A Low-Cost, Stable Reference Capacitor for Capacitive Sensor Systems

Ferry N. Toth, Dorus Bertels, Gerard C. M. Meijer

***Abstract*—A low-cost reference capacitor has been developed for capacitive sensor systems. The capacitance has been constructed using low-cost material. Over a temperature range from −25 to +75°C the temperature coefficient is less than 18 ppm/°C.**

I. Introduction

MANY capacitive sensor systems require a low-cost reference capacitor with a very high stability [1]–[4]. In these systems an accurately known value is not essential, since an overall system calibration will be performed. Table I shows a set of possible specifications for such a reference capacitor.

In general, the stability of capacitors is influenced by both geometrical properties, such as electrode area, electrode distance, bending, shift and tilt; and material properties, such as the permittivity of the dielectric. Furthermore, contamination and humidity can also greatly influence the capacitance. Of course, many problems can be solved by applying materials with a very low thermal-expansion coefficient as a substrate. For instance, Zerodur glass with gold-plated electrodes can be used. However, the cost of the resulting capacitor would be too high for applications in consumer and low-cost industrial products.

So that the reference capacitor can track the capacitance of the sensing capacitor, the same type of dielectric is necessary. The reference capacitor can be constructed as a simple parallel-plate capacitor. This type of capacitor has several advantages:

- the capacitance is easy to calculate,
- the capacitance is insensitive to lateral displacements of the electrodes, and
- the capacitance is relatively insensitive to the tilt of the electrodes.

Unfortunately this type of electrode is very sensitive to changes in the electrode distance and to bending, which are very likely to occur when low-cost materials, with unmatched thermal coefficients of expansion, are used.

The geometrical problems can be solved by using a cross-capacitor as proposed by Thompson and Lampard [5]. In this paper, we present a low-cost version of this type of reference capacitor. A modified geometry is applied to simplify the mechanical construction.

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TABLE I
Possible Specifications for a Low-Cost Reference Capacitor

Parameter	Specification	Remarks
Capacitance	< 1 pF	The capacitance should be of the same order of magnitude as the sensing capacitor, which often ranges from 0.1 to 1 pF
Long-term drift	< 1000 ppm / 10 years	This requirement depends on the period between recalibrations
Temperature coefficient	< 20 ppm/°C	Over a temperature range from -25°C to +75°
Humidity effect	< 1000 ppm	Must track the sensing capacitance. The effect on the ratio must be small
Contamination effect	< 1000 ppm	Contamination can be caused by condensed water droplets, water absorption by the insulators, etc.
Cost	< 1$	For application in consumer and low-cost industrial applications

II. Basic Principles

Thompson and Lampard have shown that in an (otherwise arbitrary) line-symmetrical conductive cylindrical shell divided into four parts (Fig. 1), the value of the cross-capacitances is equal to

$$C_{cross} = \left(\frac{\epsilon \ln 2}{\pi}\right) \cdot l \tag{1}$$

where l is the length of the shell, and ε is the permittivity. This capacitance depends only on the length, and not on the distance between the electrodes. This property makes the value easy to calculate. The experimental version proposed by Thompson and Lampard (Fig. 2) is not very suitable for our purpose, since the materials and structure make fabrication rather costly.

Heerens [6], [7] presented an analysis of various types of capacitors, including a circular cross-capacitor (Fig. 3). The advantage of this type of capacitor is its symmetric and simple construction.

When $R \gg d$, the capacitance value C_c amounts to

$$C_c = \left(\frac{\varepsilon \ln 2}{\pi}\right) \cdot 2\pi R \cdot \left[1 + 0.00043507\left(\frac{d}{R}\right) - 0.050\,631\,437\left(\frac{d}{R}\right)^2 + \cdots\right]. \tag{2}$$

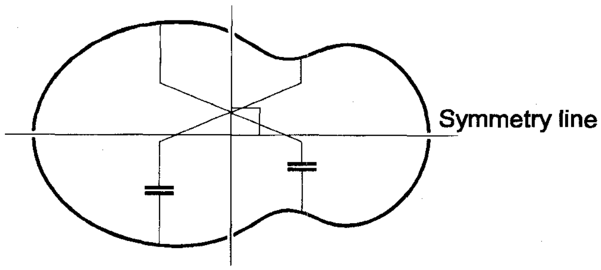

Fig. 1. Cross section of cylindrical shell.

