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Capacitive Measuring Device

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ABSTRACT

A measuring device with a differential capacitive transducer (CT) is described. In the measuring circuit in series with the CT the model resistor is connected via an electronic switch. The voltage divider, which is formed by this connection, is powered by high frequency sinusoidal current. The output value of the measuring circuit is the phase angle between the total voltage of the voltage divider and the voltage drop on CT. This angle is converted to duration of unipolar rectangular pulses, which is measured by discrete counting method. Measuring process control and measurement results processing is performed by programmable microcontroller. The technique and results of metrological research are presented.

Keywords: Capacitive transducer, information parameter, invariant conversion, duration of pulses, discrete counting method, conversion accuracy.

INTRODUCTION

Capacitive transducers, due to the simplicity of construction and low cost, are used to measure a large number of various technological values, such as movement, approximation, humidity, acceleration, fluid level, gas concentration etc. In recent years, with the advent of MEMS technology and devices [1], that combine microelectronical and micromechanical components, the use of capacitive sensing elements has increased many times over. Moreover, the sensitive elements are being implemented in differential performance.

MAIN BODY

To measure the informative parameter of CT, usually the method of its conversion to potentially-current signals is being used. This method cannot provide an invariant measurement without the use of additional corrective chains, because these signals are influenced by changes of supply voltage of measuring circuit, offset voltage and drift of operational amplifiers, internal noise and external interference. In order to eliminate the effect of the listed interfering factors, in capacitive measuring device which is considered in this paper, pulse-width conversion of informative parameter of differential CT is used.

In the measuring circuit of device (Fig. 1) in series with the CT the model resistor R_0 is connected via an electronic switch (ES). The voltage divider, which is formed by this connection, is powered by high frequency sinusoidal current of generator G (if necessary - via current-limiting element). The output value of the measuring circuit is the phase angle φ between $\dot{U}_S$ voltage (the total voltage of the voltage divider) and $\dot{U}_X$ (voltage of CT). In general, for the angle φ we can write:

$$tg\,\varphi = \frac{\operatorname{Im}\left(\dot{U}_S/\dot{U}_X\right)}{\operatorname{Re}\left(\dot{U}_S/\dot{U}_X\right)} = \frac{\operatorname{Im}\left[\dot{I}\left(R_0 - jX_C\right)/\dot{I}\left(-jX_C\right)\right]}{\operatorname{Re}\left[\dot{I}\left(R_0 - jX_C\right)/\dot{I}\left(-jX_C\right)\right]} = \frac{R_0}{X_C} = \omega R_0 C$$

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For positions 1 and 2 of EP: $tg\varphi_1 = \omega R_0 C_1$ and $tg\varphi_2 = \omega R_0 C_2$, where $C_1 = C_0 + \Delta C$, $C_2 = C_0 - \Delta C$, and C_0 is the initial value of these parameters, which is constant and known (indicated in the passport data of the ES). If the increase of capacities ΔC is the informative parameter of differential CT, we can write

$tg\varphi_1 - tg\varphi_2 = \omega R_0 (C_1 - C_2) = 2\omega R_0 \Delta C$, accordingly

$$\Delta C = \frac{tg\varphi_1 - tg\varphi_2}{2\omega R_0} \tag{1}$$

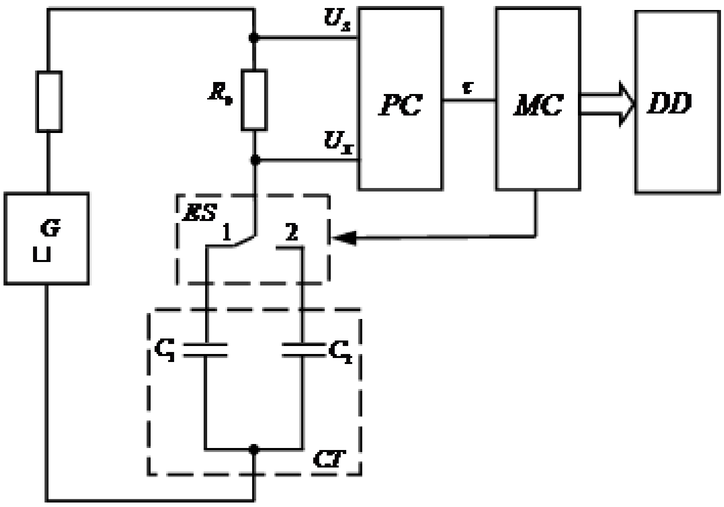

Fig1. *Block Diagram of capacitive measuring device*

It is obvious, that the voltage of generator does not affect the results of conversion of informative parameter of CT. It is only necessary to measure the φ_1 and φ_2 values of φ angle, which is accomplished by the same hardware.

