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CAPACITIVE SENSORS WITH ULTRA-SMALL CAPACITANCE FOR SMART MEASUREMENT AND CONTROL SYSTEMS

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Abstract. *This article discusses methods of low capacitance measurement of capacitive sensors. The results of the study of the amplitude-frequency (AF) and phase-frequency (PF) response of measurement circuits of capacitive sensors for low capacitances measurement, consisting of RC - differentiating elements are presented. The input and output parameters of the differentiating circuit and the complex transfer function are analyzed. The research results show that low capacitances measurement by measuring the rectangular pulses duration is the most effective measurement method.*
Key words: *low capacity, amplitude – frequency response, phase - frequency response, differential circuit, water flow measurement, charge, discharge, capacitive sensor.*

Annotatsiya. *Ushbu maqolada o‘ta kichik sig‘imlarni o‘lchash usullari muhokama qilingan. RC elementlardan tashkil topgan kichik sig‘imlarni o‘lchash sig‘imli datchiklarining o‘lchash zanjirlarining amplituda-chastota (ACh) va faza-chastota (FCh) tavsiflarini tadqiq qilish natijalari keltirilgan. Differensiallash sxemasining kirish va chiqish parametrlari va kompleks uzatish funksiyasi tahlil qilingan. Tadqiqot natijalari shuni ko‘rsatadiki, tog‘ri to‘rtburchakli impulslarning davomiyligini o‘lchash orqali kichik sig‘imlarni o‘lchash eng samarali o‘lchash usuli hisoblanadi.*
Tayanch so‘zlar: *kichik sig‘im, amplituda-chastota (ACh), faza-chastota (FCh) tavsifi, differensiallovchi zanjir, suv sarfini o‘lchash, zaryat, razryad, sig‘imli datchik.*

Аннотация. *В данной статье рассматриваются методы измерения малых емкостей емкостных датчиков. Приводятся результаты исследования амплитудно-частотных (АЧХ) и фазочастотных (ФЧХ) характеристик измерительных цепей емкостных датчиков измерения малых емкостей, состоящих из RC – дифференцирующих элементов. Анализируются входные и выходные параметры дифференцирующий цепи и комплексной передаточной функции. Результаты исследований показывают, что измерения малых емкостей с помощью измерения продолжительности прямоугольных импульсов является самым эффективным методом измерения.*
Ключевые слова: *Малая емкость, ФЧХ, АЧХ, дифференциальная схема, расход, заряд, разряд, емкостной датчик.*

1. Introduction

Recently, the digitization of manufacturing processes and the widespread implementation of smart technologies have been developing rapidly in all countries of the World.

The successful implementation of such tasks directly creates the need to solve urgent issues such as improving the elements of digital technology, creating elements of microelectronics with new miniature dimensions, elements of smart sensor technologies, and their further development. Due to this, the development of digital technology elements in the World market is developing rapidly, and its volume will exceed 773 billion US dollars in 2023 [1]. According to the growth diagnosis of the world market of digital technology, the annual growth in 2024-2032 is expected to be 7.6%, from 815 billion US dollars in 2024 to 1 trillion 467 billion US dollars by 2032 [1,2]. Figure 1 below shows the growth dynamics of digital technology in the world market.

