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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy
in Technology

RESEARCH AND DEVELOPMENT OF FACTORS AFFECTING THE ACCURACY OF MEASUREMENTS OF A CAPACITIVE SENSOR OF LARGE LINEAR MOVEMENTS

Speciality:	3337. 01 - Information-measurement and management systems (by fields)
Field of science:	Technical sciences
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Sumqayit – 2025

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GENERAL CHARACTERISTICS OF THE WORK

Relevance and degree of development of the topic. The modern level of development of information technologies (IT) and electronic devices (ED) has brought to the agenda the need to design information-measuring and control systems (IMCS) in a new structure. The main goal is the creation of intelligent information-measuring systems, the integration of their functional modules with smart technologies, the compatibility of all devices and equipment with each other, etc. It is this approach that ultimately leads to the creation of an IMCS with high metrological characteristics.

SMART technology integrates the concepts of concise and clear, measurable, quantifiable, achievable with available resources, significant and time-dependent. As can be seen, very serious requirements are imposed on the initial measuring instruments to meet these requirements. For all these reasons, the technology of creating transmitters (sensors) is of exceptional importance in measurement technology, and this field has emerged as a new direction. Due to insufficient use of smart technologies when designing existing transmitters, their metrological indicators are significantly lower, and the information-measuring systems built on their basis are far from intelligent.

The above-mentioned characteristics are also valid for capacitive transmitters (CT). In addition to the reasons mentioned, another problem with this type of transmitters is that in order to obtain a stable signal at their outputs, they need to be powered by a high-frequency voltage of hundreds of kHz and sometimes even tens of MHz. In this case, parasitic capacitances, considerable losses in connecting wires and other elements occur.

Various methods are used to increase the measurement accuracy, stability, output signal power, and other indicators of the CT. For this purpose, it was used to connect a larger load to the control circuit of the primary amplifier of the transmitter. However, these or other means have little effect on the schematic improvement of the stability of the CT and significantly complicate the design of the device.

Studies have shown that the reason for instability in the development of a measurement system based on power sensors is the imperfection of the construction of these transmitters. In particular, from the incorrect placement of the tools insulating the construction, which leads to errors in the operation of electronic devices due to the instability of the properties of these tools.

Capacitor parameters only depend on their geometric properties and not depend on the properties of the materials used in the correct selection of these materials. Therefore, selecting the type of metal for the board and the insulation for attaching them by correctly, is possible to bring the temperature effect of changing the surface field and the distance between the boards to a minimum level.

Such price qualities as the ability to control the output of a small functioning system and the high accuracy of the working activity of the mechanical force required to move the moving part of the transmitters can reduce supplier errors at a price equal to one hundred or even a thousand percent, which makes the devices indispensable.

The main disadvantages of large displacement capacitors are their small transmission or conversion ratio, high shielding requirements for parts and the need for high-frequency operation. However, in most cases, having achieved sufficient shielding due to the construction of the transmitter, they give good results at 400 Hz.

During the operation of large displacement capacitors, it is very important to avoid incorrect starts caused by atmospheric precipitation, process liquids, etc.

Object and subject of research. The object of research of the dissertation is large linear displacement capacitors, their structural schemes, metrological characteristics, parameters, influencing factors, autocompensation schemes, correction algorithms and other issues. The subject of the research is the identification of conversion characteristics of large displacement capacitors, autocompensation of influencing factors, improving measurement accuracy, development of solutions and tools for evaluating the results.

The aim and objectives of the research. The main goal of the dissertation is to develop of large displacement capacitors, the research of factors affecting measurement accuracy, the estimation of measurement errors, the development and application of an efficient scheme for auto-compensation and corrective algorithms.

In accordance with the purpose of the research, the following tasks are set in the dissertation work:

1.Research of electric capacitance transmitters, analysis of factors affecting their measurement accuracy.

2.Study of the working of a moving core - large displacement (LD) capacitance transducer and factors affecting its informative parameters.

3.Analysis of factors affecting the sensitivity of capacity converters of different construction, their determination and compensation, development of a method and algorithm.

4.Study of the factors affecting the sensitivity of the moving core capacitance transducer, development of the error correction algorithm.

5.Development of methods and tools for expanding the measurement range of a large linear displacement capacitance transmitter.

6.Study of measurement errors of large linear displacement capacitance transmitter, development of correction algorithms for error generators.

Research methods. The main research methods of the dissertation work are theory of measurement and control based on theoretical research, laboratory experiments and real tests against the background of fundamental and traditional experimental approaches, modeling, planning of experiments, evaluation of measurement results, probability theory, mathematical-statistics, information technology and other fundamental theoretical-practical tools.

Main provisions for the defense.

1.Research methods of large displacement capacitors, identification of their conversion characteristics;

2.Study of the factors affecting the accuracy of capacitance transmitters and determining their correlations with the parameters of the transmitter;

3.External factors affecting the parameters of moving-core TVs and their autocompensation.

4.Metrological characteristics of BY TVs, measurement accuracy, hybrid test measurement method and algorithm synthesis.

5.Development of test measurement algorithms and electronic circuits for increasing the measurement accuracy of capacitance transmitters;

6.Development of correction algorithms for measurement errors and error organizers of capacitance transmitters.

Scientific innovations. The main scientific innovations of the work are as follows:

1.Structural and algorithmic models of large-displacement capacitance transmitters have been developed [1-4].

2.A non-linear approximation method was proposed for the identification of the conversion functions of capacitance transmitters.[8].

3.In order to increase the measurement accuracy of capacitance transmitters, the optimal selection of additive, multiplicative and combination tests and the methodology of drawing up basic test equations are provided. [8].

4.Corrective algorithms for uncorrelated static errors, inadequacy error and final error of the tested capacitance transmitters were developed.

5.The distribution law of the final error and its zones were determined, and the factors affecting the measurement result were evaluated.

Theoretical and practical value of work. The results obtained in the work have both theoretical and practical significance.

Theoretical value - theoretical study of any capacitor, nonlinear approximation of the rotation function with high accuracy, a testing algorithm to improve measurement accuracy, development of algorithms that warn error and error organizers.

Practical value - application of the obtained results measurement methods and diagrams at control and measuring objects, high-precision measurements of technological parameters, auto-calibration of measuring instruments, transmitters, automatic compensation of measurement errors and other similar areas.

The methods, algorithms and diagrams developed in the dissertation work will allow to obtain high efficiency in measuring technology and equipment.

Implementation of the study results.

- The results on the topic of dissertation work were obtained in the Sumgait State University Department of "Information and Computer Engineering" Research work to 2006-2021 years.

- The results of the research work were tested in the "Intelligent information-measuring systems" laboratory No. 22 of the Institute of Management Systems of ANAS, the "Information and computer technology" department of SSU, the "Neftgazavtomat" SPE (Scientific and Production Enterprise), and the adequacy of the results was confirmed by acts.