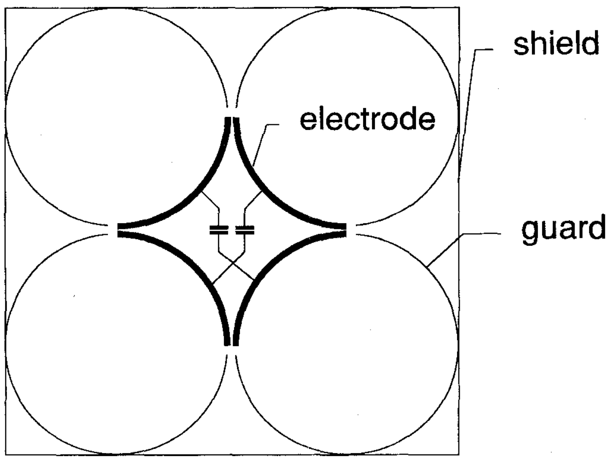

Fig. 2. Cross section of Thompson–Lampard capacitor.

In a practical implementation, however, the diameter of the structure is limited, and some sort of spacer is necessary.

A. Spacer

With an outer spacer, serious problems arise when the thermal expansion coefficients of the different materials do not match. This mismatch can lead to mechanical stress and unpredictable mechanical distortions of the shape. Since the electrodes are constructed out of printed-circuit board (PCB), an outer spacer is not feasible.

An inner spacer at the center of the circular electrodes shows a much better mechanical stability because of the one-point connection between the electrodes and because of the symmetry of the structure. However, it does influence the electric field and therefore the capacitance. This can be resolved by applying guard electrodes.

B. Linear Thompson–Lampard Capacitor

Analytical calculations on the circular structure are complex, since the cross-capacitances are described by a sum of Bessel functions. Numerical solutions based on the finite-element package "Maxwell" do not yield the desired accuracy.

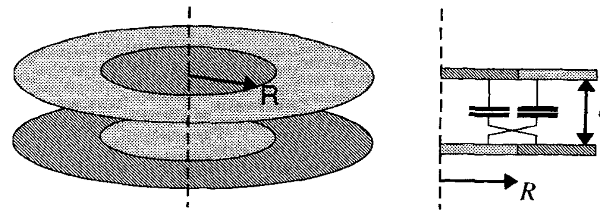

Fig. 3. A circular cross-capacitance.

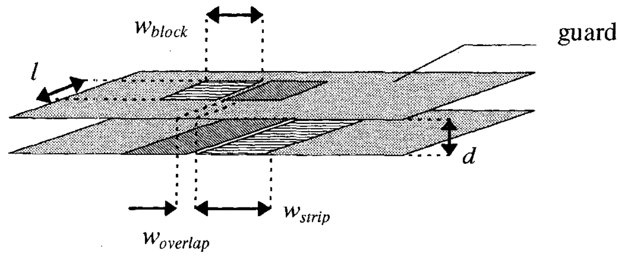

Fig. 4. Strip-block capacitor.