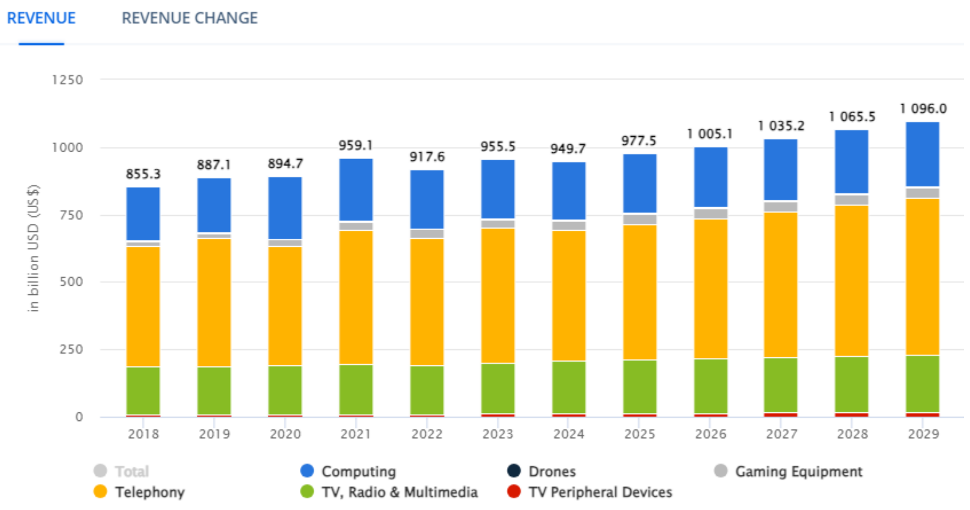


Fig.1. ***Growth dynamics of digital equipment in the world market.***

In the development of smart technologies, sensors with a miniature size are the main elements in measuring and controlling the state of various objects. Therefore, the development of capacitive sensors with extremely small capacitance is one of the urgent scientific research issues of today.

Today, in the era of advanced measurement and information technologies, many methods of capacity measurement are used.

One of the methods of measuring ultra-small capacitances is the method of using a new signal generator with a third-order high-frequency filter, which has a very low sensitivity to low or high frequency of parasitic signals [3].

Figure 2 below shows the structure diagram of this measurement method. In this scheme, a third-order filter was used to suppress low-frequency parasitic signals.

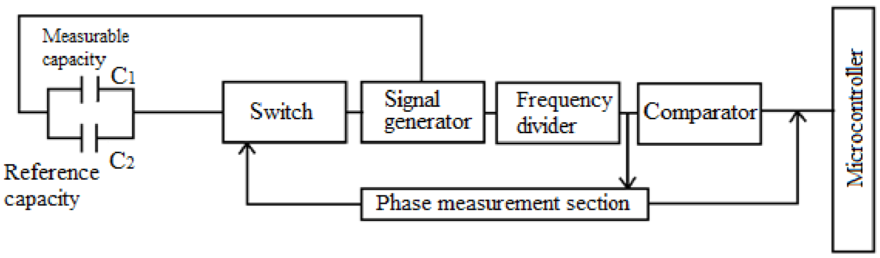


Fig. 2. ***Structural diagram of ultra-small capacitance measurement using a signal generator.***

It consists of a network of two-port capacitance sensors and two parasitic capacitors. One way to eliminate the two parasitic capacitances is to create a special potential difference at the two terminals of the system and pass a special current to the input. And the microcontroller is used to measure the signal period in this circuit. Microcontroller is mainly used to measure 3 periods i.e. reference time, drift time and measured time. These periods, measured by the microcontroller, are transmitted using numbers, and these numbers are used to determine the capacitance value[4,5].

Capacitance measurement range is 0÷2pF and sampling time is 330ns. The measuring range of the current method is not designed to measure the capacitance value in large pipes.

Another type of small capacitance measurement is based on the measurement method of RC circuit phase delay [6,7]. Due to the phase delay, the state of the rectangular pulse signal entering the RC circuit is changed, and for that reason, the possibility of adjusting the pulse width appears [8,9,10].

Figure 3 below shows the block diagram of the measurement method.

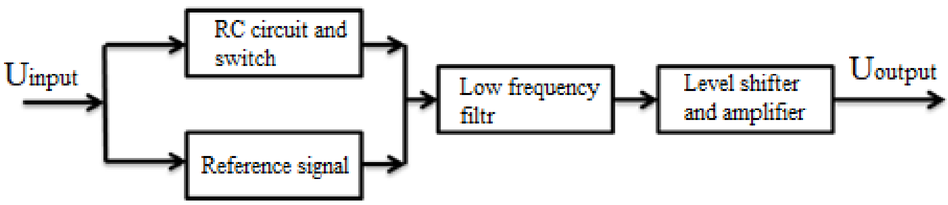


Fig. 3. ***Block diagram of the capacitance measurement method based on RC circuit phase delay.***

In this method, the output signal is filtered with a low-pass filter, but a high frequency is required for the existing circuit. There is another method with a high linear characteristic, the block diagram of which is shown in Figure 4 below.