Work approval. The main results of the research were discussed at the following conferences:

4th International Scientific and Technical Conference of IEPP (Baku-Sumgait, 2003); International Scientific and Technical Conference devoted to the 50th anniversary of television and 80th anniversary of radio in Azerbaijan (Baku, 2007); Republican scientific conference of postgraduate and young researchers dedicated to the 85th anniversary of national leader Heydar Aliyev (Baku, 2008); International Conference «Scientific and Technical Progress and Modern Aviation» dedicated to 75th anniversary of Academician A.M. Pashayev (Baku, 2009); International Scientific Conference «Modern scientific and technical and applied problems of energy» (Sumgait, 2015); XX Republican scientific conference of doctoral students and young researchers (Baku, 2016); International conference «Information technologies and mathematical modeling» (Kazan, 2017); XXI Republican scientific conference of doctoral students and young researchers (Baku, 2017); International scientific conference of professors and teachers, doctoral students and young researchers dedicated to the 100th anniversary of the People’s Republic of Azerbaijan (Baku, 2018); International scientific conference «Modern problems of applied physics and energy» (Sumgait, 2018); Celebration of the 100th anniversary of the People's Republic of Azerbaijan. International Scientific Conference «Information Systems and Technologies, Achievements and Perspectives» (Sumgait, 2018); Republican scientific conference «Actual issues of training of personnel in energy specialties» (Sumgait, 2019); 1st International scientific and practical conference «Modern information measurement and management systems: problems and perspectives» (Baku, 2019); II International Scientific Conference "Information Systems and Technology: Achievements and perspectives." (Sumgait, 2020). IV Republican scientific conference «Mathematical application issues of mathematics and new information technologies» (Sumgait, 2021); The International Conference on Energy and Environmental Technologies in Engineering and Architecture (Bakı, 2024); Republican Scientific and Practical Conference on "Actual Problems of Metal and Alloy Physics" dedicated to the 50th anniversary of AzMCU, (Baku, 2025).

Published scientific articles. 28 scientific publications: 9 articles, 3 published in foreign journals (3 articles are included in the international database RSCI (Russian Science Citation Index)), 19 articles in the materials of scientific and practical conferences.

The name of the organization in which the dissertation work was carried out: The dissertation work was fulfilled at Sumgait State University.

Dissertation volume and structure. The dissertation consists of an introduction, four chapters, main conclusions, a list of 122 references, appendices and a list of abbreviations. The total volume of the work is 147 pages, and the main volume is 125 (164,000 characters) pages, including 5 tables and 32 pictures. Chapter 1 - 42000, Chapter 2 - 52000, Chapter 3 - 40000, Chapter 4 - 30000 marks

CONTENTS OF THE WORK

In the introduction – installation principle of large-displacement capacitor transmitters, preliminary considerations about methods and means of measurement is presented and the need and actuality justified. At the same time, the scientific and technical bases of designing capacitance sensors based on new technologies, ensuring their high metrological characteristics, and the relevance of research conducted in this direction were evaluated. The object and subject of the research, the purpose and tasks of the research, the research methods, the main issues defended, the scientific innovations obtained as a result of the research, the theoretical and practical value of the work, the realization of the results of the research, the approval of the work, published scientific works, the volume and structure of the dissertation are presented.

In the first chapter – Capacitors and their construction principle were analyzed. It is known that capacitance converters (CC) are divided into single-capacitance and double-capacitance transmitters. Two-capacitance transmitters are differential or semi-differential. The construction of a single capacitance transmitter is simple and consists of a variable capacitance condenser. Their disadvantage is that they are sensitive to external factors such as humidity and temperature. In two-capacitance transmitters, differential constructions are used to compensate for the mentioned errors. A disadvantage of this type of transmitter compared to single-capacitance transmitters is that at least three shielded connecting wires are required between the transmitter and the measuring device to compensate for parasitic capacitances. But, this deficiency is compensated by a significant increase in accuracy, stability and expansion in the field of application of such devices.

Their low accuracy, the need for periodic calibration, sensitivity to parasitic capacity and the temperature coefficient of the resistor is a drawback of the method of measuring capacity. Parametric capacitors are based on output signal processing circuits, the analog voltage of capacitance change, the current output of the time-pulse modulator (TPM) or leakage, as well as the conversion of parasitic capacitances into a frequency signal with minimal losses. To obtain output signal from capacitors are as follows:

– method of measuring the capacitance of the transmitter in a direct current - at this time, the voltage that drops on the capacitor boards powered by a direct current source;

– measurement of capacitance oscillations at loading of capacitor boards in several pulse sequences connected from one or several pulses, for example, microcontroller;

– measuring the capacity used in the RC generator as a time transmitter;

– measurement of impedance in the capacitor powered by alternating current (AC), in demodulator circuit;

– capacitance measurement in the load amplifier;

– capacitance measurement in the sigma-delta circuit of the modulator, etc.

It should be noted that the output resistance of the capacitor transmitter is high Ohm (1... 100 MOhm), which requires a high input resistance circuit for voltage measurement. First two methods are implemented quite easily, but they have a high sensitivity versus the noise.

In the third method changes the magnitude of the capacitance with frequency or transformation into a TPM signal, and is also carried out in a simple way. An RC generator used in transmitters with a change in distance between boards produces a linear frequency output signal with proportional frequency. Due to the coating of boards the option of capacitors is linearized with a measurement of pulse width.

The slight inertia of capacitor transmitter and transducers allows them to be used to measure rapidly changing volumes and control fast processes.

It is used to change the distance of boards between the electrodes of the capacitor transmitter or transducers, set the capacitance meters of the lower and upper pressure, rotating bodies, micrometers, etc. In particular, conductors using elastic deformations of electrodes are intended. In one case, transmitter electrodes with membranes operate as a pressure measuring device, in the other, bimetallic electrodes operate as a temperature measuring device.

Changing area of the boards of capacitor transmitter or transducers, for example, to monitor the state of the arrows of measuring instruments, to convert the opening angle of doors, the angle of inclination of the arrows of ground machines, etc., is widely used in radio engineering and automation. The same transmitter group includes position controllers and compute counters.

Generally, the movement of electrodes of capacitor transmitter and transducers having a varying distance between the boards and a varying area of the board should be limited. This allows the use of measuring instruments in subsequent systems where any noticeable load on the measuring device is unacceptable.

The change in the dielectric conductivity of the medium between the boards is widely used in production processes. Thus, it is used as the main measuring means for monitoring the level of substances in the liquid state and granular form, as well as in determining these types of substances.

In recent years, the most complex issues of automatic control with the help of suppliers have been solved, such as the control of the separation boundary of two unrelated liquids, as well as rapid analysis of the content of substances in the chemical, oil refining, food, woodworking, paper and other industries.

A change in capacitance of the condenser may occur during a change in boards spacing, dielectric conductivity, area of the boards or a simultaneous change in the listed dimensions. These properties of capacitors with variable capacitance are the basis of capacitors.

