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Identification and Automatic Compensation of Variable-Parallel-Conductance Effect in Capacitive Sensors

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Abstract:

Among some disadvantages, capacitive sensors are attributed with low manufacturing costs, the simple construction and flexible form as well as low power consumption. By issue of advanced silicon technology interfacing circuits for capacitive sensors is no more a difficulty.

Switched capacitor technique combined with sigma-delta modulators is very attractive Signal processing method for capacitive sensors. However this interfacing technique needs high speed and precise switches, with low charge injection and ultra-short break-before-make time. The latter requirement finds great importance, when the capacitive sensor has a considerable conductance. The situation will be more dramatic if the parallel conductance doesn't remain constant and depending on environmental conditions varies during the measurement. This paper introduces a method, which identifies and compensates the variable-parallel-conductance effect in capacitive sensors automatically.

Key words: Capacitive sensors, switched capacitor circuit, parallel conductance, time varying, and measurement error.

Introduction

Capacitive sensors can directly measure a variety of physical parameters. The most important are dielectric measurements and geometrical measurements. Indirectly, measure capacitive sensors many other variables which can be converted into motion or dielectric constant [1]. The main disadvantages are the presence of parasitic elements, mainly sensor conductance.

By issue of advanced silicon technology signal processing circuits for capacitive sensors is no more a difficulty. This art of sensor interfacing has a large potential to be realized as ultra-compact and low power integrated sensor interface [2].

Common signal processing circuits for capacitive sensors are square wave driven AC-Bridge and harmonic driven AC-Bridge. Recently the sigma-delta modulators and switched capacitor circuits were developed and used widely [3]. However these two techniques need high speed and precise switches, with low charge injection and ultra-short break-before-make time. The latter requirement finds great importance, when the capacitive sensor has a considerable conductance for example in the case of concentration measurement or determining the relative dielectric constant. The situation will be more dramatic if the parallel conductance is not constant and varies depending on environmental conditions (such as contamination accumulation on the sensor environment) during the measurements. This is the case especially in industrial and other contaminated working environment. In this case we are encountered with a time varying sensor characteristics.

Effect of parallel conductance in a switched capacitor interface

A generic switched capacitor interfacing circuit is depicted in Fig. 1. The on-resistance of the switching elements SW is neglected and the conductance of the sensor element C_s is modeled with R_p [4].

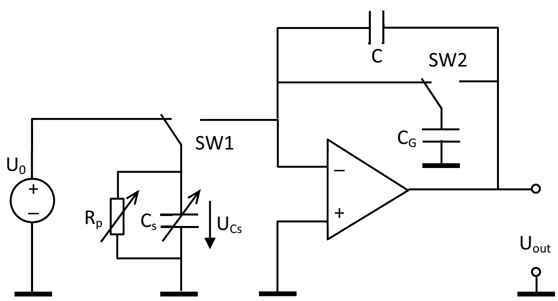

Fig. 1. Generic switched capacitor sensor interface (capacitive sensor Cs with parallel conductance Rp).

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With ideal switching elements a measurement cycle consists of two steps (Fig 2a):

1. Charging phase: the sensor is charged up to U_0 (switch on left state 1)
2. Measurement phase: the sensor is discharged on op-amp input (switch on right state 2)

These steps are repeated with a switching frequency f_{sw}.

In real switching elements to avoid momentary shorting when switching channels a delay time between breaking and making is provided (so called break-before-make delay). In this case a measurement cycle consists of three phases (Fig. 2b):

1. Charging phase: the sensor is charged up to U_0 (switch on the left state 1)
2. Break-Before-Make phase: The sensor voltage doesn't change and remains on the level of U_0 (switch on the idle state 2)
3. Measurement phase: the sensor is discharged on op-amp input (switch on the right state 3)

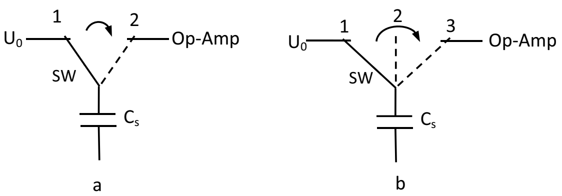

Fig. 2. Switching states of an ideal switch (a) and a real switch (b)

In presence of a sensor parallel conductance the sensor is charged as before during the charging phase up to U_0, but during the Break-Before-Make time (state 2) the saved charge in the sensor is dissipated in sensor conductance. This leads to an exponential decay of sensor voltage. Hence the charge amplifier experiences less charge in the measuring phase, which causes a measuring error in turn, dependent on sensor conductance and t_{BBM}. Fig. 3 depicts the error in output voltage due to variation in parallel conductance of the sensor. This effect appears especially when the used switching element has a considerable break-before-make time delay.

