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LINEARIZATION OF TRANSFER CHARACTERISTIC OF INTELLIGENT CAPACITANCE SENSOR

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Abstrakt. *Intelligent capacitive sensor which does not require the inclusion of devices such as a microprocessor, microcontroller or programmable logic controller is described. When using the scheme of linearization in intelligent capacitive sensor, the relative conversion error that is introduced by elements such as resistors, capacitors and operational amplifier can be as low as one hundredth of a percent.*

Keywords: intelligent capacitive sensor, electric capacitance, linear characteristic, nonlinearity, linearizing function, transfer characteristic.

Introduction. In measuring technique as well as in control automation technique, various capacitance sensors are used [1 – 9].

The increasing numbers of electronic systems in aviation have transformed the aircraft into safe and intelligent machine. Capacitive technologies play very important role in the fields of aviation instruments and sensors. The transduction of the capacitance into electrical quantities is a very common but important requirement. The noncontact working principle is one of the main advantages of this technology.

The capacitive transducers are frequently encountered due to their small size, low power consumption and low temperature errors. However, their use always implies the choice of a suitable capacitance measuring technique, with good order of accuracy, precision and reliability.

Intelligent sensors are becoming a reality in aviation systems and instruments. These sensors are more sophisticated than traditional sensors as they collect, analyze and transmit data.

A smart transducer as a rule is an analog or digital transducer or actuator combined with a processing unit and a communication interface. Because the tasks are performed by microprocessors, any gadget which mixes a sensor and a microprocessor is usually called as an intelligent sensor. To qualify as an intelligent sensor, the sensor and processor must be part of the same physical unit.

In practice, the capacitive sensors have small capacitances and their precise and accurate measurement is a problem as a rule.

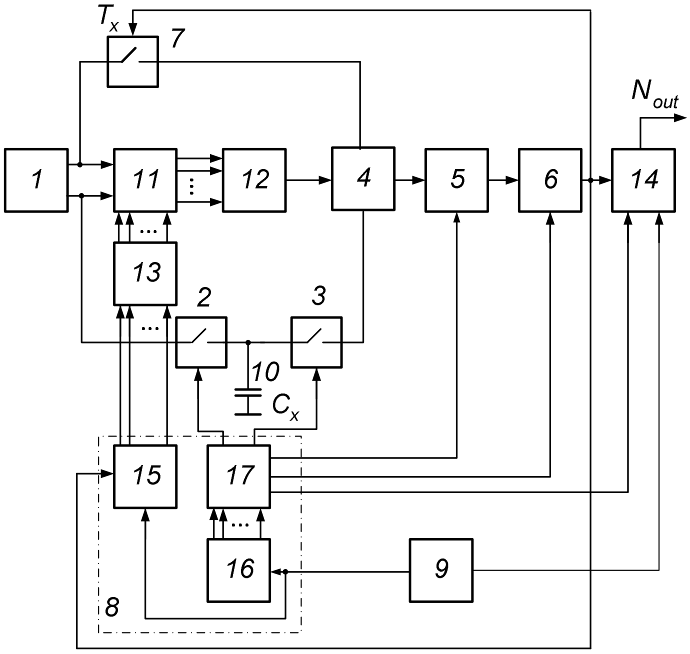
For example, in a capacitive position sensor, the electrified plate is the sensor surface and the second plate is the target. The electronics continuously change the voltage on the sensor surface. This is the excitation voltage. The amount of current required to change the voltage is detected by the electronics and indicates the amount of capacitance between sensor and target. An AC bridge circuit or other active electronic circuit is typically used to convert the capacitance change into a current or voltage signal and output. In ordinary capacitance-based position measurement, the size of the sensor and the target, and the dielectric medium (usually air) remain constant. The only variable is the gap. All changes in capacitance are therefore the result of a change in the position of the target relative to the sensor.

In the general case of capacitive sensor capacitor is the element with electric capacitance, which value depends on sensor input value. And physical principles, on which capacitor structure is based, are different in different sensors though there is wide range of their differences. It includes both ordinary mechanic constructions, in which the capacity of capacitor is assigned by mutual alignment of plates, and unconventional designs, based for example on ferroelectrics or pyroelectrics.