Obviously, the construction of the TV is determined primarily by the type of quantity measured and the method of influencing the change in capacity. Detailed data on the changing nature of the transmitter capacity, application areas and constructions were analyzed. The possible application areas of capacitance transmitters are the most diverse.

They are used in regulation of processes production and control systems almost in all industries.

Parameters included in the convention characteristic of capacitance transmitter are analyzed. In automatic monitoring and control systems both simple primary elements and complex intermediate systems contain independent units and elements. However, despite the complexity of the structures and using area of conductors, they are uniquely characterized by the following basic parameters:

- the initial price of the capacity:

$$C_0 = f\left(\varepsilon, S, d\right) = f(\varepsilon, g), \varphi;$$

- maximum capacity change:

$$\pm\Delta C = f\left(\pm\Delta\varepsilon, \pm\Delta S, \pm\Delta d\right) = f(\pm\Delta\varepsilon, \pm\Delta g);$$

- reaktiv müqavimət:

$$X_c = \frac{1}{2\pi fC_0},$$

- active resistance - R_C,
- active losses: $tg\delta = f(R_C, C_0, \omega)$, here, $\omega = 2\pi f$, sec^{-1}
- electric load storage time: $\tau = R_C C_0$, *sec;*
- the strength of the interaction of the electrodes:

$$F = f(\varepsilon, S, d, U) = f(\varepsilon, g, U),\ N\cdot m^{-1};$$

- sensitivity of change: $\gamma = f(\Delta C, C_0)$.

Each CT, along with the main parameters, has functional properties that are determined by its static and dynamic characteristics. Static characteristic reflects analytical or graphical dependence of variables on functional dependence of CT between output and input parameters, and dynamic characteristic depends on degree of change of output value of transmitter parameter.

Thus, various types of conductors used in measuring physical parameters were analyzed, their advantages and disadvantages were classified. Identified that the CT conversion characteristics (CC) is non-linear and the effectiveness of the partial non-linear approximation algorithm and test measurement is justified with high accuracy.

In the second chapter, a wide selection of large displacement capacitors, different influence principles, samples, optimal structure, constructions, rotation characteristics, mathematical models were investigated.

In order to develop large displacement capacitors on the basis of modern technologies, increase their efficiency, metrological characteristics are involved in the study, improvements in their metrological characteristics and expansion of functional capabilities using new methods and tools are recommended, different topological options have been proposed.

It is clear that condense of a capacitor is determined by the ratio of the amount of electrical load solved on its boards to the potential difference between their boards. At the same time, the cost of capacitance of the capacitor depends on the shape of its boards, their close positions and the characteristics of the atmosphere between them. The main characteristic of the atmosphere between CT boards is dielectric constant, and this parameter expands the possibilities of its application.

Depending on which parameter of the CT is affected by the magnitude of the non-electric measurement, there are the following different aspects:

- based on changing the distance between boards ;
- to the change of the overlapping area of the boards ;
- CTs based on changing the relative dielectric reputation of the medium.

Taking into account the large-scale constructive implementation of CT, to ensure the simplicity of calculations, depending on the activity of the boards, the concept of the capacitor holding indicator, which is used in the formulation of the capacitor capacitance type, is included. For capacitors with parallel and smooth shape, in $\lambda = \frac{S}{d}$ is expressed and the capacitor capacitance by $C = \varepsilon_0 \varepsilon \lambda$ is given.

CTs have one transducer element - capacitor unipolar, two transducer elements - capacitor differential and bridged. In the case of differential transducers or bridged transducers, one or two capacitors may be either constant capacity or interconnected variable. Televisions are as low capacity they commonly used in high frequency alternating current circuits. The power frequency of the bridge circuit is compared to the load capacity and is selected due to the cost of capacity resistance obtained from the calculation.

To increase the capacitance of the transducer, the gap between its electrodes has a sufficiently high relative dielectric reputation and is filled with a dielectric liquid (usually methanol ε = 32.63) capable of changing environmental factors.

Displacement transducers operating on the principle of changing the mutual coverage area of capacitor boards are most often used in bridge circuits (Figure 2.1).

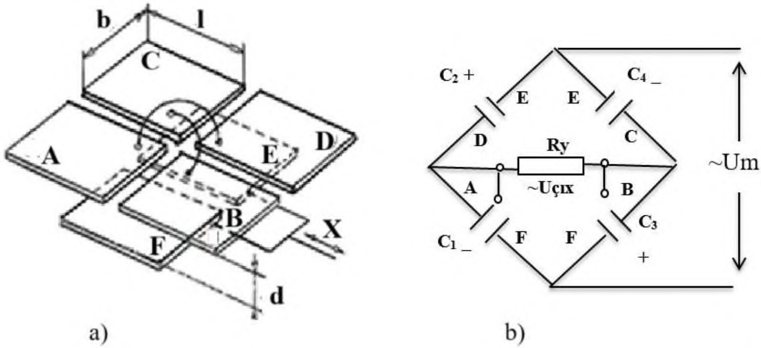

Figure 2.1. Capacitance displacement converter

In bridge circuits, the capacitance of a condenser consisting of two parallel boards is proportional to the area of the movable board located in front of the corresponding area of the stationary board. The value of the capacity on the bridge branch of the bridge scheme is determined as follows:

$$C_n = \frac{\varepsilon_0 b}{d}\left(\frac{l}{2} \pm x\right) or\ C \pm \Delta C = \frac{\varepsilon_0 b \cdot 1}{2d} \pm \frac{\varepsilon_0 bx}{d}. \qquad (2.1)$$

The content of the opposite bridge branchs capacitors are approximately equal to each other $C_2 = C_3$ and $C_1 = C_4$. By the symmetry of the transcuder, the movement of moving boards in the X direction leads to a violation of the balance of the body and the appearance in the diagonal of the body of an output signal with a certain pole depending on the direction of movement of moving U_{out} due to the symmetrical arrow of constant boards group .