The measurement error can be calculated analytically as below. The output voltage for a sensor without conductance is calculated as [5]

$$U_{out} = \frac{-U_{Cs}}{C_G} C_S = \frac{-U_0}{C_G} C_S \qquad (1)$$

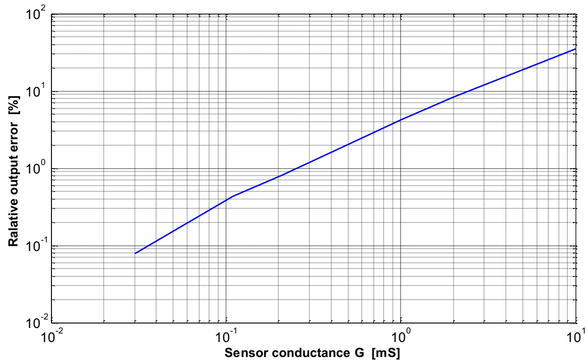

Fig. 3. Measurement error because of sensor conductance in a capacitive sensor with switched capacitor interface circuit having break-before-make time delay.

where C_G is a gain regulating capacitor. In presence of a sensor conductance $G=1/R_p$ the sensor voltage U_{Cs} in the charging phase is as eq. (1). In the measuring phase after a break-before-make time t_{BBM} the output voltage is

$$U_{out-cond.} = \frac{-U_{Cs}}{C_G} C_S = \frac{-U_0}{C_G} \exp\left(-\frac{t_{BBM}}{R_p C_S}\right) C_S \qquad (2)$$

The measurement error due to the sensor conductance is therefore

$$\Delta U_{out} = 1-\exp\left(-\frac{t_{BBM}}{R_p C_S}\right) = 1-\exp\left(-\frac{t_{BBM}}{R_p C_S}\right) \qquad (3)$$

According to eq. (3) the multiplicative measurement error is an exponential function, which increases with increasing the sensor conductance and the break-before-make time delay as well.

In real capacitive sensors the capacitance of the sensor varies around a constant offset value $C_s=C_{0s}\pm\Delta C_s$. In order to increase the measurement sensitivity, normally the offset is compensated in the interface circuit. This can be done for example with the circuit shown in Fig.4.

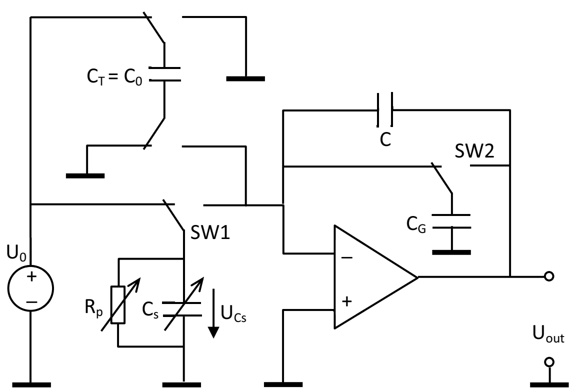

Fig. 4. Compensation of sensor offset in interfacing circuit by using a constant capacitance C_T.

For $C_T = C_{0s}$ the output voltage is proportional to the capacitance deviations $\pm\Delta C_s$. The used constant compensating capacitor C_T for this purpose shall be very stable in capacitance for a long period.

Effect of sensor parallel conductance on output voltage of the interfacing circuit for given t_{BBM} and R_p is depicted in Fig 5. The solid curve is the output voltage for a sensor with zero conductance ($R_p=\infty$). At $t=2\ ms$ the sensor capacitance changes from C_{0s} to $C_{0s}+\Delta C_s$. With $C_T=C_{0s}$ the output voltage for $t<2\ ms$ is fully compensated and is equal to Zero. Increasing the sensor parallel conductance leads to a considerable measurement error (dashed line). The offset in the time interval *0-2 ms* in presence of a sensor parallel conductance is not completely compensated. Moreover the output voltage due to the ΔC_s is not correct. The measurement error for a parallel conductance of *0.3 mS* amounts to 5%.

