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DEVELOPMENT AND STUDY OF HIGH-PRECISION INFORMATION-MEASURING AND CONTROL COMPLEX OF OIL PRODUCTION, PRIMARY TREATMENT, TRANSPORTATION AND STORAGE PROCESSES

3337.01- Information-measuring, and control systems

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DISSERTATION ABSTRACT

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GENERAL DESCRIPTION OF THE WORK

Relevance of the subject. Irreversibly integrating into the modern world economy, the independent Republic of Azerbaijan has achieved rapid and sustainable economic development, owning huge oil and gas pipelines in the Caucasus transport corridor and playing the role of an economic bridge between Asia and Europe. Today, the main task facing our country's oil refineries is to consolidate the successes achieved in recent years, continuously export high-quality oil and petroleum products (OPP) to world markets, and fully meet domestic demand.

Oil and gas extraction platforms, primary oil refineries, oil tanks, main pipelines, terminals and other facilities built by the concern jointly established with the world's largest oil companies for the exploitation of hydrocarbon resources, discovery, extraction, processing of crude oil reserves and export to the world market are not integrated into a single information network, consisting of huge and complex technological schemes. At the same time, there are a number of serious shortcomings in oil production and refining, along with the acquisition of new products, increasing productivity and economic efficiency. Oil production, transportation and storage facilities (tanks) operate separately as independent economic units. A unified automated information-measurement and control system (complex) that combines these facilities, covering all technological processes and other operations, is still not available. Modern control-measuring and management tools applied in the mentioned areas are not able to fully meet the requirements of the day. These facilities can not be considered effective because of their complexity, inaccuracy, ineffectiveness, low level of automation, lack of automatic control over th e hermeticity of technological lines and many other serious reasons.

Due to all these reasons inaccurate oil records take place at oil industry facilities and leads to large-scale production losses, economic damage, ecological and environmental pollution.

Since these issues are the main topic of the dissertation, their simple and effective solutions were studied, the use of modern technology and the introduction of integrated automation in the processes of production, processing, storage and transportation of oil and petroleum products, which are our national treasure, were chosen as the main direction.

Thus, the development of such a complex, covering the facilities of the oil industry, having a high accuracy of measurements and an effective control algorithm, being able to keep commercial accounting (metering) at all unites, as well as constantly maintaining the overall balance of the quantity of the product is relevant issue.

In the direction of complex automation of oil, gas and chemical industries, renowned workers of science of Azerbaijan, academicians A.A. Abdullayev, I.A. Ibrahimov, T.M. Aliyev, T.A. Aliyev and other outstanding scientists have endowed our country with a large number of original theoretical and practical methods, automated devices, instruments, control and measuring systems and, most importantly, a force of professionals. It is an indisputable fact that Azerbaijani specialists have made a great contribution to the integrated automation of oil and gas facilities in the former Soviet Union.

As can be seen, the development of such PTC for oil and gas industry facilities, its the real application, the introduction of automated control from a unified center, high-precision metering and balance of production and consumption will result in reducing losses, maintaining ecological balance, increasing profitability and economic performance. All these determine the novelty of the issues raised in the dissertation, new solution methods, processes that differ in accuracy and efficiency from existing methods and tools determine the relevance of the topic.

The main areas of research of the dissertation are covered in the following provisions:

1. Development of new methods and means of preparation and primary separation of oil mixture extracted from oil fields.
2. Development of high-precision measuring systems for oil metering units.
3. Development of commercial metering system for the flow consumption and composition of liquid fuel in the main pipelines.
4. Development of commercial metering (the record) system of oil in oil storage tanks and terminals.
5. Operational control over the movement dynamics and quantity of the product in oil storage tanks.
6. Study of metrological performance of primary measurement systems.
7. Development of software and hardware complex with the corporate network.
8. Implementation of study results, etc.

Objective of the work. The objective of the work is to develop testable information and measurement systems with high measurement accuracy for oil industry facilities (oil production, primary treatment, separation from mixtures, storage, transportation by pipeline) and centralized software and hardware complex and information support, ensuring their integration into a single information space.

Study method: The conducted research work is based on theoretical research, laboratory experiments and real tests on the background of fundamental and traditional experimental approaches. Elements of measurement theory, modeling, planning of experiments, probability theory, mathematical statistics, information technology and systems, and elements of other relevant fundamental theoretical and practical laws were used.