When using a bridge circuit in an imbalance condition as a measurement circuit, it should be taken into account that complex resistances consisting of active and reactive components are included in the branch of a changing bridge circuit, and the conditions of the bridge operation in an inbalanced state can be ensured under one of three conditions: firstly, all bridge branches have only reactive resistance; secondly, branches only have active resistance; thirdly, two neighboring branches have only reactive resistance and the other two have active resistance. As we look,to all branchs of the bridge have only reactive resistance. From the condition of the bridge operation in imbalanced state, it is obtained as follows:

$$U_{out}\frac{U_m\,(X_1X_4 - X_2X_3)\cdot R_y}{(X_1+X_2)(X_3+X_4)\cdot R_y + X_1X_2(X_3+X_4) + X_3X_4(X_1+X_2)} \quad (2.2)$$

here, $X_1 = \frac{1}{\omega C_1}$, $X_2 = \frac{1}{\omega C_2}$, $X_3 = \frac{1}{\omega C_3}$, $X_4 = \frac{1}{\omega C_4}$, $U_s -$ the source voltage of the bridge circuit; $R_l -$ load capacity in the bridge diagonal; $\omega -$circular frequency of the current $sec^{-1} = \frac{1}{2\pi\cdot f}$ $and\ U_{out} -$ is the output voltage of the load resistance. $X_1 = X_4 = \frac{1}{\omega(C-\Delta C)}$ and $X_2 = X_3 = \frac{1}{\omega(C+\Delta C)}$ assumed it existed, if, after a series of conversions, we enter it into the expression U_{out} , we get the following formula:

$$U_{out} = \frac{U_s\,\Delta C\cdot R_l}{C\left(R_l + \frac{1}{\omega C}\right)}. \quad (2.3)$$

In its turn

$$\Delta C = \frac{\varepsilon_0\cdot b\cdot(\pm X)}{d}\ \ and\ \ C = \frac{\varepsilon_0\cdot b\cdot l}{2d}, \quad (2.4)$$

Then, U_{out} expressed by geometric dimensions of the capacitance transcuder , will have the following form:

$$U_{out}=\frac{U_s\frac{\varepsilon_0\cdot b\cdot(\pm X)}{d}R_l}{\frac{\varepsilon_0\cdot b\cdot l}{2d}\left(R_l+\frac{1}{\frac{\omega\cdot\varepsilon_0\cdot b\cdot l}{2d}}\right)}=\frac{U_s(\pm X)R_l}{\frac{l}{2}\left(R_l+\frac{2d}{\omega\cdot\varepsilon_0\cdot b\cdot l}\right)},\quad(2.5)$$

Or

$$\frac{U_s(\pm X)R_l}{\frac{l}{2}R_l+X_c},\ \ here\ \ X_c=\frac{2d}{\omega\varepsilon_0 b\cdot l}.\quad(2.6)$$

The obtained expression is a static characteristic of the displacement capacitance transducer built in accordance with the bridge circuit and a change in the area of mutual coverage of capacitor boards. Such the displacement capacitance transducer can be used not only in smooth electrodes, but also in any symmetrical configurations.

Bridge circuit displacement CTs have high sensitivity, linear static characteristic, high resistance to noise and are not exposed to the environmental influence. Differential capacitance measurement transducers are used to improve accuracy, sensitivity and reduce the impact of electrostatic forces affecting the boards of capacitance measurement transducer and to include into their bridge circuit.

Based on this principle in operation, the constructions of a CT for various assignments and CC are given. At the same time, the principle of setting functional circuits of CT is given. At this time, the CT input signal $x(t)$ is converted into an $y(t)$ output signal:

$$y=F[x(t)],\quad(2.7)$$

Televisions capable of changing power supply depending on the construction characteristic, operating principle and electric circuit solutions have different types of static characteristics. When designing televisions that can be changed by parameters, when choosing their electric circuit and circuit parameters, an attempt is made to obtain a static characteristic close to a linear dependence. To achieve this, the converter circuit parameters are selected closer to the balance prices of the active and reactive resistances of the electrical circuit[1].

In this section presents the electrical circuits for several single capacitance transcuders and their parameters.

Thus, a theoretical study of linear displacement capacitance transmitters (LDCT) was carried out, models of a schematic connection of variable capacitance capacitors are given; the principle of installation of linear displacement capacitance transmitters is set and their conversion characteristics are investigated; the possibilities of using in measuring level and humidity were investigated, real samples were considered; the principles of construction and functional diagrams of large

LDCTs for various assignments were given and finally the static characteristics of the variable capacitance transducers were investigated.

In the third chapter – has been studied schematic models, parameters, conversion characteristics of large displacement capacitance transmitters (LDCT), affecting factors and other matters.

The sensor part of the capacitance transmitters consists of a high-sensitivity capacitor and forms one of the main elements of control and measuring systems used in automation and other areas.

They provide advance information about controlled and managed processes in the system or device settings.

The measured physical quantity influences the sensitive element (input), at the output an electric signal is formed to this action proportionally, which is valued in the corresponding electronic module. Due to the above-mentioned advantages and reliability, LDCT is widely used in various fields: industry, production, technological process, robotics, machine, equipment, household, etc., in the fulfillment automated control measuring, signal system and manage functions. The disadvantage of these transducers to ensure

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[1] Luneev, D.E. Calculation and analysis of measuring transducers with varying electrical capacitance. -Astrakhan: Publishing house of ASTU, 2008.

stability in the measurement process to use the auxiliary tools, that reduces the efficiency of the device.

To increase the measuring range of LLDCT, it is necessary to increase the number of capacitor plates. As an example, the electrical scheme of the capacitance transmitter given in figure 3.1 was considered.

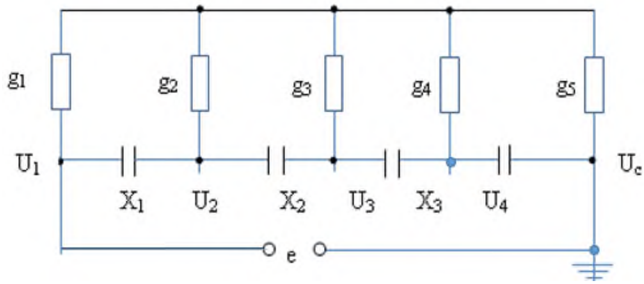


Figure 3.1. Electrical scheme of direct connected capacitance transmitters

The circuit consists of 4 capacitors with parallel plane plates connected in series, 5 resistors with the same nominal value connected to their combined midpoints, a core moving between the capacitor plates and a variable voltage power source. The advantage of connecting capacitors in series is that the range of capacitance changes for each element is small, which ensures high sensitivity.

At the scheme $X_{1,} X_2$ *and* X_3 – mesured parameters; $U_{1,} U_{2,} U_3$ *and* U_4 – suitable output voltages; $g_{1,} g_{2,} g_{3,} g_4$ *and* g_5 – suitable electrical conductances

According to the graph structure of the electrical circuit given in Fig. 3.1, the following system of linear equations is constructed:

$$U_2(x_1 + x_2 + g_2) = U_1x_1 + U_3x_2 + U_cg_2$$
$$U_3(x_2 + x_3 + g_3) = U_2x_2 + U_4x_3 + U_cg_3$$
$$U_4(x_3 + x_4 + g_4) = U_3x_3 + U_cg_4 \qquad (3.1)$$
$$U_c(g_1 + g_2 + g_3 + g_4 + g_5) = U_1g_1 + U_2g_2 + U_3g_3 + U_4g_4$$

