The capacitive proximity sensor based on transients in RC-circuits

A G Yakunin
Head of the Chair, AltSTU, Barnaul, Russia
E-mail: almpas@list.ru

Abstract. The principle of operation of the capacitive proximity sensor is described. It can be used in various robotic complexes, automation systems and alarm devices to inform the control device of the approach to the sensor sensitive surface of an object. At the heart of the device is the measurement of the change in the current of the transient accompanying the charge of the reference capacitor because of the parallel connection to it the capacitance formed by the sensitive sensor surface and the external object. At the heart of the device is the measurement of the change in the current of the transient accompanying the charge of the reference capacitor caused by the parallel connection to it the capacitance formed by the sensitive sensor surface and the external object. As shown by theoretical and experimental studies, the value of this capacity, depending on the purpose of the device, can vary within very wide limits. In this case, the sensitive surface can be both a piece of ordinary wire several centimeters long, and a metal plate or grid, the area of which can reach units and even tens of square meters. The main advantage of the proposed solution is a significant reduction in the effect of spurious leakage currents arising at the capacitance of the measuring electrode under the influence of pollution and humidity of the environment.

1. Introduction
Capacitive measuring converters of non-electrical quantities are now widely used along with other sensors in a wide variety of fields of science and technology, including automation of production processes [1–3] and in the field of robotics [4, 5]. With capacitive sensors, linear [6] and angular [7, 8] movements can be monitored, fluid level [9], tactile inforces [10, 11], pressure [12] and other physical quantities. It is also known to use capacitive devices as proximity sensors in production [13] and in alarm protection systems along with acoustic, radio wave and optical converters [14].

The main advantage of capacitive devices is their relative simplicity, small dimensions, low power consumption, manufacturability and low cost. Nevertheless, despite the above advantages, the field of capacitive converters using is rather limited. So, for example, as proximity sensors they are almost not used in chemical and dusty industries, as they change their characteristics in the presence of dust and under the influence of aggressive media. The inconstancy of the properties of the controlled environment leads to a change in the currents of parasitic leakage of the sensor capacitance, which causes a large number of false positives. Since for such applications of capacitive sensors the environment is the dielectric of the measured capacitance, and the surrounding things, controlled objects and surfaces are the electrodes, it is not possible to solve the problem by improving the technology of manufacturing the sensors themselves, as described, for example, in [4]. Therefore, for such applications, one of the promising ways to improve the technical and economic parameters of capacitive sensors is the use in them of new operating principles, the development of new circuitry...
solutions, as well as the improvement of methods for processing signals and extracting information from them, which is the subject of this work.

Therefore, for such applications, one of the promising ways to improve the technical and economic parameters of capacitive sensors is the use in them of new operating principles, the development of new circuitry solutions, as well as the improvement of methods for processing signals and isolating the information component from them, which is the subject of this work.

2. Analysis of existing decisions

At present, there are three main approaches for finding the capacitance value of a capacitive converter. The simplest is to measure the voltage at the output of the voltage divider, the circuit of which is shown in Figure 1a or is close to it. In this circuit, the generator G must generate a sinusoidal voltage. The disadvantage of this solution is the non-linear dependence of the output signal on the capacitance value. In addition, this approach is least resistant to the influence of the leakage resistance not shown in the figure, which shunts the capacity of the converter. Because of this, at the present time the basis of most capacitive sensors is the circuit in which the unknown capacitance is the frequency-setting element of the generator (Figure 1b) and enters the parallel or series oscillatory circuit or in the frequency-dependent positive feedback loop of the multivibrator.

In order to improve the accuracy of the measurement and increase the sensitivity of the sensor, it is often used not direct measurement of the frequency but a variety of difference schemes, when the capacitance is determined from the beat frequency after the summation of the frequencies of the reference and measuring oscillator, or by changing the duty cycle of the measuring pulse relative to the reference pulse. But in all variants of such solutions it is completely impossible to get rid of the parasitic resistances influence. In addition, in all cases a nonlinear relationship exists between the measured capacitance and the informative parameter. To exclude the effect of parasitic resistance, it is possible in impedance meters, when, for example, in the circuit shown in Figure 1a, not only the amplitude but also the phase of the output voltage is measured. However, such solutions are significantly more complex and have not been used in such simple devices as proximity sensors.