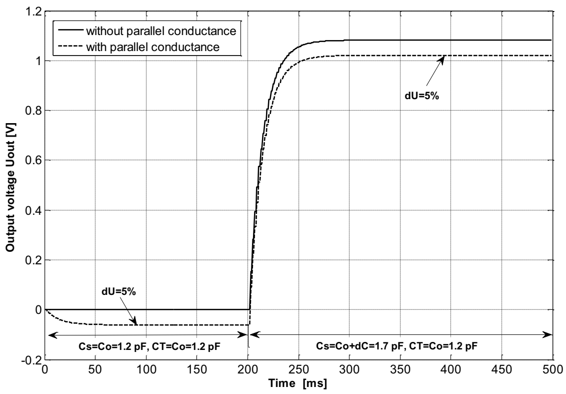

Fig. 5. Measurement error due to sensor parallel conductance.

The sensor parallel conductance influences the output voltage not only for $t>2\ ms$, but also for $t<2\ ms$. This is because the both constant and variable parts of the sensor are affected by parallel conductance, where the constant capacitor C_T is not affected by parallel conductance. In other words occurs an imbalance in offset compensation so that $U_{out} \propto \Delta C_s$ holds no more. In this case the output voltage is calculated as

$$U = \frac{-U_0}{C_G}\exp\left(-\frac{t_{BBM}}{R_p C_S}\right)C_S + \frac{U_0}{C_G}C_T \qquad (4)$$

With $C_T=C_{0s}$ and $C_s=C_{0s}+\Delta C_s$

$$U = \frac{-U_0}{C_G}\left(\exp\left(-\frac{t_{BBM}}{R_p C_S}\right)-1\right)C_{0S} - \frac{U_0}{C_G}\exp\left(-\frac{t_{BBM}}{R_p C_S}\right)\Delta C_s \qquad (5)$$

For $t_{BBM}=0$ or $R_p=\infty$ the offset is fully compensated and the output voltage is proportional to $\pm\Delta C_s$. Otherwise the offset compensation with this circuit is no more possible, especially when parallel conductance varies randomly.

Identification of variable parallel conductance of capacitive sensor

According to eq. (2) parallel conductance of sensor leads to a multiplicative error. Normally multiplicative type errors can be compensated by multiplying the output by inverse of the error term. In this case the multiplicative error term contains two unknown parameters R_p and C_s. In a digital signal processing circuit the C_s value can be evaluated and fed back to the compensation block, but there is no information about the sensor parallel conductance R_p which can change during the measurement randomly.

In order to identify the sensor parallel conductance a known resistor R_s is connected in series with the sensor as Fig. 6. In other words we build a voltage divider consisting of R_s and R_p. For calculation of R_p the voltage of the sensor element is sampled and measured steadily. The sensor voltage and the R_s as well as U_0 as constant values are fed into the compensator block. The compensator calculates the conductance $G=1/Rp$ as following:

$$R_p = \frac{U_{Cs}\cdot R_S}{U_0 - U_{Cs}} \qquad (6)$$

In order to keep the voltage of the sensor near to U_o, the R_s shall be smaller than 0.1 $R_{p\text{-}min}$.

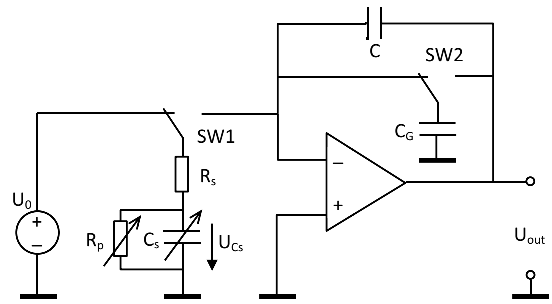

Fig. 6. Circuit for identification of sensor parallel conductance by using a resistor R_s connected in series to the sensors.