Scientific Innovations. The main scientific innovations of the research are:

1. Analytical expressions were obtained to determine the quantitative and qualitative indicators of the oil emulsion [16].
2. The existing metering unit of oil well debit was modernized, and a tested metering system based on the measurement of hydrostatic pressure difference was developed to improve the measurement accuracy and efficiency [2, 19, 21].
3. The oil separation device (separator) was modernized, the reference measurement system and algorithm were developed to ensure high measurement accuracy [19, 21].
4. To improve the efficiency of the initial oil separation process, an automated measuring system and an algorithm were proposed that ensured the mixing of chemical reagents with high measurement accuracy in the inlet collector of the separator [28].
5. A mathematical model linking the integral characteristics of oil flow rate with local parameters was obtained and monotonous nonlinear dependence of functional composition of emulsion in separator device was established [22, 26].
6. An automated calibration system based on piezometric measurement for oil tanks of various geometric sizes and a method for designing individual calibration tables were developed [18, 20].
7. A new structured, multiparameter commercial accounting system and information support for commercial product accounting in oil tanks were developed [22, 27].
8. Long-term fuel turnover in the oil reservoir was modeled in the form of a stochastic process, selective characteristics were determined, information provision was developed [5-8, 10, 17].
9. Hybrid test algorithms were developed for measurement systems, schemes were built for their implementation, algorithms for correction of measurement errors were developed and studied [14, 15, 39, 40].

10.Algorithms for correction of measurement errors were developed and studied [12, 13, 16, 27, 28, 30, 32, 33, 37, 38].

The practical significance of the work. The results of the dissertation are of theoretical and practical significance. The developed measurement methods, devices and algorithms can be applied for metering of commercial oil with high measurement precision, implementation of balance, prevention of losses and evasion of metering.

The main provisions of the defense are as follows:

1. Study of oil metering units, the development of methods and means of determining the quantitative and qualitative indicators of oil.
2. Development of high-precision methods and tools for determining the composition of oil in the primary processing facilities, evaluation of quantitative and qualitative parameters.
3. Study of the flow process, development of a tested measurement system and algorithm for high-precision determination of liquid fuel parameters.
4. Study of existing methods and means of commercial metering of products in oil tanks, development of a new structured tested information and measuring system, and information provision.
5. Development of automated calibration method and system for oil tanks of various geometric sizes and shapes.
6. Mathematical modeling of the process of long-term circulation of liquid fuel in oil tanks and determination of sampling characteristics.
7. Study of metrological characteristics of primary measuring instruments, development of a hybrid test algorithm for high-precision identification of nonlinear transformation functions.
8. Development and implementation of a hybrid algorithm for testing prim ary measurement systems with a nonlinear transformation function and eva luation of error components.

Implementation of the results of the research . Research results were discussed at numerous International Scientific Conferences and symposiums, published in prestigious journals, received patents, tested at oil and gas industry facilities and in the "Laboratory for the establishment of means of control and measurement of the oil and gas products transportation process" of the Institute of Management Systems, significant results obtained during the scientific and research works carried out at ANAS according to the plan of the State Budget were included in the reports of ANAS.

Approbation of work: The main provisions of the dissertation released for defence were widely discussed at the following scientific symposia and conferences: 2ND International Advanced Technologies Symposium (Istanbul, 1999), Second International Symposium on Mathematical & Computational Applications (Baku, 1999), Modern Problems of Informatization, Cybernetics and Information Technologies (Baku, 2003), 4th MEPP-2003 (Baku, 2003), Modern Problems of Informatization, Cybernetics of Information Technologies (Baku, 2004), 5th International Scientific and Technical Conference on Microelectronic Transducers and Devices based on them (Baku, 2005), Third International Conference on Technical and Physical Problems in Power Engineering (2006, Ankara), 7th International Scientific and Technical Conference "SIEE-2006" (Odessa, 2006), The International Conference on Problem of Cybernetics and İnformatics (Baku, 2006, 2008, 2010, 2012), The 2nd International Conference on Control and Optimization with Industrial Applications (Baku, 2009), International Scientific and Technical Conference on Modern Problems of Oil and Gas Complex of Kazakhstan" (Aktau, 2011), XVI International Conference on Information Technologies and Mathematical Modeling (Kazan, 2017), I International Scientific and Technical Conference on Problems of obtaining, processing and transmission of measurement information (Ufa, 2017), 6th International Conference on Control and Optimization with Industrial Applications (Baku, 2018), International Scientific and Technical Conference on Measurement and Quality: Problems and Perspectives (Baku, 2018), 1st International Scientifis-Practical Conference on Modern Information, Measurement and Control Systems: Problems and Perspectives (Baku, 2019), 7th International Conference on Control and Optimization with Industrial Applications (Baku, 2020).