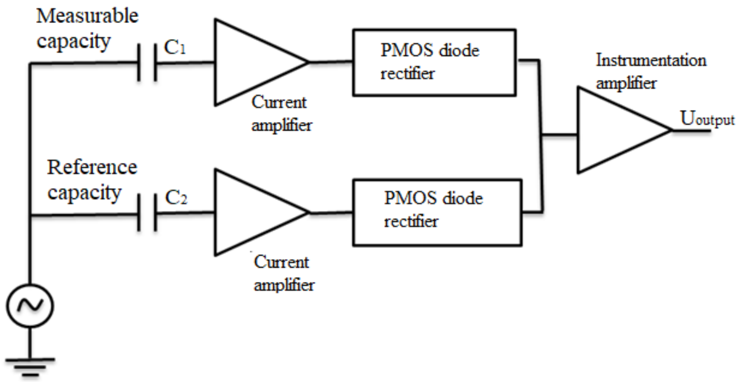


Fig. 4. ***Block diagram of the capacitance measurement with high permissible value and linear characteristic [11, 12].***

The reference capacitor C2 and the measured capacitor C1 are used in the shown block diagram.

They have one common electrode and the same voltage is supplied to it through the source. In this method, a change of capacitance to 1 fF (femto farad) produces a change in voltage of 1.32 mV.

This method is very effective in very small capacitance measurement, but the circuit is often used in diagnostic techniques in the medical field, and a standard capacitance is required.

According to the literature, research review [13], the discharge time periods of the capacitor determine the capacitance value from the response time of the RC circuit of the voltage level.

In the measurement process, an alternating voltage source (AC), a known resistance and a measured capacitance are used [14,15,16], the voltage is U_c.

The time that elapses until the threshold value of the unknown capacitor C_x due to the step voltage U_{pulse} is used to calculate the initial voltage value U_0 and U_{max} of the capacitance C_x.

The voltage value of the across the capacitor is found from as the expression (1) below.

$$U_c(t) = U_{импъулс} = U_0 + (U_{max} - U_0) \cdot (1 - \exp(-\frac{t}{RC_x})) \quad (1)$$

When comparing the value of the capacitances at the time t =T, the resistor R and the threshold value U_{th}, respectively, as shown in (2), the discharge voltage U_0 and the charge voltage U_{max} can be obtained from the constant coefficient k:

$$C_x = T\frac{\ln(k)}{R} \quad (2)$$

This method is implemented using analog electronics and logic elements, as well as a microcontroller unit to charge and discharge the capacitor and measure the time interval.

This method is capable of measurement 0.1 pF-10 mF capacitance with an accuracy of 0.1 pF. The error in the full measurement range is less than 0.5%.

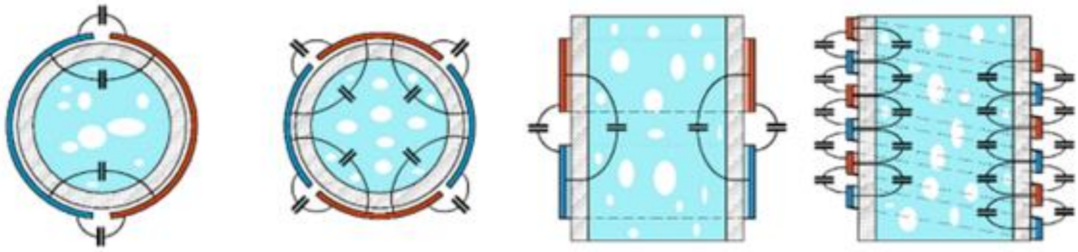
2. Research methods and the results

When water flow measurement in large pipes, all capacitances on the pipe wall represent electric field force lines passing through the two-phase flow.

Figure 5 below shows various forms of capacitance measurement due to two-phase flow in a pipe.

The sensitivity of capacitive sensors with different electrode shapes was analyzed by Kendoush, Sarkis, Jaworek and Krupa as well as Reis et al.[17,18].

In the shape presented in Figure 5(a), the total capacitance of the electrode is smaller compared to the other shapes, but the relative change in capacitance is larger. Accordingly, the detection of two-phase flow is relatively ineffective due to the low sensitivity of all sensors except for two cylindrical structures.



a) b) c) d)

Fig. 5. ***Schematic view of "two-phase detection" and stray capacitances for different designs of two-electrode capacitance sensors:***
a) two concave, b) two pairs of cylindrical, c) two ring, d) two spiral types [17].