Therefore, for those cases when parasitic resistance is unstable, varies widely, and determination of its value is not required, it is more promising to apply solutions when the capacitance is determined from the parameters of the transient processes, namely, by the value of the capacitor charging current at the beginning of the transient process after feeding to it voltage. One of the variants of such a solution is shown in Figure 1c, where Sm is the input preamplifier with function of summation and current-to-voltage converter, AU – automatic control unit, [15]. In such a device, the capacitance value is determined from the voltage value \( U_1 \), which is adjusted by the adjustment system to minimize the total current getting to the preamplifier input. If the voltage \( U_1 \) has the same sign as \( U_0 \), the control voltage to the key \( K_1 \) must be supplied via the inverter shown in the figure with a dashed line. The advantage of this solution is the linear dependence of the output signal on the value of the capacitance \( C_2 \) measured and its weak dependence on the leakage currents flowing between its plates. Если напряжение имеет тот же знак, что и, управляющее напряжение на ключ \( K_1 \) должно подаваться через инвертор, показанный на рисунке пунктирной линией. This is explained by the fact that at the moment of switching the charge current of the capacitance has a maximum value and, in the absence of resistance of the connecting conductors, does not depend on the value of the resistance connected in parallel to the measured capacitance through which the leakage currents flow. However, in such a scheme it is not possible to completely get rid of the influence of spurious leakage resistance, since its decrease tightens the duration of the charge pulse of the capacitor and increases its amplitude. Therefore, as the leakage currents of the measured capacitance increase due to an increase in, for example, the humidity of the medium and contamination of the surface on which the measuring capacitor covers are placed, the compensating voltage \( U_1 \) will decrease, which is equivalent to decreasing the measured capacitance. In addition, in the diagram shown in Figure 1c, the measuring capacitor is not grounded, which significantly limits the possibilities of using this circuit in automation systems, since in them one of the covers of the measuring capacitor is most often an earthed object.
The modifications proposed in [16] of the scheme presented in Figure 1c, described in the next subsection and shown in Figure 2, are deprived of the indicated shortcomings.

3. The proposed approach to minimizing the effect of spurious leakage currents on the operation of a capacitive converter

The first fundamental difference of the solution proposed in [16] from the one shown in Figure 1c is that the second terminal of the measured capacitance \( C_x \) is not connected to the input of the current to voltage converter, but is grounded. This allowed to significantly expand the scope of possible application of the device for the above reason. In this case, an increase in the value of the capacitance measured in this circuit does not lead to an increase, but to a decrease in the overcharge current of the capacitor \( C_1 \), but the linear coupling between the capacitance and the current of the recharge current is kept in a sufficiently wide range.

The second difference is that at the output of the converter a sampling-storage scheme is added, so that only a very short time interval is selected from the entire time diagram, corresponding to the start of the process of recharging the compensation and measuring capacitors. Due to this, even more than the prototype, the effect of the parasitic resistance of the measuring capacitor on the magnitude of the output signal was suppressed.

4. Results of calculations and experimental studies

For the analysis of the operation of the circuit shown in Figure 2, the model of its measuring cell, shown in Figure 3, was used. The transfer of one of the terminals of the capacitor \( C_f \) from the preamplifier input to the ground is entirely acceptable, since in the current to voltage converters their input voltage is almost invariably and close to zero.
Figure 3. The equivalent circuit of a rechargeable cell with a measured \( C_X \) and a reference \( C_1 \) capacitor and a shunt resistor \( R_X \) through which a leakage current flows.

For such a circuit, the voltage across the capacitors and the current of their charge when the key is closed will be described by the expressions

\[
U_c(t) = R_X \cdot U_0 \cdot \frac{1 - \exp\left(-\frac{R_1+R_X}{R_1 \cdot R_X \cdot C}\right)}{R_1 + R_X};
\]

\[
I(t) = U_0 I(t) = U_0 \cdot \frac{C \cdot \exp\left(-t \cdot \frac{R_1+R_X}{R_1 \cdot R_X \cdot C}\right)}{C \cdot R_1};
\]

(1)

(2)

where \( C = C_1 + C_X \).

In order to explicitly assess the effect of capacitance \( C_X \) and leakage resistance \( R_X \) on the values of currents and voltages described by these expressions at different instants of time, let us consider the corresponding sensitivity functions representing their \( C_X \) derivative:

\[
F_U(t) = U_0 \cdot \frac{R_1+R_X}{R_X+(R_X C)^2} \cdot t \cdot \exp\left(-t \cdot \frac{R_1+R_X}{R_1 \cdot R_X \cdot C}\right);
\]

\[
F_I(t) = -U_0 \cdot C_X \cdot \frac{R_1 \cdot R_X \cdot C - t \cdot (R_1+R_X)}{R_X R_1^2 C^3} \cdot \exp\left(-t \cdot \frac{R_1+R_X}{R_1 \cdot R_X \cdot C}\right).
\]

(3)

(4)

The graphs of the voltage and current sensitivity versus time curves for different values of \( R_X \) for the case when \( R_1 = 5 \, \text{k}\Omega; \, C_1 = 200 \, \text{pF} \) and \( U_0 = 10 \, \text{V} \), are shown in Figure 4.

Figure 4. The dependence of the voltage sensitivity (a) on the capacitor \( C_X \) and the current flowing through it (b) on the time for different values of the leakage resistance \( R_X \).