Publications: More than 80 scientific papers were published on the subject of the dissertation: 12 articles meeting the requirements of the Supreme Attestation Commission were published in authoritative foreign journals, 28 articles in journals of the Republic of Azerbaijan, 4 patents (1 Eurasian patent), 45 conference materials and 3 scientific monographs (decisions of Scientific Council of ANAS) accordingly.

Structure and scope of the dissertation: The dissertation summed up in 300 pages of text consisting of Introduction, six Chapters, main Conclusion, list of References and Appendixes, 32 Figures and 5 Tables.

A BRIEF OVERVIEW OF THE RESEARCH

The **Introduction** substantiates the relevance of the subject, presents the leading scientific institutions working in this area, defines the goals and research issues, shows the main scientific innovations, theoretical and practical significance of the work, the application of the proposed methods, models and devices, approbation, structure and scope of work.

In the First Chapter, the research involves facilities of the oil and gas industry, analyzes the scientific and theoretical aspects of this field, the existing methods and means of operation, technologies, and the levels of automation [17, 35]. The research involves modern technological schemes in oil production, collection of the extracted oil mixture, purification from layer water, natural gas and mechanical mixtures, primary oil treatment, physical and chemical properties of commercial oil [1-40].

The flow parameters of the oil were studied, the methods of measurement and means used to determine the amount of flow were analyzed, their technological level and level of automation, and shortcomings were evaluated. Since flow is a dynamic process, the measurement means and methods used in such an environment cannot provide high-accuracy. It was revealed that the structure of oil metering units (OMU) is complicated, the level of automation is very low, calibration of the primary measuring instruments is carried out manually in operating conditions, etc. For all these reasons it is not possible to control the quantity of production with high accuracy, production efficiency and economic indicators are greatly reduced. Thus, it was decided to set OMU at the level of modern SMART transmitters and intelligent information - measuring systems (IMS) [31, 35].

To effectively address these issues, the research involved the following questions:

- collection of production from the fields, primary preparation, processing methods and level of automation of technological equipment;
- improving the efficiency of primary oil refining, physical and chemical properties of crude oil, oil separation process, operating facilities and their activities, detection of shortcomings;
- integrated automation of oil production facilities, application of modern technologies, ensuring high precision measurement at metering units, integration of methods and means based on new principles for optimal management.

This section also deals with issues of oil production, oil collection, control over quantity and composition, bringing oil to marketable level, transportation through pipelines, and delivery to warehouses, high measurement and operational metering during storage processes. As a result of the research, it was concluded that all these processes and stages are fully automated, the original measurement methods and tools, intelligent information-measuring systems providing high measurement accuracy are developed in a new structure and adapted to real operating conditions.

In the concept presented at the end, the classification model defines a combination of oil production, oil pipelines, oil storage facilities, terminals, etc. in a single corporate network, and bringing them to the level of software and hardware complex (SHC).

In the Second Chapter, new methods and means were developed to determine quantitative and qualitative indicators of produced oil, and the amount of substances in the mixture separately. To improve the efficiency of separation of oil from mixtures, the existing technologies have been modernized, in the inlet manifold of the separator, a tested IMS was developed that controls the doses of chemical reagents to be mixed with the LM, the quantity of composition of the filled LM, and the separation process with high accuracy.

In order to fully separate commercial oil (CO) from the liquid mixture (LM) produced from oil wells, the composition of the LM must be determined in advance [25, 36]. Metering of production LM is required to conduct for each well separately. In this case, the oil flow (flow rate) of the wells is determined and recorded. The permissible error of the metering device is ± 2.5% for the weight of crude oil and,[1] as it seems, the accuracy limit is low.