The widespread use of the differential CT is due to the stability of parameters in a wide range of measuring temperature of CT. The presence of two identical halves of the sensor in one case makes it possible to implement a relative conversion of working capacity, however, the advantages inherent in the differential structure are fully manifested only when the informative parameter is the relative increase of capacity $K(C) = \Delta C / C_0$ [2]. Such conversion automatically provides ratiometric accuracy correction of CT, it can significantly reduce the temperature error and eliminate the influence of dielectric permittivity of interelectrode environment on the conversion result. In this device, the conversion function of this informative parameter is equal to:

$$K(C) = \frac{tg\varphi_1 - tg\varphi_2}{tg\varphi_1 + tg\varphi_2} = \frac{\sin(\varphi_1 - \varphi_2)}{\sin(\varphi_1 + \varphi_2)}. \tag{2}$$

From eqn (2) it is obvious that in this case the frequency of generator and the resistance of resistor (and therefore the resistance of transient contacts of CT), are not explicity figuring in results of conversion, which means that their influence is reduced.

RESULTS AND DISCUSSION

To measure the angle φ the phase converter PC is used (Fig. 1), wherein the angle φ is converted to unipolar rectangular pulse duration τ . PC comprises a high-speed dual comparator and a logic element "Exclusive OR" [3]. Comparator inputs are sinusoidal voltages u_S and u_X , the output is meanders, which are shifted in phase by an angle φ (Fig. 2). These meanders proceed to the input of "Exclusive OR" element, whose output voltage u_τ is obtained in the form of a sequence of unipolar rectangular pulses, the duration τ of which is directly proportional to the φ angle. In the realized sample of the meter, considered here, for PC high-speed dual comparator AD9698SO (company Analog Devices) and gate "Exclusive OR" type SN74LS86 (company ON Semiconductor) are used.

The pulses from the output of the PC is input to a programmable microcontroller (MC), where τ is measured, φ is calculated by the obvious formula $\varphi = \frac{\tau}{T} \cdot 360^o$ and $\Delta C / C_0$ is calculated by eqn (2). MC also controls the periodic switching of the analog switch ES and simplifies process of pairing device with the computer, as it is possible to connect MC to the computer via COM-port by RS-232 interface and continuously transmit measurement results to the computer.

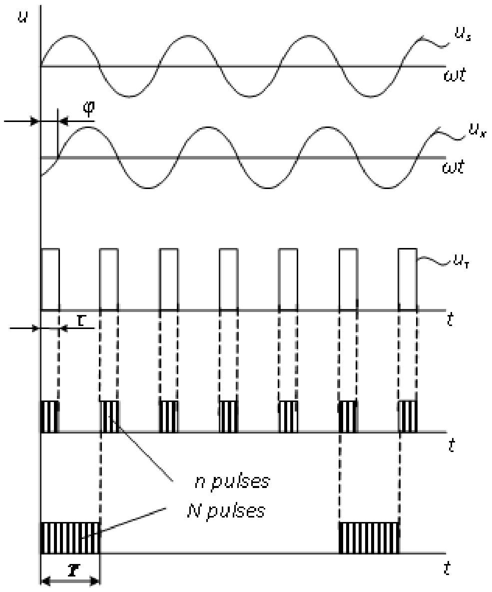

Fig2. *To measure the angle of phase shift by the method of discrete calculation*

In MC, time durations τ and T are being measured by discrete counting method, through filling them with pulses of exemplary frequency of MC clock generator with use of its integrated timer. Timer indication will be

$$\varphi = \frac{\tau}{T} \cdot 360^o = \frac{nT_0}{NT_0} \cdot 360^o = \frac{n}{N} \cdot 360^o . \tag{3}$$