Therefore, to calculate the sensitivities for lateral displacements and electrode-distance variations, we will approximate the circular structure by a strip-block capacitor (Fig. 4). Heerens [7] shows that the strip-block capacitor can be treated as a transformation of the circular structure (with guard electrodes), where the radius R becomes infinite. An analytical solution does exist for this type of capacitor, as shown in (3), at the bottom of the page. By adding both cross-capacitances and assuming w_{strip} and $w_{block} \gg w_{overlap}$, we arrive at

$$C_b \approx \frac{\varepsilon l}{\pi}\left\{\ln 2 + \ln\left[\cosh\left(\frac{\pi w_{overlap}}{2d}\right)\right]\right\}. \tag{4}$$

Since the strip-block capacitor is less symmetrical then the circular cross-capacitance, the sensitivity to parameter variations can be larger. Therefore (4) can be used as a basis to calculate the worst-case sensitivities of the summed cross-capacitances.

III. Nonidealities

A. Guard Electrodes

The guard electrodes ensure that the capacitance will not be influenced by the field changes caused by the spacer. To limit the influence of the guard electrode on the capacitance, Heerens' guard rule [7] for capacitive sensors was applied

$$\delta < e^{-\pi x/d} \tag{5}$$

$$C_s = \frac{\varepsilon l}{\pi}\ln\cdot\left\{\frac{\cosh\left(\frac{\pi w_{overlap}}{2d}\right)\cosh\left[\frac{\pi(w_{overlap}-w_{strip}-w_{block})}{2d}\right]}{\cosh\left[\frac{\pi(w_{overlap}-w_{block})}{2d}\right]\cosh\left[\frac{\pi(w_{overlap}-w_{strip})}{2d}\right]}\right\}. \tag{3}$$

where δ is the relative error, x is the guard width, and d is the electrode distance. Therefore, when guards with a width larger than $3d$ are applied, the relative error will be less than 100 ppm.

B. Gaps

Although gaps are necessary between electrodes, they distort the electric field and therefore influence the capacitance. This influence can be limited by applying Heerens' gap rule [7] for capacitive sensors

$$\delta < e^{-\pi d/s} \tag{6}$$

where s is the gap width. When the gap width is chosen to be smaller than $\frac{1}{3}$ of the electrode distance, the error is less than 100 ppm.

C. Sensitivity to Electrode Distance Variations

An imperfect alignment causes a sensitivity to distance variations. For the strip-block capacitor this sensitivity can be easily calculated from (4)

$$\begin{aligned} S_d &= \frac{1}{C_b}\frac{\partial C_b}{\partial d} \\ &\approx \frac{-\pi^2}{4(d^3 \ln 2)} w_{overlap}^2. \end{aligned} \tag{7}$$

For the circular cross-capacitor, sensitivities of the same order of magnitude can be expected. With an estimate alignment error $w_{overlap}$ of 0.1 mm and with an electrode distance d of 1 mm, the sensitivity of a circular cross-capacitor amounts to 36 ppm/μm. For a simple parallel-plate capacitor, this would be 1000 ppm/μm. For example, if the spacer had a thermal expansion coefficient of 10 ppm/K, the contribution to the temperature coefficient of a parallel-plate capacitor would be 10 ppm/K too. However, the temperature coefficient of the circular cross-capacitor will be only 0.36 ppm/K.

D. Sensitivity to Lateral Displacements

The cross-capacitance is also sensitive to lateral displacements, although they are normally limited by the spacer. In the case of the circular cross-capacitor this sensitivity is very small, because the lateral displacement on one side of the spacer is compensated on the other side.

When the strip-block model is used as a first-order approximation, we find a zero sensitivity. This is due to compensation. With a circular cross-capacitor, we can expect a small residual sensitivity.

E. Sensitivity to the Tilt of the Electrodes

According to Thompson and Lampard, provided that the structure is line symmetrical and the electrodes are correctly aligned, the capacitance will always equal $\varepsilon l/(\pi \ln 2)$. Tilt can then be described as a change in the line of symmetry together with a lateral displacement of the electrodes. The displacement can be calculated from

$$\begin{aligned} \delta_\alpha &= R\left[\frac{1}{\cos\left(\frac{\alpha}{2}\right)} - 1\right] \\ &\approx R\frac{\alpha}{2} \end{aligned} \tag{8}$$

where α is the angle of the tilt and R is as in Fig. 3. In our experimental electrode R equals 12 mm; therefore, a tilt of 1° or 17 mrad will cause a displacement of 0.1 mm.