Group Metering Equipment (GME) is used in oil production, and in this case, several directions are selected. The total amount and composition of the incoming LM are determined. These data stipulate the regulation of the process at the next stage of separation of LM.

For the measurement process to be effective, It splits into two different flow lines, large and small, turning to a swirl in the LM flow entering from the directions. After measuring in the small flow line, the low output oil is transferred to the oil preparation unit (OPU) and mixed into a large flow manifold by adjusting the LM parameters at the outlet.

Determination of quantitative and qualitative indicators of liquid fuel:

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[1] Khanov N.I., Fathutdinov A. Sh. et al. Measurements of quantity and quality of oil during collection, transportation, processing and commercial metering. -SPb.: Publishing house of SPbUEF, 2000, p 270. (page 99).

The integral of the product of the time taken to measure and measured value of the instantaneous flow rate through the operating range of the flowmeter installed in the flow pipe determines the amount of LM:

$$V = \int_0^{T_1} q_i dt, \quad (1)$$

here, q_i - instantaneous product flow rate in i-th measuring period, $m^3/hour$, T_i - is time elapsed since the beginning of the reporting period, *hour*.

The meter readings are set as follows:

$$Q_i = 3600 \cdot \frac{N_i}{k_i \cdot t_{s_i}}, \quad (2)$$

here, N_i - number of impulses of flow meter in the duration of measuring period t_{s_i}; k_i- is conversion coefficient in the duration of converting period t_{s_i} ($impulse/m^3$).

The amount of liquid flowing through the flowmeter is determined by coefficients reflecting the ratio of temperatures under normal conditions:

$$V = V_t \cdot k_t \cdot k_p, \quad (3)$$

here, V_t - volume value at temperature t, k_t,k_p- coefficients of dependence on temperature and pressure, respectively:

$$k_t = 1 - \beta(t_m - 20), \quad (4)$$

here, β - coefficient of thermal expansion of the product, $^0C^{-1}$; t_m - temperature of the product passing through the flow transducer.

$$k_p = 1 + f \cdot p_m, \quad (5)$$

here, f - product compression ratio, MPa^{-1}, p_m -excess pressure of the product in the flow transducer, *MPa*.

In some cases, especially at the oil metering unit, the commercial gas contains free gas, and a correction factor is included to account for the volume of this gas in the product volume.

$$V_0 = V_t \cdot k_t \cdot k_p \cdot k_{sq}, \quad (6)$$

here, k_{sq} -coefficient, taken into account as the amount of free gas, and is determined as follows

$$k_{sq} = 1 - \frac{V_{sq}}{100}, \quad (7)$$

here V_{sq} -volume of free gas in the product at operating conditions (pressure and temperature), %.

Normally, the volume and density of the product are measured at the measuring units under different conditions, so the density meter is installed in the Quality Control Block (QCB). Consequently, the results of volume and density measurements should be brought to the same state.

Thus, the mass of the product in the QCB will be determined by the following formula:

$$m = V_t \cdot \rho_{KNB} \cdot k_t \cdot k_p \cdot k_{sq}, \quad (8)$$

here, V_t -volume measured according to the current temperature and pressure of the product in the flow transducer, m^3; ρ_{KNB} -product density at a given temperature and pressure in the Quality Control Block, kq/m^3; k_t, k_p -correction factors for temperature and pressure are determined as follows:

$$k_t = 1 - \beta(t_ç - t_{KNB}), \quad (9)$$

and

$$k_p = 1 + F(p_ç - p_{KNB}), \quad (10)$$

here $t_ç$, $p_ç$ and t_{KNB}, p_{KNB} -the corresponding values of temperature and pressure in the flow transducer and in the QCB, respectively.

If considering the mass of residual substances in the oil, the net mass of the product is as follows:

$$m_x = m - m_{art.}, \quad (11)$$

here, m_x -net product weight under normal conditions; m -specified weight of product; $m_{art.}$ -excess mass in the product.

According to the technical specification, the excess mass in the product includes water, salt, sulfur, mechanical mixtures and other substances. Along with these parameters, the average value of product quality indicators for any reporting period is determined:

$$p_{ort.} = \frac{\sum_{i=1}^{n} V_i \cdot P_i}{\sum_{i=1}^{n} V_i}, \quad (12)$$

here V_i -volumes measured in the i-th time interval, P_i -parameter values in the $i-$ intervals, n -number of measuring intervals.

