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Capacitive Measurer of Linear Displacement

[1] Boris MAMIKONYAN and [2] Lusine ABRAHAMYAN
[1] National Polytechnical University of Armenia, Gyumri Branch
2, Mher Mkrtchyan, 3103, Gyumri, Armenia
[2] National Polytechnical University of Armenia, Yerevan Educational Complex
105, Teryan, 0009, Yerevan, Armenia
[1] Tel.: +374312-46832, fax: +374312-43528
[1] E-mail: b_mamikonyan@seua.am

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Abstract: The features of constructing of a linear displacement measurer with differential capacitive transducer are considered. The measuring circuit is analyzed, which makes possible to implement a linear algorithm for determining the measured displacement. With an appropriate choice of the base element, in the production conditions the device can provide measurement of linear displacements with a limit of the permissible basic comparative error not exceeding 0.12 %.

Keywords: Measurement, Measuring circuit, Capacitive transducer, Phase signal, Microcontroller, Computer.

1. Introduction

Capacitive measuring transducer (CMT) are widely used for conversion of various physical and mechanical values into an electrical signal. The advantages of the CMT are simplicity of design, low weight and dimensions, low inertia, high mechanical and electrical overload capacity, low cost, great functional flexibility, high temperature stability over a wide range of temperature changes [1, 2]. Preference is given to the differential design of the CMT: the presence of two identical halves of the CMT in one body allows to implement comparative transformation of the working capacity, to protect from the influence of external symmetrical handicaps, reduces the influence of electrostatic forces acting on the CMT plates, maintain high metrological characteristics in the temperature range up to 200 °C [3].

2. Research Object

For the measurement of small displacements, it is advisable to use a CMT with a variable gap [1]. For such a CMT with a plane-parallel electrode system, the static conversion characteristic is determined by the known formula

$$C_X = \varepsilon_0 \varepsilon S / d \,, \tag{1}$$

where $\varepsilon_0 = 8,854 \cdot 10^{-12}$ F/m is the dielectric permeability of the vacuum (air) which is the physical constant, ε is the comparative dielectric permeability of environment between the electrodes, S and d are the overlap area and the distance between the electrodes.

It follows from (1) that the sensitivity of the CMT to the air gap

$$K = \frac{\partial C_X}{\partial d} = -\frac{\varepsilon_0 \varepsilon S}{d^2}$$

That's why the increase of sensitivity is achieved by reducing the initial gap between the electrodes and increasing the size of the CMT. The resolution of the CMT with variable gap can reach 10-6 µm [4].

The measured movement x affects on the parameter d, increasing or decreasing it, and the capacitance C_X is inversely proportional to this distance. The electronic secondary converter can be constructed in such a way that its output voltage (or current) will be proportional to capacitance C_X rather than capacitance $X_C = 1/\omega C_X$ [1]. The output signal will be directly proportional to the measured displacement.

However, it is necessary to take into account peculiarities of the application of the CMT in control and monitoring systems: the CMT have a small initial capacity, which in most cases lies in the range from 10 to 10^3 pF. This circumstance leads to the need to use high frequency voltage from $1 \cdot 10^3$ to $(1 \div 2) \cdot 10^8$ Hz for the operation of sensors. Using low frequencies, for example, an industrial frequency of 50 Hz, the CMTs have a large reactive resistance, which limits their use in measuring circuits.

The use of a high-frequency signal leads to the need for additional analog and digital conversion in order to obtain unified signals (current, frequency or voltage) convenient for remote transmission over distances and subsequent use in control and monitoring systems [5].

Modern CMTs have sufficiently high metrological characteristics, their error of primary conversion does not exceed ± 0.1 % [5]. Therefore, the main direction of improving the accuracy of modern information and measurement systems based on the capacitive method is the improvement of known or the design of new methods for processing measuring signals (methods of converting electrical capacitance into an electrical signal) of the CMT, as well as methods for recording and compensating external disturbances.

The differential CMT displacement, based on the change of the distance d between the plates, is a flat condenser with electrodes 1, 2 and 3 (Fig. 1). Electrodes 1 and 2 are fixed immovably, and electrode 3 is the reproducing part of CMT. The function of transforming differential CMT displacements is the dependence $\Delta C = C_1 - C_2 = f(x)$.

In the initial position of the movable electrode, when the measured movement $x = 0$, we do have

$$d_1 = d_2 = d_0,\ C_1 = C_2 = C_0 = \frac{\varepsilon_0 \varepsilon S}{d_0} = \frac{A}{d_0},$$

$$\Delta C = C_1 - C_2 = 0.$$

Under the action of displacement x the capacity of the CMT is changing as follows

$$C_1 = \frac{A}{d_0 - x},\ C_2 = \frac{A}{d_0 + x}, \quad (2)$$

and we obtain a nonlinear function of displacement transformation x:

$$\Delta C = \frac{2A \cdot x}{d_0^2 - x^2} = \frac{2A \cdot x}{d_0^2 \left(1 - x^2 / d_0^2\right)}$$

In this regard, to limit the error of non-linearity, the measuring range is limited by the value $x \le 0{,}1 d_0$.

