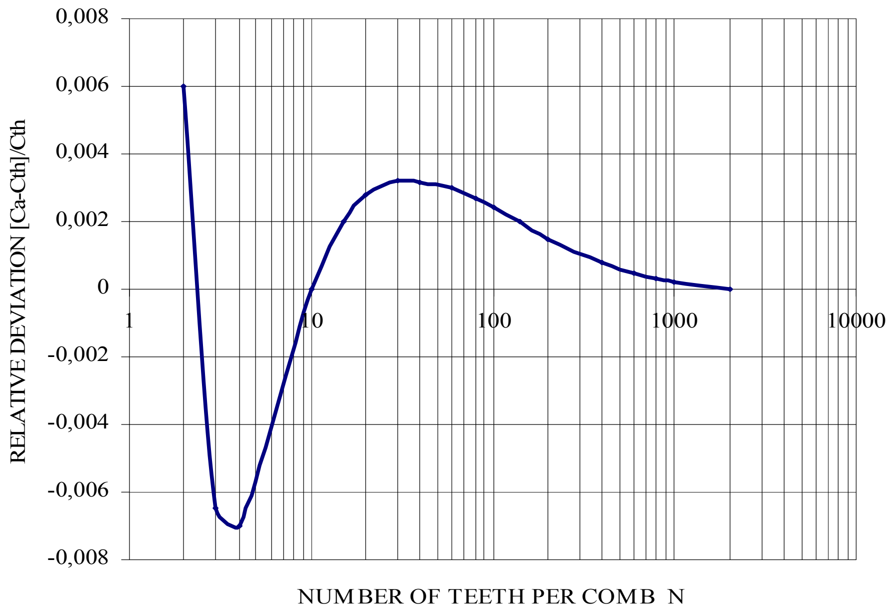

Fig. 3. Relative deviation between approximate and theoretical capacitance calculations for various numbers of teeth per comb.

Using the practical radio $r = 3$ in eqn. (3), we have to calculate the theoretical values C_{th} for various N by means of

$$C_{th} = \sum_{i=1}^{n} (2N-2i+1) \frac{\varepsilon_0 \varepsilon_r l}{\pi} \ln\left(\frac{(2i-1)^2 16}{(2i-1)^2 16 - 9}\right) \tag{5}$$

Using curve fitting with the results of this analytical calculation for $\varepsilon_r = 1$, we can define a simple calculation formula for this capacitance:

$$C_A = \frac{\varepsilon_0 \varepsilon_r l}{\pi} \ln\left(\frac{116}{17}\right) \frac{N^2}{N+1} \tag{6}$$

Together with the deviation curve of Fig. 3, this provides for accurate fast and easy capacitance calculations in strain gauge designs.

Results and discussions.

<u>The Absolute Character of the Capacitive Strain Gauge.</u>

Equations (5) and (6) shows that, for given values of N and r, the change in capacitance principally only depends on the change in the length l and variations in ε_r. The influence of ε_r can be eliminated if the environment above the device is properly conditioned. If that environment is air, the influence of pressure is $5x10^{-9}$ per Pascal.

The influence of the change in length on the capacitance of the comb structure is perfectly linear and the gauge factor k has by definition the value one in

$$\frac{\Delta C}{C_A} = k \frac{\Delta l}{l} \tag{7}$$

In contrast to resistive strain gauges, the electrical characteristics of the electrode layer in the capacitive strain gauge are not crucial, because the impedance of the capacitor is a factor of 10^6 to 10^7 higher than the residual layer resistances. This is also the reason that internal creep and hysteresis in the sensor have no influences on the measuring results: another reason for declaring this type of gauge to be absolute.

Practical Dimensioning of the Gauge

Good insight into the possibilities of the gauge can be obtained by calculating two realistic designs. Table 1 gives the dimensioning data and calculation result, taking into account that with common three-terminal capacitor measuring systems, a capacitance of $5x10^{-7}$ pF can be detected.

TABLE 1. Expected performances of two realistic strain gauge designs

Guard width s (μm)	20	20
Ratio r	3	3
Number of teeth per comb N	20	50
Total width W_{TOT} (mm)	3.2	8.0
Effective length L (mm)	10	20
Expected capacitance C_{th} (pF)	1.028	5.290
Measurable strain ε	$5x10^{-7}$	$1x10^{-7}$
Comparable results for common strain gauges ϵ	$5x10^{-6}$	$1x10^{-6}$

Investigations on a Printed Circuit Board Prototype

To compare the theoretical concept of the comb structure with practical results, a prototype was made on a printed circuit board according to the layout of Fig.4. The total sensor length was 0.1905 m and N was 10. It was possible to switch off each tooth per comb, so for extra checking we could measure the so called "in-between" capacitances. These values are formed by N teeth in one comb and N-1 teeth in the other one.