As can be seen from the expressions (3.4) for \( F_U(t) \) and \( F_I(t) \) and the corresponding graphs, in both cases the value of the resistance \( R_X \) does not affect the magnitude of the maximum sensitivity. However, for the function \( F_U(t) \), the position of the maximum sensitivity peak depends on the value
of $R_X$, which makes it very difficult to use the $U(t)$ dependence for determining $C_X$. If we use the dependence of the charge current on time to find the capacitance, then, as can be seen from equation (4) and the graph in Figure 4b, it is possible to get rid of the influence of $R_X$ on the measurement results if the charge current is measured at the shortest time from the start of the key switching. With reference to the realizing method of measuring the $C_X$ circuit, shown in Figure 2, this moment corresponds to the voltage drop at the output of the generator $G$. At this moment, the sensitivity value is maximal and equal to

$$F_1(0) = -\frac{U_0}{R_1(C_1+C_0)^2}$$

(5)

As follows from this expression, the sensitivity value here is also not constant, depends on the ratio between the capacities of the capacitors $C_X$ and $C_I$ and assumes the maximum value at $C_X = C_I$. The form of dependence $f_I(C_X/C_I) = -R_1 F_I(0)/U_0$ normalized on the value $U_0/R_1$ and on $C_I$ is shown in Figure 5.

![Figure 5](image)

**Figure 5.** Dependence of the maximum of the relative sensitivity function on the current from the ratio of the measured capacitance to the capacitance of the reference capacitor $C_I$.

As can be seen from this dependence, when the measured capacitance deviates from the capacity of the reference capacitor by more than 2 times, the sensitivity decreases by approximately 20% of its maximum possible value. In this case, a decrease in the capacitance $C_X$ relative to $C_I$ is less preferable than its increase, since at $C_X \rightarrow 0$ the sensitivity drops to zero much more rapidly than when it increases. It follows that for best results it is necessary to select the values of the capacitances $C_I = C_2$ in accordance with the expected range of variation of the quantity $C_X$.

Along with the need to reconcile the circuit parameters with the value of the measured capacitance in order to achieve high performance properties of the sensor, it was also necessary to solve a number of other problems related to the optimization of the circuitry solutions used in it. For this purpose, a sensor model was developed that allows to take into account factors such as the spread of the parameters $R_1$, $C_1$, $R_2$, $C_2$ of the direct and compensating RC circuits, the dependence of these parameters on temperature, the presence of a delay on the inverting element, the finite duration of the pulse generator edges, the imperfection of the sample and hold circuit and current-to-voltage converter. Comparison of simulation results with experimental data, an example of which is shown in Figure 6, showed good adequacy of the developed model.

The optimization of the capacitive converter carried out with the help of this model made it possible to design control devices taking into account the specific conditions of their operation and functional purpose. Thus, a capacitive proximity sensor constructed using the developed optimization technique provided a sensitivity of 100 mV / pF at a sensitivity threshold of 0.1 pF in the range of measured capacitance from 50 to 500 pF, a temperature range from -40 to +45 °C, and a parasitic
shunt resistance from 5 kΩ to infinity. And the current consumption of such a sensor does not exceed 0.35 mA at a supply voltage of 5 V.

![Signal at the output of the current to voltage converter](image)

**Figure 6.** The signal at the output of the current to voltage converter at the beginning of the switching. The dashed line is the experimental result, the solid line is the results of mathematical modeling in the MathCAD environment.

5. **Summary**

The proposed method for constructing a capacitive converter gives a real improvement in reliability, sensitivity, and other technical and economic characteristics of proximity sensors developed on their basis. Parasitic leakage current in the dielectric, on which the measuring electrode of the converter is fixed, do not have practically no effect on the output signal, which is an undoubted advantage of this solution. But, since the output signal of the converter is nonlinearly dependent on the value of the capacitance being measured, it is advisable to use this converter primarily as an approximation sensor or another element of discrete automation used in various industries. In particular, it can be successfully used in the highly dusty conditions of production, connected, for example, with grain processing [17, 18], and also in the technical means of burglar alarm as a preemptive action detector [14]. In the latter case, to reduce the number of false positives and increase the reliability of reliable identification of unauthorized access attempts, one can use algorithms presented, for example, in [19, 20]. In addition, the application of the sensor together with modern means of microcontroller technology such as Arduino or Raspberry allows implementing promising methods of digital signal processing that can significantly increase the reliability of its operation. The use of microcontrollers or System-on-a-Chip will allow the use of such sensors in automatic control or non-destructive testing systems, provide the possibility of automatic tuning to a measurable capacitance, and also check the efficiency of the sensor and identify abnormal situations such as a break in the measuring electrode or its shorting to a ground.

**Acknowledgments**

The author expresses his deep gratitude to the leadership of the Altai State Technical University named after I.I. Polzunov (AltSTU) for financial support of the publication of this article and former graduate student AltSTU Avtsinov V.B. for participating in conducting theoretical studies, performing experimental studies of the proximity sensor, as well as for developing and implementation of equipment using the developed sensors.

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