A Study of a High-Resolution Linear Circuit for Capacitive Sensors

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Abstract—A circuit for capacitance measurements is described. The circuit permits offset capacitance compensation using a dc voltage. The electronic circuitry with its testing is described. The output voltage is a linear function of the capacitance measured. Experimental data show good agreement with values predicted by the linear formula. Experiments show it is possible to measure capacitance changes with a resolution of a few femtofarads (fF).

Index Terms—Capacitive sensor, femtofarads (fF), linear circuit, low-capacitance measurement, offset compensation.

I. INTRODUCTION

CAPACITIVE sensors are used to measure force, humidity, pressure, vibrations and the like. Many capacitive sensors produce very small capacitance variations with relatively large fixed offset capacitance. This paper describes a circuit for capacitance measurement suitable for capacitive sensors of this kind. It can be used for measurement of small capacitance changes and compensate for offset capacitances and drift. Related work in this area can be studied in [1]–[6].

II. CAPACITANCE SENSING CIRCUIT

A block diagram of the electronics is shown in Fig. 1. A sinusoidal voltage, $U_1$, is applied to the capacitance, $C_s$, to be measured. The signal $U_1$ is also an input voltage to multiplier $M$. The other multiplier input is connected to variable DC voltage $U_c$. The output of the multiplier is a voltage $kU_1$, the factor $k$ is given by $k = U_c/10$. $U_1$ drives a current $I_s$ through $C_s$ while $kU_2$ drives a current through $C_m$. $I_s$ and $I_m$ have the same phase shift. Currents $I_s$ and $I_m$ produce output voltage $U_0$; full-scale voltage is determined by $R_2$. The key component in the electronics is a current to voltage converter. The output of that is a linear function of the capacitance $C_s$, as established by the following relationships:

$$U_1 = A \sin(\omega t)$$

(1)

$$U_0 = \frac{R_f}{R_2} (C_s + kC_m) R_4 \omega A \sin(\omega t + 90^\circ)$$

(2)

where $U_0$ is the input to a phase sensitive detector, which is of the type discussed in [7].

$U_1$ is phase shifted by $90^\circ$ and used as the reference signal $U_{\text{ref}}$. The output of the phase sensitive detector, $U_{dc}$, is a dc voltage directly proportional to $C_s$, as given in (3). The factor $4/\pi$ is due to rectification and amplification of the signal in the phase sensitive detector [7].

$$U_{dc} = \frac{4R_f}{\pi R_2} (C_s + kC_m) R_4 \omega A.$$ (3)

The voltage $U_c (k = U_c/10 \text{ V})$ can be used to compensate for the fixed part of the sensor capacitance. Hence output voltage $U_{dc}$ can be made proportional to the changes in capacitance, $\Delta C$, where sensor capacitance can be expressed in the form $C_s = C_0 + \Delta C$. The value of $U_c$ required to compensate for $C_0$ can be determined manually or automatically with a computer or with negative feedback. In the computerised case an ADC/DAC unit can be used to measure output signal and to create the correction signal $U_c (k = U_c/10)$. $U_c$ can be computed directly, the idea is then to compensate $U_{dc}$ only by the use of term $k (k = U_c/10 \text{ V})$. The influence of $U_c$ on $U_{dc}$ is shown in (3) and results in (4). Iterative numerical methods can be used [6]. When negative feedback is used, $U_{dc}$ can be connected to an integrator, which produces $U_c$ as an output [1].

$$U_c = \frac{10\pi R_2}{C_m R_f R_4 \omega A} U_{dc}.$$ (4)

The smallest detectable capacitance change $\delta C$ depends on $\delta U_{dc}$, the resolution of the measurement of $U_{dc}$. Using (3), the theoretical resolution is given by

$$\delta C = \frac{\pi R_2}{4R_f R_4 \omega A} \delta U_{dc}.$$ (5)
III. TEST CAPACITANCE

The net capacitance used for measurement circuit experiments is established by two series-connected capacitors. One of the capacitors is fixed, $C_{\text{f}}$, and the other is a high precision variable capacitor [see Fig. 2(a)]. It is possible to create small controllable capacitance changes by using capacitances in series. Changing the capacitance of one of the capacitors will give a smaller change of their total capacitance, $C_{\text{t}}$, since

$$C_{\text{t}} = \frac{C_{\text{f}} C_{\text{v}}}{C_{\text{f}} + C_{\text{v}}}.$$  \hspace{1cm} (6)

The test capacitance is placed in a shielded and grounded box [see Fig. 2(a)] and connected to the sensing electronics by coaxial cables with grounded shields. There will be stray capacitances between the capacitor/connector shields and the ground, $C_{\text{sg1}}$ and $C_{\text{sg2}}$ in Fig. 2(b). These capacitances will not influence the measurements. The stray capacitance $C_{\text{sg1}}$ is connected between the voltage generator and ground. The current $I_{\text{sg1}}$ through $C_{\text{sg1}}$ is never measured and will hence not affect the measurements [see Fig. 2(b)]. The stray capacitance $C_{\text{sg2}}$ is connected between the virtual ground of the OP amplifier A1 and ground; due to the very small potential difference it will have only a very slight effect on the measurements. There are also stray capacitances between the connectors that can be seen as a capacitance parallel to the test capacitance, $C_{\text{sp}}$, in Fig. 2(b). This capacitance adds directly to the test capacitance. It is therefore important to keep this capacitance constant. It can be subtracted in the measurements by manipulating the DC voltage $U_c$.