The new structure of the OMU is as follows:

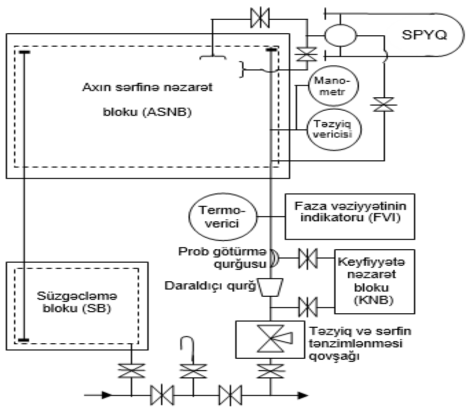

Figure 1. Oil Metering Unit (OMU)

In this scheme, in addition to volume, density, pressure, temperature, quality indicators are also determined when determining the amount of product in real time, and the viscosity of the fluid passing through the meter is also taken into account. Therefore, the new OMU takes into account and compensates for factors that affect measurement accuracy under operating conditions.
For reporting purposes, the OMU takes the average of the daily temperature and pressure measurements:

$$t = \sum_{i=1}^{n} t_i /n \text{ and} p = \sum_{i=1}^{n} p_i /n, \quad (13)$$

here, t_i, p_i -measured values of temperature and pressure in the corresponding i-th interval; n-number of measurements.
Based on the measurement results, the mass of the produced fluid is determined according to the following algorithm and the value of the liquid volume measured in the OMU is corrected taking into account the free gas contained in it:

$$V_m = V \cdot k_{sq}, \quad (14)$$

here, V -fluid volume measured at the metering unit under operating conditions, m^3; k_{sq} -correction factor, which takes into account the effect of free gas on the liquid volume.

$$k_{sq} = 1 - \frac{V_{sq}}{100}, \quad (15)$$

here, V_{sq} -volume of free gas in LM, %
If the oil is counted for a single volume and free gas dissolved in it, the net weight of the fluid is usually determined by the following formula.

$$V_x = V \cdot (1 - \frac{Q}{100}) \cdot k_t \cdot k_p \cdot k_{hq} \cdot k_{sq}^N, \quad (16)$$

here, Q -volume of water contained in the fluid, %; k_t, k_p -coefficients taking into account the effect of temperature and pressure on the oil volume; k_{hq}, k_{sq}^N -coefficients taking into account the effects of soluble and free gases in the oil volume.

$$k_t = 1 - \beta_N \cdot (t_{x\text{ə}tt} - 20), \quad (17)$$

here, β_N -volume expansion coefficient of the oil,°C^{-1}; t_{line}-temperature of the fluid on the measuring line.

$$k_p = 1 + f \cdot p_{line} \quad (18)$$

here, f -the oil compression ratio, Pa^{-1};p_{line} -pressure in the measuring line,*Pa.*

$$k_{kq} = 1 - V_{hq}, \quad (19)$$

here, V_{hq} -1m^3 the volume of gas in the oil, m^3.

The volume of gas remaining in the $1m^3$ oil is determined by the following formula [19]:

$$V_{hq} = \frac{1{,}205 \cdot 10^{-3} \cdot V_{hq_m} \cdot \rho_{n_q}}{0{,}274 + 0{,}2 \cdot \rho_{n_q}} \cdot \frac{100}{100 - Q}, \quad (20)$$

or

$$V_{hq} = \frac{1{,}205 \cdot 10^{-3} \cdot V_{hq_m} \cdot \rho_{n_q}}{0{,}274 + 0{,}2 \cdot \rho_{n_q}}, \quad (21)$$

here, $V_{hq.m},\ V_{hq.n}$ -volume of gas dissolved in a single volume of fluid and normalized volume of anhydrous oil at the final stage of separation; ρ_{n_q} -is the relative error of the gas, which is the ratio of the gas density to the density of air under normal conditions.

Thus, the coefficient, which takes into account the influence of free gas in oil, is determined by the following formula:

$$k_{sq}^{N} = 1 - V_{sq} \cdot (1 - Q/100)\ /\ 100, \quad (22)$$

here, Q-amount of water in the fluid, volume in percentage.