Now we consider the above mentioned three phases of the measurement cycle as below:

1. Charging phase: the sensor is charged through the voltage divider R_s and R_p. The sensor voltage at the end of the charging phase is now

$$U_{Cs-1} = U_0\frac{R_p}{R_p + R_s} \qquad (7)$$

2. Break-Before-Make phase: the charge stored in the sensor is dissipated in parallel conductance of the sensor. The sensor voltage at the end of this phase is

$$U_{Cs-2} = U_{Cs-1} \cdot \exp(\frac{-t_{BBM}}{R_p C_s}) = U_0 \frac{R_p}{R_p + R_s} \exp(\frac{-t_{BBM}}{R_p C_s}) \quad (8)$$

3. Measuring phase: the sensor is connected to the op-amp. The current which flows out of the sensor is divided in two branches R_p and R_s, inversely to resistance of the branches i.e. R_p and R_s build a current divider. This means the effective capacitance of the sensor is reduced to C_S^* which is equal to

$$C_S^* = C_S \frac{R_p}{R_p + R_s} \quad (9)$$

The output voltage of the circuit is then

$$U_{out} = \frac{-U_{Cs-2}}{C_G} C_s^* = \frac{-U_0}{C_G} (\frac{R_p}{R_p + R_s})^2 \exp(\frac{-t_{BBM}}{R_p C_s}) C_S \quad (10)$$

According to eq (10) connecting the series resistance Rs to the sensor leads to identify the sensor conductance, but it changes the error term and reduces the output voltage more with a factor of $(R_p/(R_p+R_s))^2$.

Eq (10) shows that the measurement error is a multiplicative term. This error can be compensated with multiplying the U_{out} by invers of the error term,

$$U_{out-comp1} = U_{out} \cdot (\frac{R_p + R_s}{R_p})^2 \exp(\frac{t_{BBM}}{R_p C_s}) = \frac{-U_0}{C_G} C_S = \frac{-U_0}{C_G} (C_0 + \Delta C_s) \quad (11)$$

Finally the additive offset term can be compensated by adding the term $U_0 C_0/C_G$ to get an output voltage, which is proportional to sensor capacitance deviation $U_{0ut} \propto \Delta C_s$.

$$U_{out-comp2} = \frac{-U_0}{C_G} (C_0 + \Delta C_s) + \frac{-U_0}{C_G} C_0 = \frac{-U_0}{C_G} \Delta C_s = k \Delta C_s \quad (12)$$

The block diagram of the total interfacing circuit containing the error compensation is depicted in Fig. 7. For calculating the multiplicative error term first the parallel conductance is calculated from $U0$, R_s and the sampled U_{Cs}. Then the multiplicative error term is calculated according eq. (11) by using R_p, R_s, t_{BBM} and Cs. The interfacing circuit identifies the sensor parallel conductance and compensates its influence on the output voltage. The sensor offset is compensated simultaneously and the output signal is a linear function of the sensor capacitance variation.