If $g_1 = g_2 = g_3 = g_4 = g_5 = g$ we accept, then $5U_c = U_1 + U_2 + U_3 + U_4$ become and we get the following system of equations:

$$U_2(x_1 + x_2 + g) - U_3x_2 - U_cg = U_1x_1$$
$$-U_2x_2 + U_3(x_2 + x_3 + g) - U_4x_3 - U_cg = 0$$
$$-U_3x_3 + U_4(x_3 + x_4 + g) - U_cg = 0 \qquad (3.2)$$
$$-U_2g - U_3g - U_4g + 5U_cg = U_1g$$

Calculated using the MathCad software package.

$$M := \begin{bmatrix} x_1 + x_2 + g & -x_2 & 0 & -g \\ -x_2 & x_2 + x_3 + g & -x_3 & -g \\ 0 & -x_3 & x_3 + x_4 + g & -g \\ -g & -g & -g & 5g \end{bmatrix},$$

$$V := \begin{bmatrix} U_1 \cdot x_1 \\ U_1 \cdot 0 \\ U_1 \cdot 0 \\ U_1 \cdot g \end{bmatrix}. \qquad (3.3)$$

In general, the accuracy of the elements of the scheme is determined based on the analytical method of calculating the sensitivity.For this, it is important to determine the sensitivity of the circuit.

$$S_x^F = \frac{dF}{F} : \frac{dx}{x} = \frac{dF}{dx} \times \frac{x}{F}, \qquad (3.4)$$

In this formula $S_x^F - F$ is the relative sensitivity of the parameter *x* to the nominal change.

$$F_1 = \frac{U_1}{U_c}, F_2 = \frac{U_2}{U_c}, F_3 = \frac{U_3}{U_c}, F_4 = \frac{U_4}{U_c},$$
$$x = R_1,\ R_2,\ R_3,\ R_4,\ R_5,\ \ C_1,\ C_2,$$

$C_3,\ C_4,\ U_c,\ f$ –due to prices $S_x^{F_1},\ S_x^{F_2},\ S_x^{F_3},\ S_x^{F_4}$ – sensitivity is estimated.

The sensitivity result shows that the instability of the power voltage does not affect the measurement result [6].

The capacitance transducers used in LDCT have the same construction. The measured *X* is determined by the action of the metal core moving between the stationary parallel boards of the linear displacement transducers. The surface dimensions of the core are the same in the dimensions of the condenser boards and the thickness should be less than the air distance between parallel boards up to millimeters, that is, minimal so that the core movement is normal.

To determine the sensitivity of the CT, it is enough to study one capacitance transducer. The CT construction in the considered case of Figure 3.2a, and the equivalent circuit is shown in Figure 3.2b.

As can be seen from the figure, the CC consists of immovable parallel plates 1 and 2 metal cores moving between them. The length of the boards a, the width b, the core and the surfaces of the boards in accordance with the d_1 and d_2, and the distance from the air between the non-removable boards is accepted d_0.

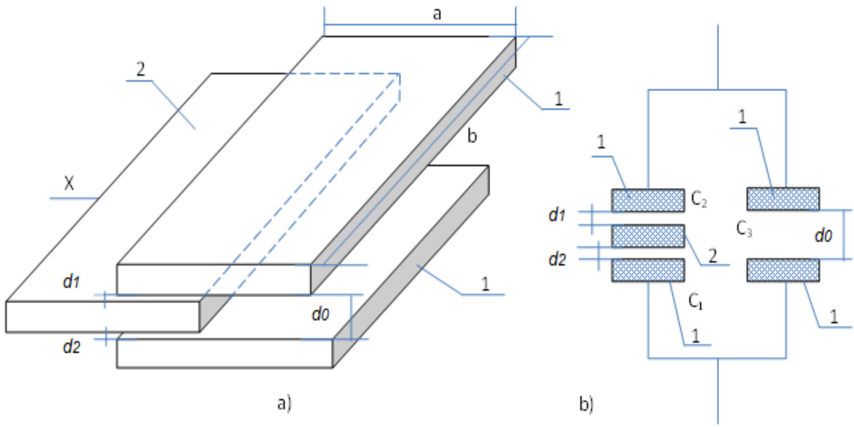


Figure 3.2. Capacity transmitter construction (a) and equivalent scheme (b)

İn accordance with the linear displacement *x* to be measured, the width *b* of the capacitance converter boards remains constant, while the length *a* decreases by *x*, that is it becomes (a – x). According to this, the transducer can be represented as a connection of three nominal capacitors (fig. 3.2, b). The C_1 *and* C_2 capacitors are connected in consistently with each other and the C_3 connected in parallel to them. Then, C_1, C_2 and C_3 will be assigned as follows

$$C_1 = \frac{\varepsilon \cdot x \cdot b}{d_1}, \tag{3.5}$$

$$C_2 = \frac{\varepsilon \cdot x \cdot b}{d_2}, \tag{3.6}$$

$$C_3 = \frac{\varepsilon\,(a - x) \cdot b}{d_0}. \tag{3.7}$$

If it is d_1=d, then it will be C_1= C_2, and the total cost of the system will be determined as follows:

$$C_x = \frac{C_1 \cdot C_2}{C_1 + C_2} + C_3;$$

$$C_x = \frac{\varepsilon \cdot xb}{2d} + \frac{\varepsilon(a - x)b}{d_0}; \tag{3.8}$$

$$C_x = \frac{\varepsilon\, b[d_0 x + 2d(a - x)]}{2d \cdot d_0}.$$

Thus, the sensitivity of the capacitance transducer will be defined as follows, corresponding to the expressions (3.8)

$$S_x = \frac{dC_x}{dx}, \tag{3.9}$$

$$S_x = \frac{\varepsilon b(d - 2\delta)}{2d \cdot d_0}. \tag{3.10}$$

or

$$S_x = \varepsilon\, b\left(\frac{1}{2d} - \frac{1}{d_0}\right). \tag{3.11}$$

If we repeat the construction in the same way and connect the capacitors with each other gradually, then the core moving between immovable boards of neighboring capacitors will change their capacitance consistently. At this time, the core between the capacitor boards should be the same and symmetrical.

For this purpose, several structural diagrams are presented in the work. The purpose of the LDCT measurement error was discussed. At this time, parallel capacitors are used as a manual transducer. The structural scheme of the transmitter consists of 4 capacitors with parallel plane boards connected between them, 5 resistors of the same resistance connected to their combined midpoints, a core (1) moved between the capacitor boards and a changing voltage power source (Fig. 3.3).

The sequential movement of the core between the capacitor boards according to the linear displacement *X* to be measured not only provides a linear acquisition of the transmitter characteristic, but also extends the measurement range and increases the measurement accuracy. Applying the method of contour currents to the electric circuit, the currents flowing through the branches corresponding to the linear displacement *X*, are assigned, including the current I_5 and the voltage drop in the resistance R_5 are determined [4,5].