Problem statement. While all these sensors have different principles of operation, developers face the problem, which is common for all sensors. It includes the necessity of acquisition of functional relationship between input and output values of sensor or device, which includes this sensor [1; 2; 4]. There are two aspects of this problem. In the first case, if the sensor has natural nonlinearity, it is necessary to implement its linearization. It means that auxiliary hard or software tools, entered into composition of intelligent sensor, are used to implement linear functional relationship between input and output values. The second case is, when the capacitance sensor has natural linear characteristic and according to certain reasons it needs to obtain required nonlinearity.

Solution of the problem. Assigned task can be easily solved, when the output value has been already converted into digital code. For this purpose there is need to be, for example, microprocessor, microcontroller, programmable logic controller or even computer in the structure of the device.

Still in the case of intelligent sensor construction this is not desirable to include to its composition hardware components of above-listed devices. In this case designers of intelligent sensor face the necessity to find other solutions, by which assigned task can be achieved with using of hardware, which is more preferable to be included in intelligent sensor. Measuring converters, considered in researches [6 – 9], and also intelligent capacitance sensor developed by authors, exemplify such devices. The scheme of such intelligent sensor is represented in Figure.



Scheme of intelligent sensor: *1* – Source of the reference voltage; *2, 3* – Keys; *4* – Integrator; *5* – Sample-and-hold device SH; *6* – Voltage-to-Time interval converter; *7* – Key; *8* – Synchronization block; *9* – Clock generator; *10* – Storage capacitor (capacitor of the capacitive sensor); *11* – Switchboard; *12* –Code managed resistive matrix; *13* – Decoder; *14, 15, 16* – Counters; *17* – Decoder

The principle of the device. Conversion of capacitance C_x of capacitive sensor into the code is implemented with the help of iterated-integration transducer. It includes such units as a source of the reference voltage *1*, box of switched capacitor – keys *2*, *3* and storage capacitor (capacitor of the capacitive sensor) *10*, integrator *4*, sample-and-hold device SH *5*, voltage-to-time interval converter 6, key *7*, synchronization block *8*, clock generator *9*, storage capacitor (capacitor of the capacitive sensor) *10*, switchboard *11*, code managed resistive matrix *12*, decoders *13*, *17*, counters *14*, *15*, *16.*

Required nonlinearity of response of intelligent capacitivee sensor is created with the help of code managed resistive matrix *12,* switchboard 11 and decoder *13*.

Such iterative-integration transducer works cyclically. During every cycle charging of storage capacitor (capacitor of the capacitive sensor) $10C_x$ from source of the reference voltage *1* is carried out, including subsequent discharging of it at the integrator *4* input. Also sampling of integrator output voltage is implemented by sample-and-hold device SH *5*. Then its storage follows during time T_C of cycle of continuous integration of sample-and-hold device SH *5* output voltage by Integrator *4*, and its transformation by voltage-to-time interval converter 6 into impulse T_x.

Impulse T_x controls the connection of code managed resistive matrix *12* with source of the reference voltage *1* by switchboard *12*. Decoder *14* controls switchboard *11*.
To derive equation of conversion of intelligent capacitive sensor let's consider its work in linear mode, i. e. without implementation of linearization. In this case resistors matrix is disconnected with generator input. Let's suppose that impulse T_x is equal to T_0 before the first of concerned cycles. So after the ending of conversion cycle the impulse T_x at the output of voltage-to-time interval converter 6 is equal to:

$$T_1 = T_0 + \frac{E_0 C_x K_{UF} K_{UT}}{C} - \frac{T_0 E_0 K_{UF} K_{UT}}{RC} = \frac{E_0 K_{UF} K_{UT}}{C} C_x + T_0\left(1 - \frac{E_0 K_{UF} K_{UT}}{RC}\right),$$

where E_0 – is output voltage of source of the reference voltage 1; C_x – capacitor capacitance of storage capacitor *10*; C – capacitance of integrator *4* capacitor; R – resistance of integrator *4* resistor; K_{UF} –voltage follower gain of sample-and-hold device SH *5*; K_{UT} –transfer coefficient of voltage-to-time interval converter *6*.