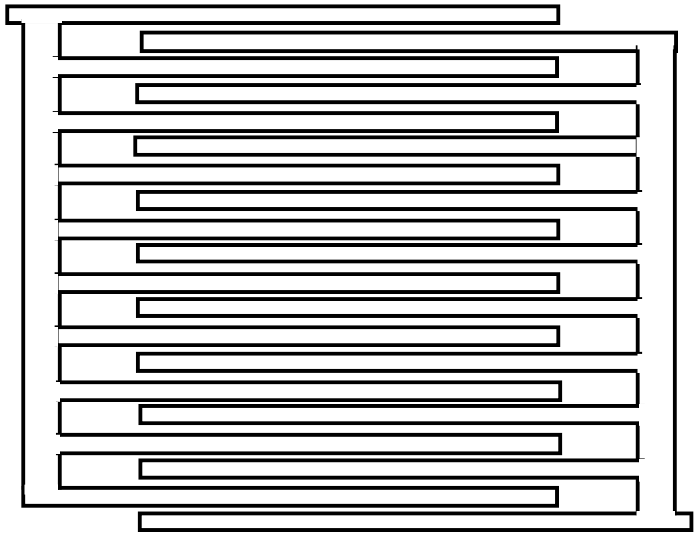

Fig. 4. Lay-out of printed circuit board prototype.

The ratio between C_{th} and the measured value C_m is 0.99845 for $N=l$ and almost linearly increases to 1.01909 for N=10. The finite length of the structure might cause this. But more probably the manufacturing tolerances in the widths *s* and *b* are the cause because they have expected influences of more than 1% in this case.

Conclusions

At the moment other experiments for making integrated circuit design prototypes of this type of gauge are in progress. In advance of these investigations, we can already make a comparison between common resistive or semiconductor strain gauges and this new type of absolute three-terminal capacitor strain gauge.

In Table 2 this comparison is made by using references 6-9. It can be seen that temperature compensation is necessary only for zero shift, due to changes in length of the strain gauge, caused by temperature expansion of the strain-inducing device.

TABLE 2. Comparison of possible influences on gauge charagteristics

Influence on measurement results of	Resistive or semiconductor strain gauges	Uniplanar capacitive strain gauge
Hysteresis	Exist	Can exist, excludable in simple design
Creep	Exist	Can exist, excludable in simple design
Orthogonal contractions or elongations	Exist	Absent
Temperature-induced changes in absolute sensitivity via changes in	Exist, removable by second gauge	Absent

dimensions		
Zero shift by temperature-induced length variations	Exist in all directions, removable by second gauge	Exist only in gauge direction, removable by second gauge
Chosen value of resistivity	Exist, gauge needs to be trimmed	Absent, gauge needs no trimming
Temperature changes of resistivity	Exist, removable by second gauge	Absent
Measure of deformation	Exist	Absent
Connection lead resistance troubles	Exist	Absent
Long connecting cable problems	Exist	Absent for three-terminal a.c. system
Electrostatic residual effect	Exist above 50 V	Absent for three-terminal a.c. system
Effect of external electric fields	Hardly exist	Exist, easy to eliminate
Nuclear radiation problems	Negligible	Absent
Zero drift due to extreme high-temperature exposure	As a rule exist	Excluded in simple design
Drift due to fatigue testing	Exist	Absent

An identical capacitive strain gauge as a reference at a place that is not undergoing deformation by stress is sufficient.

Using no temperature compensation at all, the measurement of strain in a material with a linear temperature expansion coefficient of 10^{-5}/°C would be affected by a systematic error of 10 μ-strain /°C. Therefore capacitive strain gauges of this type are less sensitive to temperature effects.

A very important fact is that capacitive strain gauges do not have any dissipation of energy at all, in contrast to resistive strain gauges. An interesting application will be the direct and absolute measurement of the Poisson contraction μ by making two identical capacitive strain gauges on a specimen, one parallel to the stress direction, the other perpendicular to it, measuring the relative change of capacitances and calculation their ratio.

Recent designs for thin-film resistive strain gauges [7-9] show that extremely accurate measurements require four wires, two for providing current and two for the voltage measurements. In that case there is no longer so much difference between the unconventional concept and the capacitive strain gauge concept with two coaxial cables.

Finally, the combination of pre-calculable deformation sensors with predictable behavior to perpendicular deformation and overall temperature, together with modern sensitive three-terminal capacitive measurement equipment, will provide for accurate measurement of strain, force and pressure.

REFERENCES

1. K. Bethe, Sensoren mit Dunnfilm-Dehnungsmessstreifen aus Metalliscen und Halbleiter Materialen, *Sensoren – Technologie und Anwendungen,* NTG-Fachberichte, Vol. 79, 1982, pp. 168-176.
2. W. Chr. Heerens, Application of capacitance techniques in senor designs, *J. Phys. E: Sci. Instrum., 19* (1986) 897 – 906.
3. Tinsley Telcom Ltd, *Strain Gauges,* TTL Publication, 2005.
4. Philipse Guide to Strain Gauges, Philips Publication, 2003.