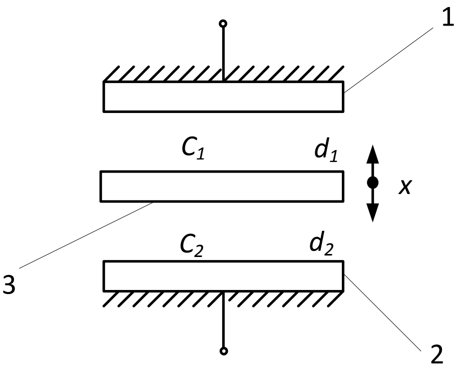

Fig. 1. Differential CMT with variable gap.

Then the maximum nonlinearity obtained at the end of the measurement range and determined by a deviation from unity of the value is $1 - x^2/d_0^2$, equal to $1 - x_m^2/d_0^2 = 1 - 0{,}01$ which does not exceed 1.0 %.

With accurate measurements, this error value is also unacceptable, besides, such a limitation of the measuring range is not always desirable. Thus, in the measuring circuit (MC), in which the passive information parameter ΔC is converted into the active value - into an electrical signal, the task of ensuring the linearity of the functional dependence between the output signal and the measured motion must be solved.

3. Research Methods

In this research, this problem is solved by selecting the appropriate MC scheme, in which the phase angle of displacement between u_S and u_X is used as the output signal (Fig. 2). In this scheme, CMT is series connected with supporting exemplary resistor R_0 via an electronic switch, which forms a voltage divider with an CMT - powered by the current of the generator of sinusoidal oscillations (G).

In the initial position of the switch, the angle of phase φ_1 of displacement between the output voltages u_S and u_X is determined by the expression

$$ctg\varphi_1 = \frac{U_X}{U_0} = \frac{IX_{C1}}{IR_0} = \frac{X_{C1}}{R_0}$$

$$ctg\varphi_2 = \frac{X_{C2}}{R_0}$$

In the second position of the switch the difference

$$F = ctg\varphi_2 - ctg\varphi_1 = \frac{X_{C2} - X_{C1}}{R_0} \qquad (3)$$

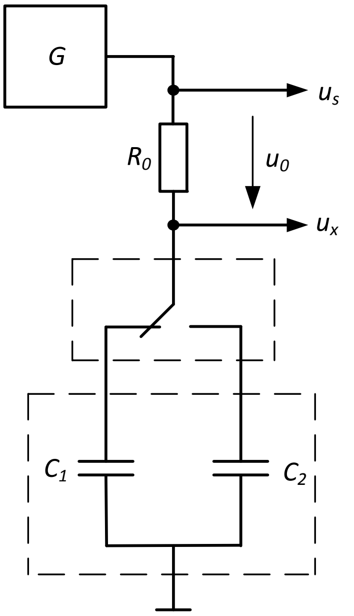

Fig. 2. The scheme of measuring circuit of CMT.

Taking into account the values $X_{C1} = 1/\omega C_1$, $X_{C2} = 1/\omega C_2$, where ω - the angular frequency of the generator, we obtain from (3)

$$F = \frac{1}{\omega R_0} \cdot \frac{C_1 - C_2}{C_1 C_2} \qquad (4)$$

Taking into account the dependences (2), expression (4) get the form

$$F = \frac{2}{\omega R_0 \varepsilon_0 \varepsilon S} \cdot x \qquad (5)$$

Consequently, the MC in Fig. 2 provides a linear dependence between the measuring displacement and value F. Thus, from (5) we obtain an algorithm for determining the displacement x

$$x = \frac{\omega R_0 \varepsilon_0 \varepsilon S}{2} \cdot \left(ctg\varphi_2 - ctg\varphi_1\right) \qquad (6)$$

From (6) it can be seen that the measurement result is not affected by the voltage and current of the generator and the measuring circuit, which indicates a high noise immunity of the measurement method. It is necessary to measure only the angle of phase displacement between two voltages, which is the most accurately measured value in the digital electrical measuring technique.

4. Electrical Circuit

In the developed device (Fig. 3), the voltages u_S and u_X are applied to the inputs of a programmable microcontroller (MCR) 4, which controls the operation of the switch and measures the φ angle values. In the MCR the φ angle is converted into a time interval τ. The time intervals τ and T (the period of voltages u_S and u_X) are measured by the discrete counting method by filling them with impulses of the exemplary frequency f_0 of the MCR generator using its integrated timer-counter. Further, the angle is calculated by the formula $\varphi = \tau \cdot 360^o / T$.