The capacity of the sensors depends on the effective electrical conductivity of the dielectric between these electrodes, in particular in the case of two-phase flow, the percentage of liquid and gas, and the spatial distribution, regardless of the geometric shape of the electrodes.

It can be concluded from the research results of the above-mentioned scientists that the most sensitive form of the sensor is a structure consisting of two contact electrodes.

Today capacitive sensing elements (capacitive sensors) are used in various fields of production.

The reason is their simple structure, high sensitivity, low energy consumption and linearity. The possibility of non-contact testing of technological processes or determining the parameters of manufactured products gives an advantage over other types of sensors.

The capacity C of a capacitor of any shape depends on its structural parameters and the properties of the medium that fills the space between the plates under the influence of its electric field, as well as the distance between the plates (3).

So, for an idealized model of a capacitor with a flat parallel electrode, the following can be written:

$$C = \frac{\varepsilon_{average}\, S}{\delta} = \frac{\varepsilon \varepsilon_0 S}{\delta}, \quad (3)$$

where, $\mathscr{E}_{average} = \mathscr{E}\mathscr{E}_0$ - average absolute dielectric permittivity of the medium; $\mathscr{E}_0 = 8.854 \cdot 10^{-12}$ F/m - dielectric conductivity of air; $\mathscr{E}$-relative dielectric constant of environment; S - effective area of the electrodes; δ - distance between electrodes.

Today, the development of transducers or sensors that do not create additional hydraulic resistance in the pipes for measurement and control water flow in the pipes of the large pumping units existing in the irrigation systems of our country is one of the urgent scientific research issues. In addition, in large pumping stations, the pipe diameter reaches up to 4 meters and makes measurement work extremely difficult.

As such a primary sensing element, the technical characteristics of a capacitive measurement sensors or transducers are largely compatible. But the value of the capacitance formed due to the current in the pipes of the pump units is very small, it is several pF. This problem requires scientific research work, such as the development of a smart measurement system for controlling extremely small capacities.

The research of small-capacitance transducer circuits for intelligent measurement and control system is one of the important engineering issues in the measurement and control of physical processes with very small capacitance in many industries. The measurement of the properties of various materials is determined by the properties of the electrical conductivity of the dielectric layer between the capacitor plates. In general, when measuring the parameters of a physical process, the change of the measured parameter must be proportional to the change of the capacitor sensor capacity.

The information received from the object that needs to be measured or controlled is converted into an electrical signal and transmitted to the next link for processing.

As mentioned above, nowadays there are various methods of measuring very small values of capacitances (pF or nF) and the data obtained from them with very small values are processed in microcontrollers or computers.

As mentioned above, nowadays there are various methods of measurement very small values of capacitances (pF or nF) and the data obtained from them with very small values are processed in microcontrollers or computers.

In real-time measurement and control, it is necessary to take into account even very small capacitance changes. In this case, it is important to ensure that the static characteristic of the sensing element is linear or that it is accurate. In addition, strict requirements are imposed on the design of an electric measurement scheme with a high permissible value (resolution) and the selection of each of its elements.

The measurement of the empty part with a capacitor sensor is local, that is, based on the height of the cylindrical electrodes, the average ratio of two phases in a certain volume is determined by the sensor (Fig. 6). The height of the electrodes should be as short as possible to minimize non-local effects, although the effects of fringe field lines cannot be eliminated.

On the other hand, these electrodes are very short and the capacitance is very small and the sensitivity of the sensor is very low[17].