F. Bending of the Electrodes

Since the actual electrodes are at some distance from the center of the structure, electrode bending can be described in terms of electrode tilt and distance variations. The sensitivity to these parameters has been discussed in the previous sections.

G. Humidity

In most applications the reference electrode will be used to measure a capacitance ratio. If the other capacitance is also an air capacitor, the ratio will be independent of the permittivity and therefore of the humidity. However, in case the other capacitor is not an air capacitor, the dielectric constant can be estimated by [8]

$$\varepsilon_{moist\,air} = \frac{a_1}{T}\left[P + \frac{a_2 P_s}{T} H\right] 10^{-3} \tag{9}$$

in which

$$\begin{aligned} a_1 &= 28 \times 10^{-3} \text{K/Pa} \\ a_2 &= 48\text{K} \end{aligned}$$

where T is the absolute temperature in K, P is the pressure of the moist air, P_s is the pressure of saturated water vapor at temperature T, and H is the relative humidity. With T = 348 K and H = 20–60% the maximum change in permittivity can be estimated to be 1000 ppm.

H. Electrode Contamination

Much work has been done in the past [9]–[12] on anomalous humidity effects. This work shows that at higher humidities, layers of water molecules can be expected to appear on the electrodes or to be absorbed by the insulators. It should be clear from the previous sections that neither of these should have a great impact on the measurement results. Conductive layers of water, on the other hand, will short-circuit the electrodes with the guards and make measurement impossible.

IV. Experimental Results

The circular cross-capacitor has been constructed according to Fig. 5, resulting in a cross-capacitor of approximately 0.15 pF and a trans-capacitor of 2.5 pF. The electrodes have been made of 1.5 mm thick double-sided PCB and the spacer of glass ceramic. During testing one capacitor was placed inside a climate chamber, and a second one was placed outside it as a reference. Measurements were performed using a modified-Martin oscillator (a linear first-order RC-oscillator)

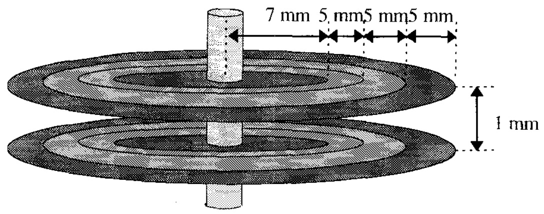

Fig. 5. Experimental version of the circular cross-capacitor.

in combination with an 80C51FA microcontroller [13]. This system allowed us to measure both trans-capacitances and cross-capacitances. The microcontroller was connected to a PC, where a short program written in LabView obtains the trans-capacitances, the cross-capacitances and a time stamp and writes the values to disk.

A. Temperature Cycle from −25°C to +80°C

Both capacitors (one inside and one outside the climate chamber) with their cross-capacitances and trans-capacitances were measured as a function of time. The cross-capacitor outside the climate chamber was used as the reference, to reduce temperature effects on the measurement system to an insignificant level. After a burn-in cycle, the temperature was increased to 80°C, decreased to 20°C, further decreased to −25°C and then back to 20°C.

Fig. 6 shows the measured changes in the cross-capacitances and trans-capacitances, resulting in temperature coefficients of 18 ppm/°C and 115 ppm/°C, respectively. From (2) it can easily be seen that the capacitance is proportional to the electrode radius. Therefore, the temperature coefficient of the capacitance will be equal to the thermal expansion coefficient. If a lower temperature coefficient is required, a material with a lower thermal-expansion coefficient can be used. Temperature compensation can also be applied. This is especially practical when the capacitance is used as a reference (and when capacitance ratios are measured). In that case

$$\frac{C_x(T)}{C_{ref}(T)} = \frac{C_x(T)}{C_{ref} \cdot (1 + \Delta T\, T_C)} \approx \frac{C_x(T)}{C_{ref}}(1 - \Delta T\; T_C) \tag{10}$$

where $C_x(T)$ is the capacitance to be measured at temperature T, $C_{ref}(T)$ is the capacitance of the reference at temperature T, C_{ref} is the capacitance of the reference at room temperature, ΔT is the temperature change, and T_C is the temperature coefficient.