The accuracy of measurement of the φ angle is determined by the accuracy of determining the number of n and N pulses. This accuracy is the sum of the random accuracy of discreteness, i.e. the possibility of losing of one pulse count in values of n and N. Absolute accuracy of the measurement will be

$$\Delta\varphi = \frac{\partial\varphi}{\partial n}\Delta n + \frac{\partial\varphi}{\partial N}\Delta N = \left(\frac{\Delta n}{N} - \frac{n}{N^2}\Delta N\right) \cdot 360^o ,$$

and the relative accuracy will be

$$\delta(\varphi) = \frac{\Delta\varphi}{\varphi} = \frac{\Delta n}{n} - \frac{\Delta N}{N} .$$

The worst case occurs when $\Delta n = 1$, $\Delta N = -1$:

$$\delta(\varphi) = \frac{1}{n} + \frac{1}{N} = \frac{T_0}{nT_0} + \frac{T_0}{NT_0} = T_0\left(\frac{1}{\tau} + \frac{1}{T}\right) . \tag{4}$$

Eqn (4) shows that the accuracy in measurement of the φ angle can be reduced only by increasing the clock frequency of generator.

Measuring circuit parameters are chosen so that at the starting point of the meter when $C_1 = C_2 = C_0$, could be the condition $\varphi_1 = \varphi_2 \approx 45^0$, where maximum sensitivity of conversion is provided. Consequently, from the condition $tg\varphi = R_0 / X_{C0} = 1$ the value of R_0 should be equal to $X_{C0} = 1/\omega C_0$. For example, when $C_0 = 50$ *pF* and $f = 50$ *kHz* we should have

$$R_0 = \frac{1}{\omega C_0} = \frac{1}{2\pi \cdot 50 \cdot 10^3 \cdot 50 \cdot 10^{-12}} = 63{,}7 \ kOhm.$$

Wherein, when determining the effects of measurement accuracy of φ_1 and φ_2 angles on total measurement accuracy $K(C)$, by eqn (2), we can simplify that equation, based on the following considerations. When incrementing the measured value, starting from zero, φ_1 and φ_2 angles are getting incremented with opposite signs and when $\varphi_1 = \varphi_2 \approx 45^0$ their sum is changing slightly, which allows to assume the value of $\sin(\varphi_1 + \varphi_2)$ to be constant in eqn (2). To prove this, let us consider two numerical examples. Let us assume that in the example above, the maximum increase in capacitance of the half of differential CT is $\Delta C_m = 10$ *pF*, so we can calculate the values of maximum increment of φ_1 and φ_2 angles.

$$tg\varphi_{1m} = \omega R_0 (C_0 + \Delta C_m) = 2\pi \cdot 50 \cdot 10^3 \cdot 63{,}7 \cdot 10^3 \cdot 60 \cdot 10^{-12} = 1{,}308;\ \varphi_{1m} = 52^0 36';$$

$$tg\varphi_{2m} = \omega R_0 (C_0 - \Delta C_m) = 2\pi \cdot 50 \cdot 10^3 \cdot 63{,}7 \cdot 10^3 \cdot 40 \cdot 10^{-12} = 0{,}872;\ \varphi_{2m} = 41^0 5';$$

$$\sin(\varphi_1 + \varphi_2) = \sin 2\varphi_0 = \sin 90^0 = 1;\ \sin(\varphi_{1m} + \varphi_{2m}) = \sin 93^0 41' = 0{,}9979;$$

$$\Delta \sin(\varphi_1 + \varphi_2) = 0{,}0021.$$

Now, let us assume that $\Delta C_m = 20$ *pF*.

$$tg\varphi_{1m} = \omega R_0 (C_0 + \Delta C_m) = 2\pi \cdot 50 \cdot 10^3 \cdot 63{,}7 \cdot 10^3 \cdot 70 \cdot 10^{-12} = 1{,}526;\ \varphi_{1m} = 56^0 46';$$

$$tg\varphi_{2m} = \omega R_0 (C_0 - \Delta C_m) = 2\pi \cdot 50 \cdot 10^3 \cdot 63{,}7 \cdot 10^3 \cdot 30 \cdot 10^{-12} = 0{,}654;\ \varphi_{2m} = 31^0 12';$$

$$\sin(\varphi_1 + \varphi_2) = \sin 2\varphi_0 = \sin 90^0 = 1;\ \sin(\varphi_{1m} + \varphi_{2m}) = \sin 87^0 58' = 0{,}9994;$$