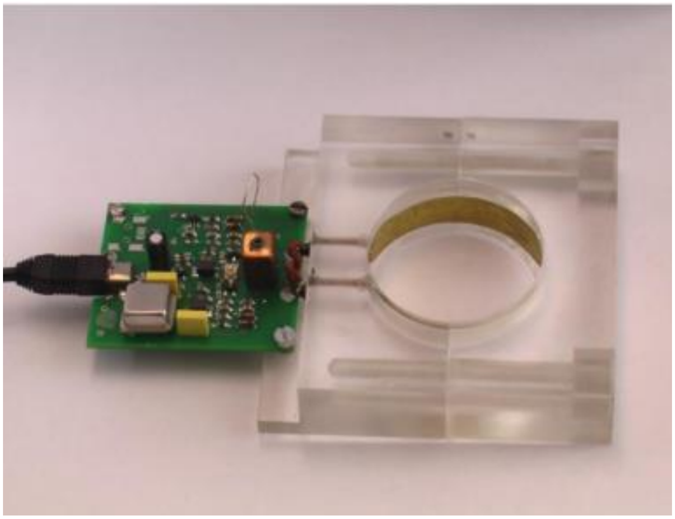


Fig. 6. ***Cylindrical capacitance sensor[17].***

The effective conductivity of a two-phase environment depends not only on the void fraction, but also on the flow pattern. However, there is no general assumption about how this conductivity depends on the flow pattern, except in the case of testing some cavity geometry.

The effective conductivity of a dielectric consisting of two phase components of different dielectric constants was summarized by Bruggeman [19,20].

3. Experimental results and discussion

Taking into account the above mentioned, the use of microcontrollers is the most efficient and accurate method for measurement very low capacitances.

One of the best technical tools for measurement and processing physical parameters with a very low value is based on measurement elapsed time of charge or discharge of capacitors using microcontrollers [21,22,23].

This method is related to the development of microcontrollers or microprocessors. It can increase measurement performance by recording and processing electrical signals in very high frequency circuits or very small time (ns).

One of the main metrological characteristics of water flow measurement in large pipes with a capacitive sensor consists of its amplitude-frequency (AF) and phase-frequency response (PF).

When water flow measurement in large pipelines, one of the important issues is to study the reaction of the measurement circuit of the measurement and control sensor to the influence of the input signal. The measurement circuit of the capacitive sensor developed in the research work is shown in Figure 7 below.

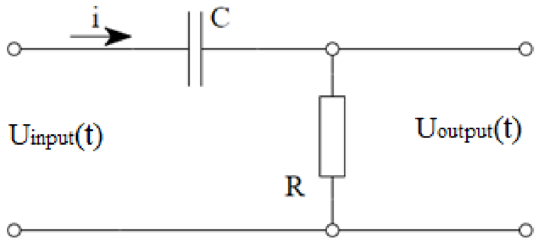


Fig.7. ***A differentiating circuit.***

The following expressions can be written for this circuit. To do this, we determine the relationship between the input and output signals of this circuit:

$$U_{input}(t) = U_{output}(t) + U_R(t) = U_c(t) + U_{output}(t) \quad (4)$$

Taking into account that $U_{output}(t) = i \cdot R$ and $i = C\frac{dU_c}{dt}$ it is possible rewrite equation (4) as follows:

$$U_{output}(t) = i \cdot R = RC\frac{dU_c}{dt} \quad (5)$$

$$U_c(t) = U_{input}(t) - U_{output}(t) \quad (6)$$

Taking into account the equation (6) we will rewrite equation (5) as follows:

$$U_{output}(t) = RC[\frac{dU_{input}(t)}{dt} - \frac{dU_{output}(t)}{dt}],$$

or

$$\frac{1}{RC}U_{output}(t) = [\frac{dU_{input}(t)}{dt} - \frac{dU_{output}(t)}{dt}],$$

or

$$\frac{dU_{output}(t)}{dt} + \frac{1}{RC}U_{output}(t) = \frac{dU_{input}(t)}{dt} \quad (7)$$

If $\frac{dU_{output}(t)}{dt} \ll \frac{1}{RC}U_{output}(t)$, in this case

$$U_{output}(t) \approx RC\frac{dU_{input}(t)}{dt} \quad (8)$$

In this case, the measurement circuit acts as a differentiating circuit. A measurement circuit with this condition means a slowly changing voltage, and the circuit shown in Figure 7 above is a good differentiating circuit for a slowly varying function.

If $\frac{dU_{output}(t)}{dt} \gg \frac{1}{RC}U_{output}(t)$, in this case

$$U_{output}(t) \approx U_{input}(t) \quad (9)$$

In this case, the output signal repeats the input signal. This condition represents a rapid change in voltage.

However, it is desirable to analyze the rate of change of the function through its spectral analysis.