As can be seen from the figure, each capacitor (capacitor) forms a series circuit consisting of two corresponding resistors *(R1R2C1, R2R3C2, R3R4C3, R4R5C4)* and the following system of equations is obtained for determining voltages by applying the method of contour currents:

$$\begin{cases} I_I\left(R_1+R_2\right)-I_{II}R_2=U_{10} \\ -I_IR_2+I_{II}\left(R_2+R_3\right)-I_{\text{III}}R_3=U_{20} \\ -I_{II}R_3+I_{III}\left(R_3+R_4\right)-I_{IV}R_4=U_{30} \\ -I_{III}R_4+I_{IV}\left(R_4+R_5\right)=U_{40} \end{cases} \tag{3.12}$$

By simplifying by accepting *R1=R2=R3=R4=R5=R* in the system of equations (3.12), we get the following system equation:

$$\begin{cases} 2RI_I-RI_{II}=U_{10} \\ -RI_I+2RI_{II}-RI_{III}=U_{20} \\ -RI_{II}+2RI_{III}-RI_{IV}=U_{30} \\ -RI_{III}+2RI_{IV}=U_{40} \end{cases} \tag{3.13}$$

where I_I, I_{II}, I_{III} and I_{IV} - are the corresponding contour currents, U_{10}, U_{20}, U_{30} and U_{40} - are the voltages between the plates of the capacitors.

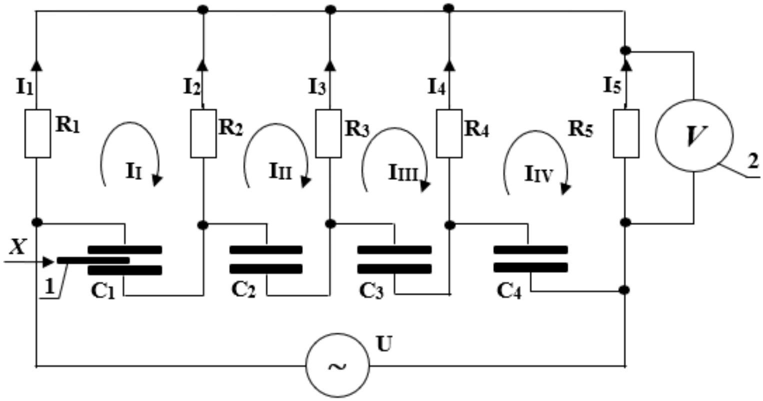


Figure 3.3. Scheme of a linear displacement capacitance transmitter consisting of 4 capacitors

Solving the system of equations (3.13), the last contour current *(I_{IV})* is determined, which is the output current flowing through the resistor *R5 (I_V=I_{IV})*. Thus the following expression is obtained:

$$I_{IV} = \frac{1}{5R}\left(U_{10} + 2U_{20} + 3U_{30} + 4U_{40}\right), \qquad (3.14)$$

Expressions for other contour currents are obtained by suitable transformations.

The active and reactive components of the output voltage are determined by the following expression:

$$U_{akt} = IR = \frac{1}{5}(U_{10} + 2U_{20} + 3U_{30} + 4U_{40}), \qquad (3.15)$$

$$U_{reakt} = IjX_c = -\frac{1}{5}\frac{1}{5R} \cdot j\frac{0.2\delta_0}{2\pi f(\varepsilon_0(a-x)\cdot b\cdot 0.2+\varepsilon_0\cdot b\cdot x)} \times$$

$$\times (20U_{10} + 35U_{20} + 40U_{30} + +30U_{40}) \qquad (3.16)$$

The full expression for the output voltage is written as:

$$U_{çıx}(x) = \sqrt{(IR)^2 + (IjX_c)^2} \qquad (3.17)$$

Using the "MathCad" software package from the equation (3.17), tests were carried out for their dependencies $U_{cix(x)} = f(x)$ and $C_{(x)} = f(x)$ the following characteristics were obtained (Fig. 3.4 a, b).

Due to the influence of external factors, the conversion characteristic of the transmitter becomes nonlinear and its identification is carried out by nonlinear approximation. In this case, a new device is proposed based on the test measurement method, where the measurement operations are determined by the real functional dependence between the current values of the capacitance and the linear displacements of the core moving between its electrodes.

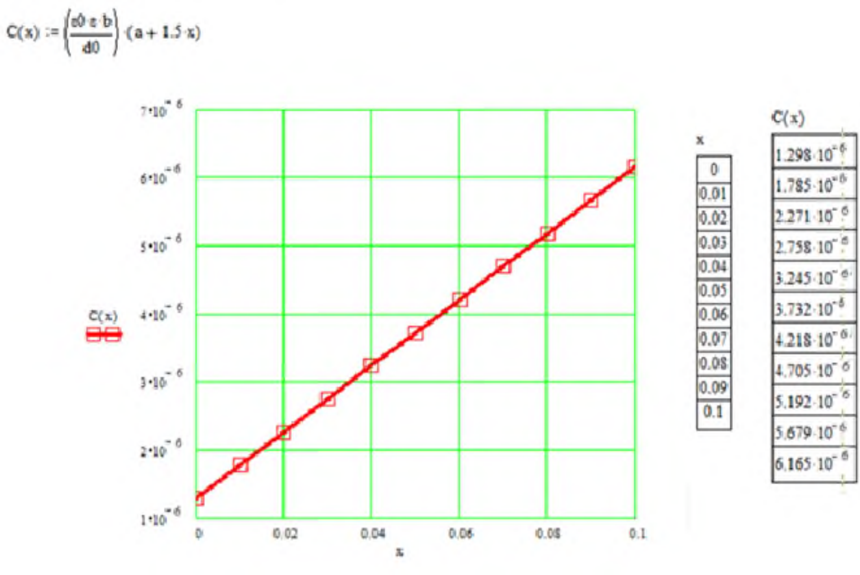
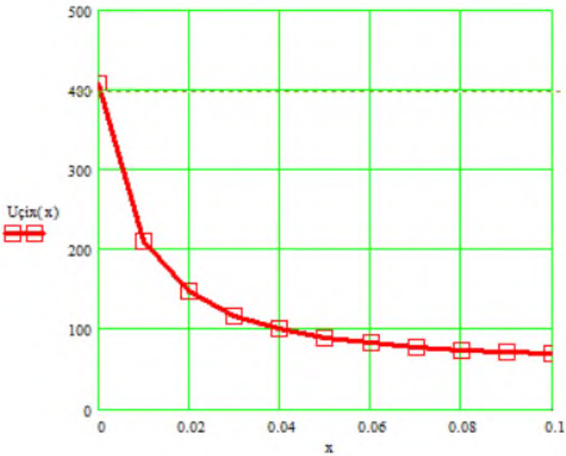


Figure 3.4.a. $C_{(x)}$=f(x) dependence

$$U_{çix}(x) := \sqrt{(IR)^2 + (IjXC(x))^2}$$



Uçix(x)	XC(x)
409.056	$1.226 \cdot 10^4$
211.025	$8.917 \cdot 10^3$
147.621	$7.007 \cdot 10^3$
117.613	$5.77 \cdot 10^3$
100.743	$4.905 \cdot 10^3$
90.266	$4.265 \cdot 10^3$
83.315	$3.773 \cdot 10^3$
78.474	$3.382 \cdot 10^3$
74.975	$3.065 \cdot 10^3$
72.369	$2.803 \cdot 10^3$
70.378	$2.581 \cdot 10^3$

Figure 3.4.b. $U_{çix(x)}$=f(x) dependence

The device uses capacitors of the same capacity connected in series to measure large linear displacements with high accuracy and increase the measurement interval.