$$\Delta \sin(\varphi_1 + \varphi_2) = 0{,}0006.$$

In practice, rarely the increment in capacitance of half of differential CT is 40% higher than its initial value. Based on the foregoing, when calculating the measurement accuracy by the eqn (2) we can put $\sin(\varphi_1 + \varphi_2) \approx const$ and assume that the only variable is $\sin(\varphi_1 - \varphi_2)$. In this case, the absolute accuracy of conversion function (2) will be

$$\Delta K(C) = \frac{\partial K(C)}{\partial \sin(\varphi_1 - \varphi_2)} \cdot \Delta \sin(\varphi_1 - \varphi_2) = \frac{1}{\sin(\varphi_1 + \varphi_2)} \cdot \frac{\partial \sin(\varphi_1 - \varphi_2)}{\partial(\varphi_1 - \varphi_2)} \cdot \Delta(\varphi_1 - \varphi_2) =$$

$$= \frac{\cos(\varphi_1 - \varphi_2)}{\sin(\varphi_1 + \varphi_2)} \cdot \left[\frac{\partial(\varphi_1 - \varphi_2)}{\partial \varphi_1} \cdot \Delta\varphi_1 + \frac{\partial(\varphi_1 - \varphi_2)}{\partial \varphi_2} \cdot \Delta\varphi_2 \right] = \frac{\cos(\varphi_1 - \varphi_2)}{\sin(\varphi_1 + \varphi_2)} \cdot (\Delta\varphi_1 - \Delta\varphi_2) \cdot$$

The relative accuracy will be.

$$\delta K(C) = \frac{\Delta K(C)}{K(C)} = \frac{\cos(\varphi_1 - \varphi_2)}{\sin(\varphi_1 - \varphi_2)} \cdot (\Delta\varphi_1 - \Delta\varphi_2) = (\Delta\varphi_1 - \Delta\varphi_2) \cdot ctg(\varphi_1 - \varphi_2) \cdot$$

Considering, $\delta(\varphi) = \Delta\varphi / \varphi$, we will get.

$$\delta K(C) = \left[\varphi_1 \delta(\varphi_1) - \varphi_2 \delta(\varphi_2)\right] \cdot ctg(\varphi_1 - \varphi_2) \cdot \tag{5}$$

Let us put expression $\delta(\varphi)$ from eqn (4) into (5).

$$\delta K(C) = T_0 \left[\varphi_1 \left(\frac{1}{\tau_1} + \frac{1}{T}\right) - \varphi_2 \left(\frac{1}{\tau_2} + \frac{1}{T}\right)\right] \cdot ctg(\varphi_1 - \varphi_2) =$$

$$= T_0 \left[\frac{\tau_1}{T} \cdot 360 \cdot \left(\frac{1}{\tau_1} + \frac{1}{T}\right) - \frac{\tau_2}{T} \cdot 360 \cdot \left(\frac{1}{\tau_2} + \frac{1}{T}\right)\right] \cdot ctg(\varphi_1 - \varphi_2) =$$

$$= \frac{T_0}{T} \cdot 360 \cdot \left(1 + \frac{\tau_1}{T} - 1 - \frac{\tau_2}{T}\right) \cdot ctg(\varphi_1 - \varphi_2) = \frac{T_0}{T} \cdot 360 \cdot \left(\frac{\tau_1}{T} - \frac{\tau_2}{T}\right) \cdot ctg(\varphi_1 - \varphi_2) =$$

$$= \frac{T_0}{T^2} \cdot 360 \cdot (\tau_1 - \tau_2) \cdot ctg(\varphi_1 - \varphi_2) \cdot$$

Considering, $\tau = \varphi T / 360$, we will get.

$$\delta K(C) = \frac{T_0}{T} \cdot (\varphi_1 - \varphi_2) \cdot ctg(\varphi_1 - \varphi_2) \cdot \tag{6}$$

From eqn (6) it is obvious, that conversion accuracy depends on the clock frequency of MC generator and the frequency of the measurement circuit supply generator. In prototype device $f_0 = 64$ MHz, $f = 50$ kHz, therefore the ratio $T_0 / T = 50 \cdot 10^3 / 64 \cdot 10^6 = 0,78125 \cdot 10^{-3}$, i.e. conversion accuracy will be estimated by

$$\delta K(C) = 0,78125 \cdot 10^{-3} \cdot (\varphi_1 - \varphi_2) \cdot ctg(\varphi_1 - \varphi_2) \cdot \tag{7}$$