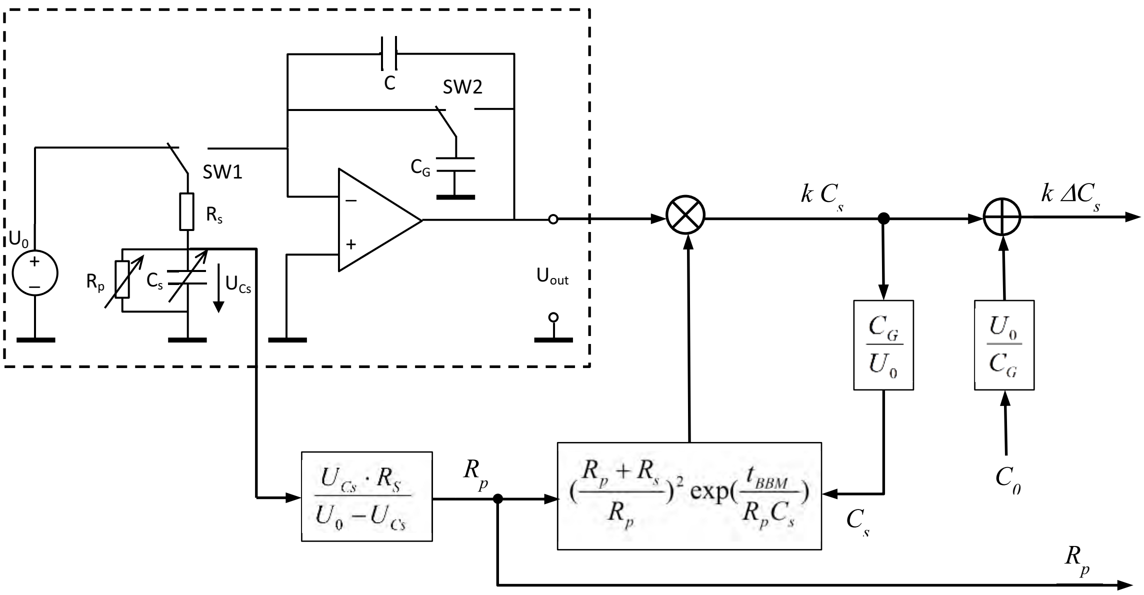

Fig. 7 Block diagram for identification and compensation of variable parallel conductance of a capacitive sensor

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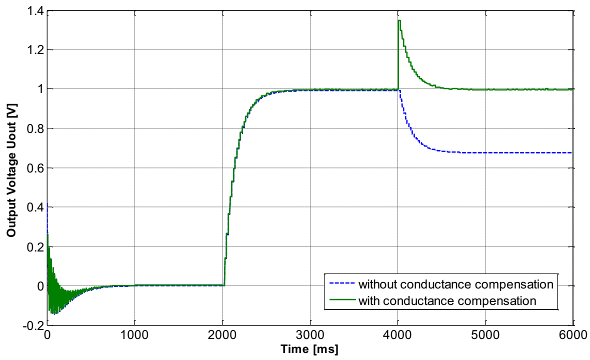
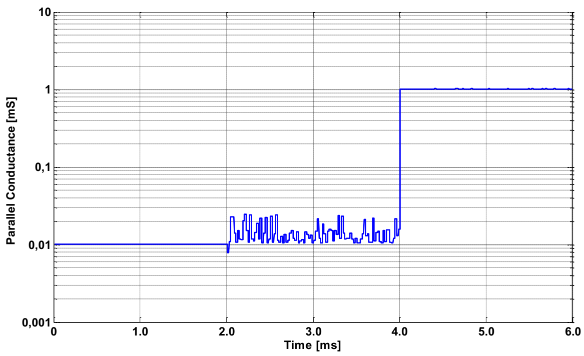
Results

In Fig 8-a compensation of parallel-conductance effect for a capacitive sensor with C_{0s} $=1.2$ nF and $\Delta C_s=0.5$ nF is shown. With $U_0=5V$ and $C_G=2.5$ nF the output voltage following a step change in sensor capacitance at $t=2$ ms after offset correction is about 1 V. Because of contamination on the sensor during the measurement at $t=4$ ms parallel conductance of the sensor increases from $10\mu S$ to 1 mS. To identify and compensation of the sensor parallel conductance a resistor $R_s=20$ Ω is connected in series to the sensor. The change of sensor parallel conductance leads to about 32% error (dashed line). The compensated output voltage is shown with solid line. Apart from a transient at $t=4ms$ the output voltage is no more influenced by sensor conductance variation. Simultaneously the sensor parallel conductance is correctly identified (Fig. 8-b).



(a)



(b)

Fig. 8 Measurement results of compensation of sensor parallel conductance. (a) Output voltage of interfacing circuit with and without compensation, (b) identified sensor parallel conductance.

Conclusions

In capacitive sensors parallel conductance leads to considerable measurement error. The mathematical modeling of the error for a switched capacitor interfacing considering break-before-make time delay of switching elements was derived. In presence of a sensor parallel conductance, compensation of sensor offset in switched capacitor interfacing circuit with $C_T=C_0$ is not sufficient.

A method for compensation of variable parallel conductance effect was developed. With this method the influence of parallel conductance can be fully compensated. Offset in signal processing is completely compensated, therefore no need to use constant offset compensation capacitor.

Parallel conductance of the sensor can be identified quantitatively in order to monitor the sensor, especially in highly contaminated environments.

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