Here, the first plates of the reference capacitances Cx and Cet. are connected to the input of the integrator 3 and include a frequency-band amplifier 1 and a demodulator 2 connected in series, a feedback circuit consisting of a modulator 5 connecting the integrator output in series with the second plate of the reference capacitance and a scale potentiometer, and an exciting support circuit consisting of a modulator 4 connected in series with the second plate of the reference capacitance and a sliding potentiometer (Fig. 3.5). As a technical result, the device is intended to increase the measurement interval and measurement accuracy of linear displacement.

The static characteristics of the CT were studied in laboratory conditions, and the measurement results and error report are presented in the appendices of the dissertation.

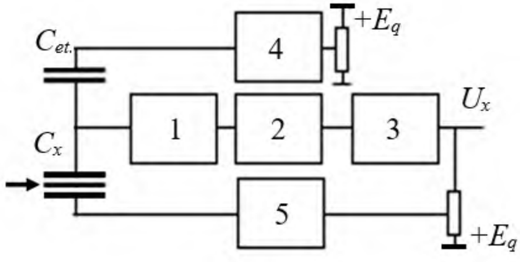


Figure 3.5. High-precision measurement device for large displacements

With the help of the proposed method and device, systematic and random errors in the measurement procedures are self-compensated, the device is self-tuning - the specified corrections are made to the current measurements.

During the study of the device, numerous tests of various variants were carried out, the results obtained and the nonlinearity of the TX were determined. In the next section, the issues of developing and studying hybrid test equations to improve measurement accuracy are considered.

In the fourth chapter, methods for improving the measurement accuracy of LDCT were investigated, algorithmic-test methods were analyzed, the efficiency of the testing method was justified.

Iterative, etalon and test methods are widely used to ensure high accuracy of measurement results. When applying this method, it is possible to simultaneously add multiplicative, additive and combination tests to the measurement tools. The main essence of the test measurement method has been widely presented in the technical literature[3].

The test measurement method is based on the high-precision identification of the conversion characteristic (CC) of the measuring device (transmitter) and serves to clarify the mathematical expression of the conversion function (CF). At this time, the largest deflection points of the CF are determined, and the appropriate test values corresponding to these points are selected. Basically, simple additive, multiplicative and hybrid tests (combinations of additive and multiplicative tests) are used.

The results of the numerous tests conducted confirm that it is sufficient to select the interpolation curve of mass-produced transmitters mainly in the form of a quadratic trinomial and to ensure the measurement accuracy:

$$y = a_{1s} + a_{2s}x + a_{3s}x^2 , \qquad (4.1)$$

Where a_{1s}, a_{2s}, a_{3s} -are the coefficients in the considered approximation fields of the polynomial.

In quadratic trinomial (4.1), with the measurement quantity x simultaneously $x+\theta$ – additive, connecting kx – multiplicative and $kx+\theta$ – mixed tests to the transmitter input are obtained by the following test in turns.

$$\begin{cases} y_0 = a_{1sN} + a_{2sN}x + a_{3sN}x^2 \\ y_1 = a_{1sN} + a_{2sN}(x+\theta) + a_{3sN}(x+\theta)^2 \\ y_2 = a_{1sN} + a_{2sN}xk + a_{3sN}\left(xk\right)^2 \\ y_3 = a_{1sN} + a_{2sN}(kx+\theta) + a_{3sN}(kx+\theta)^2 \end{cases} \qquad (4.2)$$

Here $a_{1sN}, a_{2sN}, a_{3sN}$ is the nominal values of the parameters (coefficients) of the nonlinear transformation function of the transmitter in the corresponding s approximation fields.

The system of equations (4.2) is realized through the following structural scheme.

When solving the system of equations (4.2), the following expression is obtained for the transformation function (CF):

$$y_0 = \frac{(y_1 - y_2)[x(k-1)+\theta] + y_3(xk - x - \theta)}{x(k-1)-\theta} , \qquad (4.3)$$

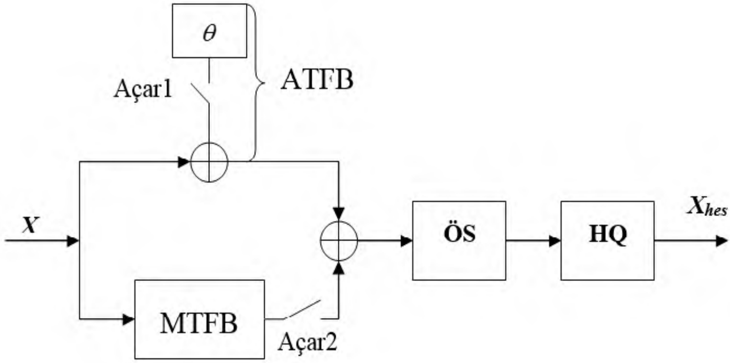


Figure 4.1. Structural diagram of the tested TIM

where ATFB is a block that forms additive tests; MTFB – block that forms multiplicative tests; S1–differential measurement sensor; ARC-analog-digital converter; HQ is a computing device.

For the price of the measurement quantity the following expression is obtained:

$$x_{hes.} = \frac{(y_1 - y_2) + (y_0 - y_3)}{(y_0 - y_3) - (y_1 - y_2)} \cdot \frac{\theta}{(k-1)}, \qquad (4.4)$$

For the absolute error from the last expression, the following is obtained[2]:

$$\Delta_T = [x(k-1) + \theta](\Delta_1 - \Delta_2) + [x(k-1) - \theta](\Delta_3 - \Delta_0). \quad (4.5)$$

If we take into account that the relative error of the tested MS is determined by the expression (4.5), then by substituting the values of the absolute error we get the following expression for all error components in each measurement tactics (MT) of the additive and multiplicative tests.

$$\Delta_T = \theta[\Delta_1 - \Delta_2 - (\Delta_3 - \Delta_0)] + x(k-1) \cdot [\Delta_1 - \Delta_2 + (\Delta_3 - \Delta_0)]. \qquad (4.6)$$

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[2]Isayev M.M. Algorithmic-test methods of increasing the accuracy of measurement systems. Baku, "Elm" publishing house, 2018, 206p.