Using the first remarkable limit $\lim_{x \to 0} \sin x / x = 1$ [4], and the resultant limit

$$lim_{x \to 0}\, x \cdot ctgx = lim_{x \to 0} \frac{x \cdot cos\, x}{sin\, x} = lim_{x \to 0} \frac{x \cdot 1}{sin\, x} = lim_{x \to 0} \frac{x}{sin\, x} = 1$$

When $\varphi_1 - \varphi_2 = 0$ follows $\delta K(C) = 0,78125 \cdot 10^{-3} = 0,078125\%$ (Table. 1)

$C_0 = 50$ pF; $f = 50$ kHz; $R_0 = 63,7$ $kOhm$; $C_1 = C_0 + \Delta C$; $C_2 = C_0 - \Delta C$; $tg\varphi = 2\pi f R_0 C$;

$K(C)_N = \Delta C / C_0$; $K(C) = \dfrac{tg\varphi_1 - tg\varphi_2}{tg\varphi_1 + tg\varphi_2}$; $\delta K(C) = 0,78125 \cdot 10^{-3} \cdot (\varphi_1 - \varphi_2) \cdot ctg(\varphi_1 - \varphi_2) \cdot$

Table1. *The results of $\delta K(C)$ accuracy calculation by eqn (7)*

ΔC, pF	C_1, pF	C_2, pF	$tg\varphi_1$	$tg\varphi_2$	φ_1 grad	φ_2 grad	$ctg(\varphi_1-\varphi_2)$	$K(C)_N$	$K(C)$	$\delta K(C)\cdot 100$, %
0	50	50	1.00	1.00	45.00	45.00	∞	0	0	0,078
1	51	49	1.02	0.98	45.58	44.44	49.99	0.02	0.02	0.078
2	52	48	1.04	0.96	46.13	43.85	24.98	0.04	0.04	0.0781
3	53	47	1.06	0.94	46.68	43.24	16.63	0.06	0.06	0.078
4	54	46	1.08	0.92	47.22	42.63	12.46	0.08	0.08	0.078
6	56	44	1.12	0.88	48.25	41.36	8.27	0.12	0.12	0.078
8	58	42	1.16	0.84	49.25	40.05	6.17	0.16	0.16	0.077
10	60	40	1.20	0.80	50.21	38.67	4.90	0.2	0.2	0.077
15	65	35	1.30	0.70	52.45	35.01	3.18	0.3	0.3	0.076
20	70	30	1.40	0.60	54.48	30.98	2.30	0.4	0.4	0.074
25	75	25	1.50	0.50	56.32	26.59	1.75	0.5	0.5	0.071
30	80	20	1.60	0.40	58.01	21.81	1.37	0.6	0.6	0.067

The results from Table. 1 shows that with the selected parameters the relative measurement accuracy will not exceed 0.1%.

CHOOSING COMPONENTS OF SCHEME.

Microcontroller. As MC, relatively simple and widely used microcontroller STM32F103C8T6 (company STMicroelectronics) is used. MC has two internal clock generators, from which HSI RC oscillator with a clock frequency of 8 *MHz* is selected, and with the help of PLL module the operating frequency of $f_0 = 64$ *МГц* is achieved.

To capture the input signal (rectangular pulses) at the moment of its transition from 1 to 0 and 0 to 1 the integrated timer TIM1 is used, which is connected to the bus APB2. This bus has a maximum speed of 72 *MHz*. Channels CH1 and CH2 of TIM1 timer are configured to operate in “Signal Capture” mode. In this mode, the timer generates an interrupt when the input signal is changing from 0 to 1 (channel CH1) and from 1 to 0 (channel CH2). The timer should have the highest priority, since the signal capturing in right moments is very important factor for the accurate measurement of duration and pulse period. The channels CH1 and CH2 are connected to signal inputs PA9 and PA8 respectively (Fig. 3).

To measure time intervals τ and T the Systick timer is used. It is a 24-bit timer, which counts down, i.e. it decrements its value for a given frequency. In this case timer frequency of 64 *MHz* is set.