During the heating phase from −25 to +20°C a very rapid change in capacitance is observed. This can be attributed to the rapid change in the temperature of the air compared to that of the electrodes. As a result, droplets are formed on the electrodes. These eventually short-circuit the inputs of the measurement system and cause the oscillator to stop. Consequently a failure of this kind is very easy to detect.

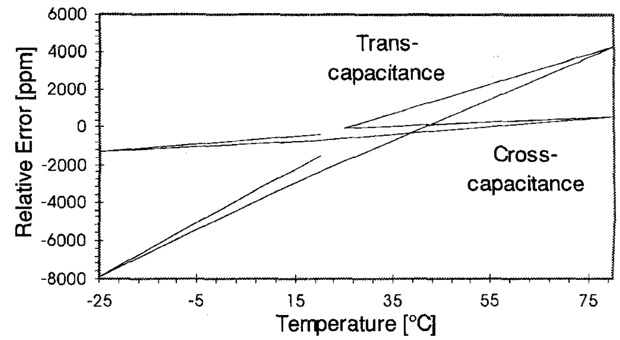

Fig. 6. Capacitance error versus temperature.

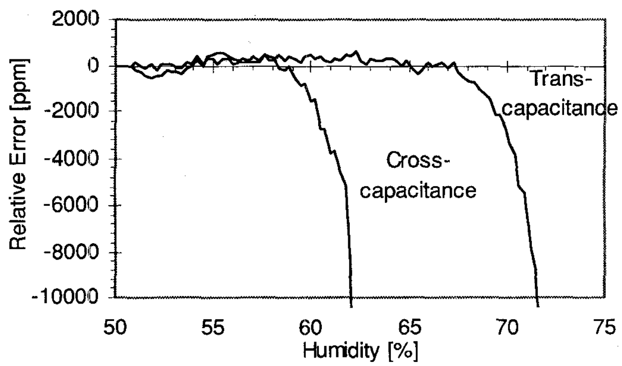

Fig. 7. Increasing humidity with 0.2%/min at 80°C.

B. Humidity Effects at 20°C and 80°C

The results of the previous section raised some questions about how the cross-capacitor behaves at high humidity levels. Therefore, additional measurements were performed at respectively 20°C and 80°C (Fig. 7). At 80°C and 60% humidity the capacitance suddenly drops due to short-circuiting between the electrodes and the guards. At 20°C and 90% humidity similar behavior is observed. Shortly after the conductive layer is formed, the oscillator in the measuring circuit stops.

V. Conclusions

A prototype of a circular cross-capacitor has been made, using a 1.5 mm printed circuit board (PCB). The electrodes were glued to a ceramic spacer of 1 mm. Over a temperature range from −25 to +75°C the measured temperature coefficient amounted to only 18 ppm/°C. Most of this can be attributed to the thermal expansion of the electrode material. As for the effects of contamination and humidity on the stability of the capacitances, measurements have shown the effects of noncondensing humidity to be less than 1000 ppm. Condensing moisture causes large errors, which can easily be detected.

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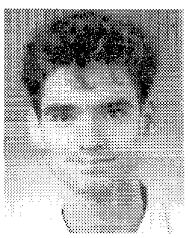

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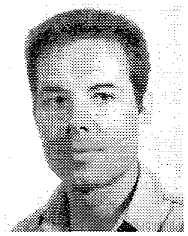

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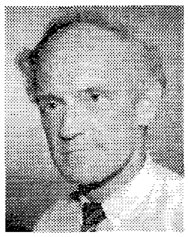

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