To construct AF and PF response of the measurement circuit of the water flow measurement sensor, it is necessary to calculate its transmission coefficient. For this, we write the following expressions for the circuit shown in Figure 7:

$$K_t(j\omega) = \frac{\underline{U}_{output}}{\underline{U}_{input}} = \frac{\underline{I}R}{\underline{I}\cdot(R+\frac{1}{j\omega C})} = \frac{R}{R+\frac{1}{j\omega C}}, \quad (10)$$

here $K_t(j\omega)$ - complex transmission coefficient of measurement circuit.

So, the expression (10) completely expresses the AF and PF response of the differentiating circuit analyzed above. Its module value is equal to:

$$|K(f)| = \frac{\omega RC}{\sqrt{1+(\omega RC)^2}} = \frac{\omega \tau}{\sqrt{1+(\omega \tau)^2}} \quad (11)$$

This expression represents the AF response of the water flow measurement sensor. Its phase is equal to:

$$\varphi(f) = arctg\left(\frac{1}{\omega RC}\right) = arctg\left(\frac{1}{\omega \tau}\right) \quad (12)$$

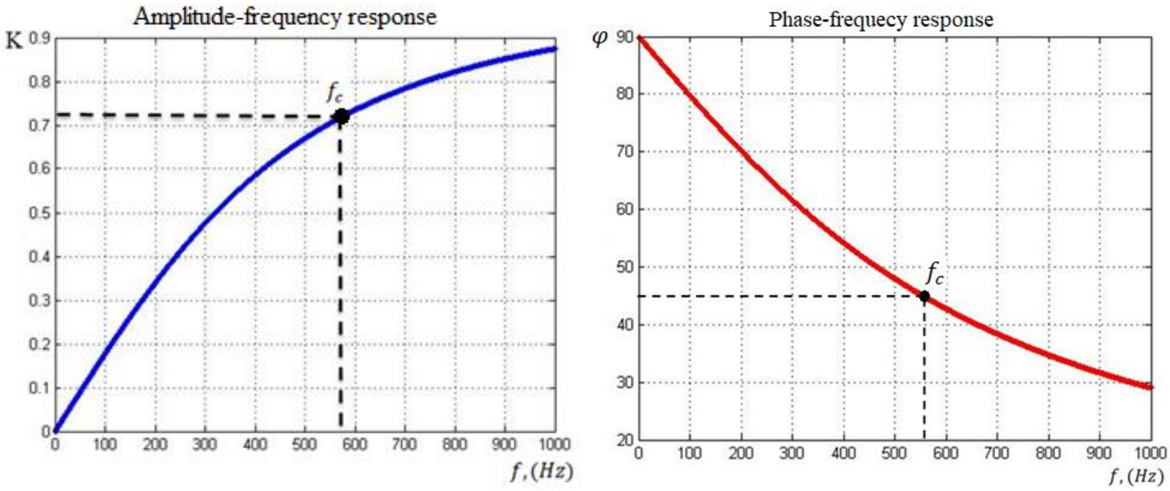
Expression (12) represents the PF response of the water flow measurement sensor. Here $\tau = RC$ time constant of the circuit.

In expressions (11) and (12) cutting frequency equal to $f_c = 1/2\pi RC$, then the modulus of K(f) can be written as follows:

$$|K(f)| = \frac{\frac{f}{f_c}}{\sqrt{1+(\frac{f}{f_c})^2}}, \quad (13)$$

here f_c – cutting frequency.

Using equation (11), (12) and (13) given above, we construct AF and PF of the water flow measurement sensor. They are presented in Figures 8.



a) *b)*

Fig. 8. ***Frequency response of water flow sensor:***
a) AF and b) PF response of the water flow measurement sensor.

4. Conclusion

From the analysis of AF and PF response of the measurement circuit in Figure 8, it can be concluded that the cutting frequency value (f_c) corresponds to the value of the transmission coefficient module K(f) = 0.707. In addition, the phase angle at this frequency is $\varphi = 45^0$. As the frequency increases to the next values, K(f) →1 tends to $\varphi = 0^0$. So, this measurement circuit of the sensor, consisting of RC, forms as high-pass filter circuit. From the information studied above, we know that there is a need to use a high frequency when measuring low capacitances.

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