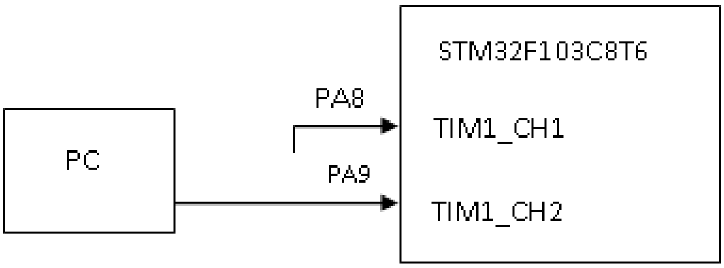

Fig3. *Wiring diagram of signal inputs of TIM1 timer*

Each time, after receiving interrupt from CH1 or CH2, the value of Systick timer is being stored in memory of MC. After receiving interrupt from CH1 twice, we will have two values, the difference of which will be the number of the pulses N, and after receiving first interrupt from CH1 and the second one from CH2, we will get the number of the pulses n. wiring diagram of MC is shown in Fig. 4.

Display. As a display, a quite common LED display CAI5461BH is used. The screen can display 4 digits. Wiring diagram of the display is shown in Fig. 4.

Electronic Switch. As a switch a precision electronic switch ADG859 (company Analog Devices) is used,. The switch is designed for switching in AC and DC circuits, it has the following parameters: channel resistance in the closed state - 1.3 *Ohm*, in the open state - ~ 10^{11} *Ohm*, Resistance match between channels - 0.01 *Ohm*, maximum current through a closed channel - 300 *mA*, unipolar supply voltage 1.8 ... 5.5 *V*, on/off times - 8 / 4.5 *ns*, frequency range - 125 *MHz*. Wiring diagram of switch is shown in Fig. 5.

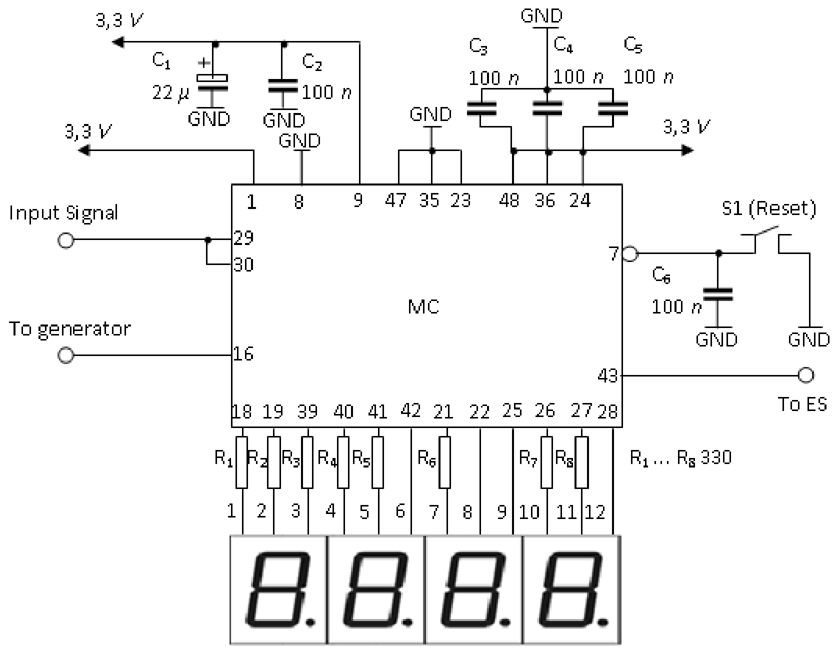

Fig4. *Wiring diagram of micro controller*

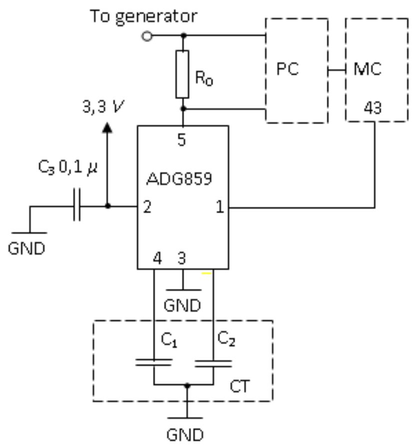

Fig5. *Wiring diagram of switch*

Switch is being controled by pinout PB7 of microcontroller (Fig. 5 output 43). Control signal with a logical value of 0 closes the channel C_1, then values n, N and φ_1 are being calculated by the formula (3), and calculation results are being stored in the memory of MC. Then, the switch receives the control signal with a logical value of 1, it opens channel C_1, and closes channel C_2, and the value of φ_2 is being calculated and saved in memory. After getting values of φ_1 and φ_2, $K(C)$ is being calculated by eqn (7) and calculation result is being displayed on the screen.