For the absolute error $\Delta_{gir.}$ brought to the input of the tested MS the following expression is obtained

$$\Delta_{gir.} = \frac{\Delta_T}{f_T'\ (x)}, \tag{4.7}$$

Here:

$$f_T\ (x) = (y_0 - y_3)[x(k-1) - \theta] + (y_2 - y_1)[x(k-1) + \theta]. \tag{4.8}$$

When the expression (4.8) is differentiated by x, the following expression is taken for $f_T'\ (x)$:

$$f_T'\ (x) = (k-1)[(y_0 - y_3) - (y_1 - y_2)]. \tag{4,9}$$

If consider the exspression (4.6) and (4.8) in (4.7), for the absolute error $\Delta_{gir.}$ given to the input of the tested MS, we get the following expression:

$$\Delta_{gir.} = \frac{\{\theta[(\Delta_1 - \Delta_2) - (\Delta_3 - \Delta_0)] + x(k-1)[\Delta_1 - \Delta_2 + (\Delta_3 - \Delta_0)]\}}{(1-k)2\theta\{a_{2SN} + a_{3SN}[(k-1)x + \theta]\}}. \tag{4.10}$$

Thus, the following expression is obtained for the dispersion of the absolute error when the measurement clocks of the tested MS are independent of each other:

$$\sigma_{\Delta T}^2 = \sigma_{\Delta_0}^2 [z - \theta]^2 + \sigma_{\Delta_1}^2 [z + \theta]^2 + \sigma_{\Delta_2}^2 [z + \theta]^2 + \sigma_{\Delta_3}^2 [z - \theta]^2; \tag{4.11}$$

In this equation $\sigma_{\Delta i}$ is the average quadratic tendency of the corresponding measurement tacts (MT).

As a result , for the absolute error , the following formula is obtained , supplied to the input of the original MS:

$$\Delta_{gir \cdot T} = \frac{\Delta_M}{k-1} - \frac{\Delta_\theta}{\theta}. \tag{4.12}$$

It follows from (4.12) expression that the organizers of the final error $\Delta_{gir \cdot T}$ of the measurement system operating on the basis of (4.8) measurement algorithm do not depend on the costs of the coefficients of the conversion function of the measurement system during implementing the optimal set of tests.

Errors Δ_θ and Δ_M generally have no correlation relationships with each other, are continuous random quantities, and comply the law of normal distribution. Therefore, the relative error ($\delta_{gir \cdot T}$) brought to the input of the MS, in turn, is a continuous random quantity, characterized by mathematical expectation (M_{δ_T}) and dispersion ($\sigma^2_{\delta_T}$).

Mathematical expectation is defined by the following expression:

$$M_{\delta_T} = \frac{M[\Delta_M]}{k-1} - \frac{M[\Delta_\theta]}{\theta}, \qquad (4.13)$$

here is the mathematical expectation of the random quantities Δ_M and Δ_θ according to $M[\Delta_M]$ and $M[\Delta_\theta]$

Dispersion is determined by the following formula:

$$\sigma^2_{\delta_T} = \frac{\sigma^2_{\Delta_M}}{(k-1)^2} + \frac{\sigma^2_{\Delta_\theta}}{\theta^2}, \qquad (4.14)$$

Here is the average quadratic tendency of Δ_M and Δ_θ quantities according to σ_{Δ_M} and σ_{Δ_θ}

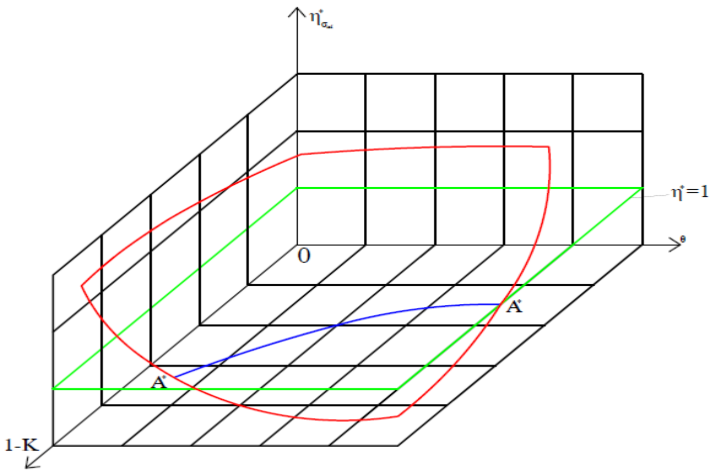

Figure 4.2. $K^*_{\sigma_{ad.}}(\theta,k)$ **Graph of dependence (** $x = x_0$ **if any)**

The following graph is obtained for the amplification factor ($\Delta_{gir.qk.ad.}$), which reflects the ratio of the mean squared trend of the uncorrelated error ($K^*_{\sigma_{ad.}}$) to the uncorrelated components of the additive error of the single-step measurement in the test OS (Fig. 4.2.).

Adequacy of the measurement results and the integrity of the identification of the TX using the test algorithms were confirmed by real tests.

MAIN RESULTS OF THE WORK

1. Transducers, their metrological characteristics, factors affecting the accuracy of measurements are analyzed and the possibilities of their use in measuring large linear displacements are determined.
2. Theoretical study of Metrological characteristics of large displacement capacity transmitters was carried out, methods for reducing factors affecting parameters were developed and adequacy was checked in real tests.
3. Large linear conductors of various purposes were investigated, the advantages of using differential sensors were justified, their conversion functions and mathematical models were specified.
4. Correlation relationships between conversion functions and their parameters of large displacement capacitive transmitters were studied, mathematical expressions were obtained, estimates were made on the basis of real samples.
5. The possibilities of using algorithmic and test methods to improve measurement accuracy in capacitance transmitters were analyzed, the hybrid test method was proved to be more efficient and confirmed by real tests.
6. Non-correlation static errors, non-adequacy error and final errors of the capacity transmitters tested were studied.
7. Mathematical models for conversion functions of large-displacement capacitive transmitters, algorithms for testing their

conversion errors were developed, mathematical and statistical estimates were made, visual graphs were presented.

8. The law of distribution of the final error and located zones in were determined, the factors affecting the measurement result were evaluated.

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The personal role of the author in works performed with joint authors:

[1-4] -development of the structural scheme of the transmitter, determining the error of the capacitance transmitter, determining the sensitivity, conducting research;

[8] -study of increasing the accuracy of capacitance transmitters by applying test algorithms;

[10] -experimental verification of oil composition and flow measurement based on capacity transmitter;

[11] -evaluation of the measurement accuracy of the capacitive differential pressure transducer in the hydrostatic pressure measurement in the oil preparation process;

[14] -the study of the error in measuring the density of oil in the flow;

The defense will be held on 12.06. 2025 at 12:00 at the meeting of the Dissertation Council ED 2.04 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Azerbaijan Technical University

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Abstract was sent to the required addresses on "10" 05 2025.

Signed for print: 08. 05. 2025.
Paper format: 60x84/ 1/16
Volume: 44118
Number of hard copies: 100