IV. EXPERIMENTS

The test capacitance, $C_8$ consists of a fixed capacitor connected in series with a variable capacitor, as in Fig. 2(a). The fixed capacitor consists both of a styrol type capacitor and the stray capacitances that can be seen as coupled in parallel to the capacitor. The variable capacitor is originally a component in a precision capacitance bridge (Sullivan and Griffiths). The variable capacitor was changed in steps of 1.0 pF. A 1.0 pF change of the capacitance of the variable capacitor causes a change of 4 fF of the total capacitance of the test capacitance; this has been checked using an impedance analyzer, HP 4284A precision LCR meter. It has 6 digits resolution and a basic accuracy of 0.05%. Before measurements are performed the circuit is nulled by manual adjustment of $U_c$. The output voltage is measured by a DVM, Prema 6001 with GPIB interface. The resolution is 100 nV and the stability is 0.0005% of reading +0.0002% of full scale (full scale was 0.2 V during the measurements). The measurement values are automatically stored in a PC. Measurements were made at 13 different settings of the test capacitance corresponding to 12 steps of 4 fF. For each setting of the test capacitance 20 values of the output voltage of the sensor electronics were sampled. The variable capacitor settings were performed manually in steps of 1.0 pF. For this measurement series the test signal $U_1$ was a sine voltage with amplitude A of 5.0 V and a frequency of 1.0 kHz. The values of the components of the sensor electronics (see Fig. 1) are $R_1 = 100 \, \text{k}\Omega$, $R_2 = 1 \, \text{k}\Omega$, $R_f = 47 \, \text{k}\Omega$ and $C_m = 100 \, \text{pF}$. The amplifiers are OP-amplifiers TL071, the phase detector is an AD-630 and the multiplier is a MC-1495.

V. RESULTS

The output for a series of capacitance changes in the range 0 to 48 fF is shown in Fig. 3. The average value for each measured capacitance is presented. A regression line drawn according to these values gives a sensitivity of $-2.07 \times 10^{14} \, \text{V/F}$, while the theoretical value according to (2) with the component values given above is $-1.88 \times 10^{14} \, \text{V/F}$. A step of 1 fF would hence cause an output of 0.2 mV. The horizontal intervals in each point correspond to the uncertainty of the reference capacitance. The vertical intervals correspond to ± two standard deviations of the measured capacitance values based on the sample of 20. The biggest standard deviation for a measured capacitance is 0.2 mV. This corresponds to a capacitance of 1 fF.

It is important to be able to compensate for drift in electronics when measuring very small values. When a good standard or reference is available the circuit described above is possible to use for compensation of drift. The circuit can also be very useful when differential capacitance sensors are used. In this case a capacitance change is measured and drift due to temperature and the like are eliminated. It is possible to measure capacitance changes down to a resolution in the region of a few fF. The measurements are performed in an ordinary laboratory environment with all usual disturbances present. It has therefore been important to shield the measured capacitance and the electronics thoroughly.

It should be noted that sensing capacitors of the type referred to here normally have stable offset capacitances. Since we measure capacitance differences, offset capacitance compensation need not be exceedingly accurate. If the offset capacitance should vary slowly in time, it can be compensated for by adjustment of $U_c$. Adjustment of this voltage can be done manually or, preferably, automatically in many cases. Automatic compensation of offset capacitances by the use of a PC with an ADC/DAC unit using direct computation (4) or iterative methods is described in [6].

A circuit of this type has successfully been used as detection electronics in a capacitive person detector [5]. The capacitance is in this case formed between two relatively large plates. The plates can be placed on the floor and in the ceiling of the guarded area. When a person enters the guarded area the conductive conditions in the space between the plates is
changed, resulting in a capacitance change. In this case a rather big fixed capacitance burdens the sensor. But it is compensated for by use of the method described above.

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REFERENCES


His research interest are concentrated on capacitive sensors for detection of humans, combining Fourier transformation and laser scanner data for object recognition and sensor data fusion. He is now a Researcher with the Division of Sensor Technology, Swedish Defense Research Establishment, Linköping, working mainly with radar sensors.