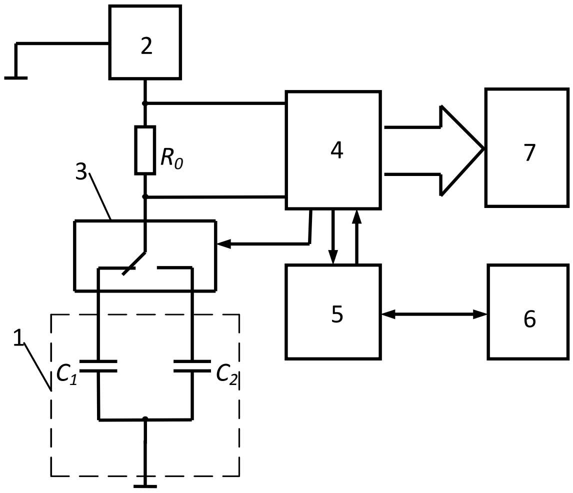

Fig. 3. Simplified scheme of connections of a linear displacement with a differential CMT.

Then, from the measured values φ, the MCR calculates the value x according to Formula (6). To increase the accuracy of the measurements, each measurement MCR repeats 10 times and determines the average value of the results. From the MCR, the digitized signals of angles φ_1 and φ_2 via the AVR309 interface converter 5 are sent to the computer 6, where they are processed and the measurement results are output to the computer monitor. The MCR displays the results of the measurement also on the digital readout device 7.

When selecting a power supply for the measuring circuit, it should be taken into account that the stability of its voltage is not significant, but the measurement result depends on the frequency of the generator. The presence of MCR dictates the appropriateness of using integrated circuits for the programmable generators of sinusoidal signals (for example, type AD9833). At each measurement, the MCR sets the frequency of the generator and uses this frequency value when calculating the measured value, so that possible changes in the generator frequency do not affect the accuracy of the measurement. The frequency of the measuring current is preferably at least 50 kHz. In this case, it should be taken into account that with increasing frequency of power supply MC accuracy in measuring the phase angle is reduced.

The resistance of the supporting resistor must be selected in such a way that the maximum sensitivity of the conversion of the CMT parameter to the angle φ is ensured. This is the case, where at the initial point of the conversion $C_1 = C_2 = C_0$, when the condition $\varphi_1 = \varphi_2 \approx 45^0$ is valid. Hence, from the condition $ctg\varphi = 1$

$$X_{C0} = R_0 \text{ or } R_0 = \frac{1}{\omega C_0}.$$

For example, with the use of CMT, these values are as follows: $C_0 = 50$ pF, $f = 50$ kHz, therefore, should be $R_0 = 127,4$ kOhm. The developed device uses a resistor type C2-29B with a tolerance of 0.1 %.

As a switch, it is advisable to select a sensitive electronic switch-multiplexer ADG859. The chip is intended for commutation of DC and AC circuits, has the following parameters: channel resistance in the closed state is 1,3 Ω, in open mode it is about ~ 10^{11} Ω, channel impedance mismatch is 0,01 Ω, maximum current through the closed channel is 300 mA, The supply voltage is unipolar, 1,8...5,5 V, the on/off time is 8/4,5 ns, the frequency range is 125 MHz, the operating temperature range is -40 °C to +125 °C. This chip best suits the operating conditions of this device.

When choosing the MCR, it should be taken into account that it must have the highest possible frequency f_0 of the clock generator and, more importantly, two internal comparators, whose inputs will receive voltages u_S and u_X (preferably through voltage-buffer repeaters, so as not to load the MC), to convert the angle φ into the duration τ of rectangular pulses. The use of an internal ADC of MCR for this purpose is inadvisable, because the value of the conversion period (sampling) of the ADC limits the minimum possible value τ, thereby substantially increasing the sensitivity threshold of the measurer.

5. Results

A method for theoretical investigation of the error in measuring the displacement by the phase method is developed. It is established that the use of time separation of the measurement channel ensures elimination of the methodical error due to the capacitance of the connector cable of the CMT and the imperfection of the element base of the measuring circuit. The expression for the comparative measurement error is obtained in the form

$$\delta(x) = \frac{f}{f_0} \cdot (\varphi_1 - \varphi_2) \cdot ctg(\varphi_1 - \varphi_2)$$

It can be seen that the measurement error can be reduced by increasing the frequency f_0 of the MCR clock generator and decreasing the frequency f of the power supply MC generator. At the same time, as the difference $(\varphi_1 - \varphi_2)$ increases, the error decreases. If, for technical reasons, a higher frequency of the supply voltage of the MC is required, then the MCR with a higher clock frequency generator should be selected.

The measurement error has been evaluated depending on all parameters influencing on the accuracy of the measurement and it is stated that with appropriately selected MC parameters and generator frequencies, the required measurement accuracy can be provided.

6. Conclusion

Analysis of the research results shows that the selected MC scheme and the used phase method of measurement, based on the time separation of the measuring channel, provide a digital invariant measurement of the informative parameter of the differential CMT. The developed device is simple in practical implementation and can provide high accuracy of measurement due to the use of phase signals instead of potential signals and current signals, which ensures high noise immunity of measurement results. With an appropriate choice of the base element, in the production conditions the device can provide measurement of linear displacements with a limit of the permissible basic comparative error not exceeding 0.12 %.

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