Similarly, after ending of the *n-th* cycle of transformation we get the formula:

$$T_n = \frac{E_0 K_{UF} K_{UT}}{C} C_x \sum_{j=1}^{n}\left(1 - \frac{E_0 K_{UF} K_{UT}}{RC}\right)^{j-1} + T_0\left(1 - \frac{E_0 K_{UF} K_{UT}}{CR}\right)^{n}. \quad (1)$$

Expression (1) consists of two parts. One is sum of parts corresponding to geometric progression, which converges at the condition

$$\left|1 - \frac{E_0 K_{UF} K_{UT}}{RC}\right| < 1. \quad (2)$$

Another one is the part $U_0\left(1 - \frac{E_0 K_{UF} K_{UT}}{RC}\right)$ decreasing at the same condition.

If the condition (2) is fulfilled at the steady-state condition ($n \to \infty$), then the impulse T_x at the output of voltage-to-time interval converter 6 is determined by the expression

$$T_\infty = \lim_{n\to\infty} T_0 = RC_x. \quad (3)$$

Time of transient process of setting of the voltage is determined by specified accuracy of transformation and actually form a few of cycles.

Code at the output of intelligent capacitive sensor in steady-state condition without linearization is

$$N_{out} = f_0 T_\infty = f_0 RC_x, \quad (4)$$

where f_0 – clock frequency.

Now let's consider the linearization of the intelligent capacitive sensor, i. e. its work in the nonlinear regime.

Linearization is performed by means of forming the auxiliary component (voltage) in accordance with equation (3).

Linearization time interval T_L is formed by the way of integration during impulses T_x of matrix currents are acting. Resistors connect in turn to the outputs $+E_0$ and $-E_0$ of source of the reference voltage 1. Polarities of reference voltages, which are connected to the corresponded matrix resistors, as well as values of their resistances, are selected against the required curve form of linearization function.

Equation, defining linearization time interval T_L can be represented in the form:

$$T_L = \frac{E_0 K_{UF} K_{UT}}{RC} \sum_{i=1}^{m} \frac{\text{sign}(T_x - t_i) + \text{sign}(t_{i+1} - T_x)}{2R_i} \text{sign} f'_{lini}, \quad (5)$$

where R_i – resistance of *i*-th resistor of resistor matrix; $i = 1,\ldots m$– number of section of piecewise-linear approximation of linearization function f_{lin}; f'_{lini} – derivative of the linearization function at *i*-th section of approximation; t_i – the time interval from the beginning of the cycle to the beginning to the *i*-th interval (connecting of resistor R_i); $\text{sign}X$ – sign function:

$$\text{sign}(X) = \begin{cases} -1 & x > 0; \\ +1 & x \le 0. \end{cases}$$

Convertion equation, taking into account expressions (3), (4) and (5) can be written as

$$N_{out\ L} = f_0(T_\infty + T_{out\ L}),,$$

where $N_{out\ L}$ – output code with linearization.

Conclusion. Intelligent capacitive sensor can be constructed according to the considered scheme; it does not require the inclusion of devices such as a microprocessor, microcontroller or programmable logic controller.

In this case, taking into account the errors introduced by such elements as resistors, capacitors and operational amplifier, the intelligent capacitive sensor can be created according to this circuit, which has relative errors of the conversion at the level of hundredths of a percent.

In this case the formation of a wide range of linearizing functions to obtain the desired conversion function can be possible.

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І. Ю. Сергеєв

Лінеаризація передавальної характеристики інтелектуального ємнісного датчика

Розглянуто інтелектуальний ємнісний датчик, який не вимагає у своєму складі таких пристроїв як мікропроцесор, мікроконтролер або програмований логічний контролер. При використанні в інтелектуальному ємнісному датчику схеми лінеаризації, відносна похибка перетворення, що вноситься неідеальністю таких елементів як резистори, конденсатори і операційний підсилювач, може бути менше однієї сотої частки відсотка.

И. Ю. Сергеев

Линеаризация передаточной характеристики интеллектуального емкостного датчика

Рассмотрен интеллектуальный емкостной датчик, который не требует в своем составе таких устройств как микропроцессор, микроконтроллер или программируемый логический контроллер. При использовании в интеллектуальном емкостном датчике схемы линеаризации, относительная погрешность преобразования, вносимая неидеальностью таких элементов как резисторы, конденсаторы и операционный усилитель, может быть меньше одной сотой доли процента.