Since the frequency of the pulse signal is 50 *kHz*, to obtain the values of n and N we need

$$T = 1/50000 = 0{,}02\,ms.$$

Leaving sufficient time for the stabilization of the switch and for calculations, switch switching will occurred every 4.0 ms, i.e. by frequency of

$$f_{sw} = 1/(4\cdot 10^{-3}) = 250\,Hz,$$

which is quite sufficient for accurate measurement of the input physical value, existing on the CT.

Generator. As the generator for measurement circuit supply the chip AD9833 (company Analog Devices) is used. The advantages of this generetor are: low cost, several power saving modes, low power consumption, a serial communication interface (three wire), simple commands and calculations, a relatively high accuracy of the output signal (10-bit DAC, and 28-bit phase accumulator that allows to receive the output signal with the precision of 0.1 *Hz*, at maximum clock frequency of 25 *MHz*), an excellent S / N ratio without any filtering ~ 60 dB. Wiring diagram of the generator is shown in Fig. 6.

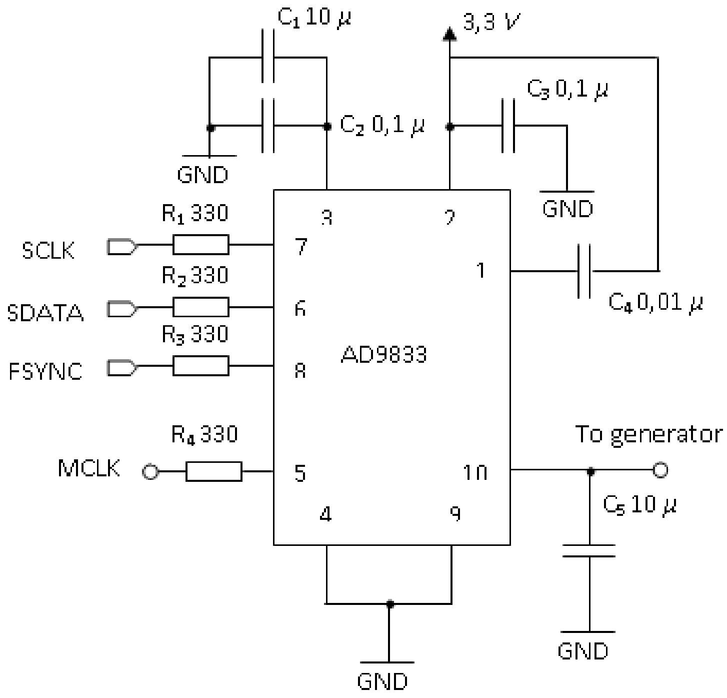

Fig6. *Wiring diagram of generator*

Generator ports SCLK, SDATA and FSYNC are used to program the generator. It is a three wire serial interface that operates at a frequency up to 40 *MHz* and is compatible with standard ports of digital signal processors and microcontrollers. The component operates with a supply voltage in the range of 3 ... 5,5 *V*. If FSYNC port value is a logical 0 we may begin transmitting 16 bit data via SDATA port into memory of the generator. SCLK determines the transmission frequency.

MCLK port is used to supply generator with $f_{MCLK} = 4\ \text{Ì Ãö}$ frequency clock signal. For this purpose, the channel CH1 of TIM3 taimer is used. The frequency of the generated sinusoidal signal depends on f_{MCLK} frequency as follows:

$$f = \left(f_{MCLK} / 2^{28} \right) \cdot FREQREG \quad (8)$$

where $FREQREG$ is the value, which is recorded in the appropriate register of the generator to adjust the frequency of the output signal.

Measurement circuit should be powered by sinusoidal current with frequency of $f = 50kHz$, therefore, the required value of $FREQREG$ can be found from the formula (8)

$$FREQREG = (f \cdot 2^{28}) / f_{MCLK} = (50 \cdot 10^{3} \cdot 2^{28}) / 4 \cdot 10^{6} = 3355443$$

CONCLUSIONS

Designed capacitance measuring device can be used for digital measurement of informative parameter of differential capacitive transducer with relative error not exceeding 0.1%. This accuracy is ensured through the use of phase signals instead of potentially-current ones.

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