The liquid volume and net oil weight adjustment requirement is determined by the conditions under which the fluid dissolves and the free gas separates or the fluid is pumped. If the oil is pumped to the separator and OMU from an open reservoir close to atmospheric pressure, and where OMU is at the pump outlet, then the volume correction is not performed, i.e., coefficients k_{hq} and k_{sq}^{N} in formulas (14) and (15) are excluded.

When pumping the fluid from the separator, if the OMU is located at the outlet of the pump and the pressure in the OMU is always higher than the separation pressure, correction for free gas is not carried out, that is, $k_{sq}^{N} = 1$ is accepted. If the presence of free gas in the fluid is determined and its quantity is measured, a correction is made for free gas. In this case the net weight of the oil is determined as follows.

$$M_{XÇ} = V_N \cdot \rho_N - (M_D + M_{MQ}), \quad (23)$$

here, ρ_N -density of anhydrous oil at 20^{0}°C, *t/m*^{3}*;* M_D -weight of salt in anhydrous oil, *t*;M_{MQ} - is the mass of the mechanical mixture in anhydrous oil.

$$M_D = V_N \cdot C \cdot 10^{-6}, \quad (24)$$

here, C -is the relative mass of salt in anhydrous oil,mq/dm^3;

$$M_{MQ} = V_N \cdot \rho_N \cdot MQ/100, \quad (25)$$

here, MQ -is the relative weight of the mechanical mixture in the dehydrated oil, in % by mass.

If the relative weight (C) of the salt is given as a percentage from the weight of the oil, it can be considered as a correction factor.

$$k_D = 1 - C/100. \quad (26)$$

The correction factor is considered in the same way in the weight of the mechanical mixture.

$$k_{MQ} = 1 - MQ/100. \quad (27)$$

If it is not required to determine the oil volume, its weight according to the expression (16) will be determined by the following formula.

$$M_N = k_t \cdot k_p \cdot k_{hq} \cdot k_{sq}^N \cdot k_D \cdot k_{MQ} \cdot V \cdot \rho_N \cdot (1 - Q/100). \quad (28)$$

The above expressions can be used as a basic model for determining the amount of dissolved or free substance particles in an oil emulsion. Thus, the obtained expressions express the multicomponent composition of the oil emulsion, and the coefficients express the concentration.

Development of methods and devices for oil production control. Measuring the flow rate of oil wells is a complex issue, and the devices currently in use do not provide high measurement precision and flexibility [23]. In this process, it is difficult to control the oil parameters because of the high stability of the oil emulsion (OE) content, time excess between the time needed for the required sedimentation level and measurements, the efficiency of the process and the technical and economic indicators of oil production are significantly reduced. To effectively solve the problem and effectively manage the technological process, it is necessary to separately determine the amount of oil and layer water in the OE. For this purpose, the well flow meter was designed according to a new principle (Fig. 2), a tested measuring system (TMS) based on a high-precision measurement of the hydrostatic pressure difference between LM and the reference fluid was developed [19].

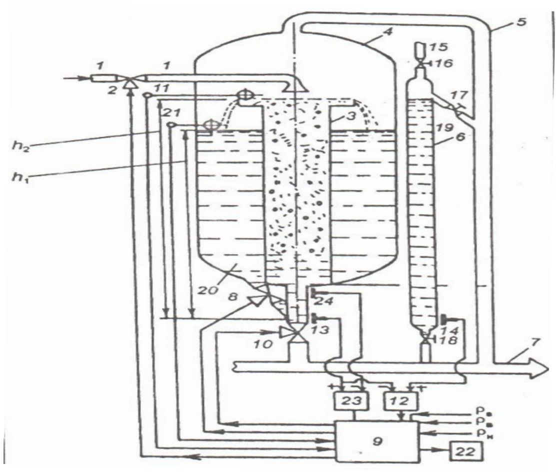

Figure 2. Measuring diagram of the Separator

The following analytical expressions were obtained to determine the amount of commercial oil and water in the LM [19, 21].

The amount of LM accumulated in container 20 will be equal to the sum of the weights of oil and water in it:

$$Q = Q_n + Q_s, \tag{29}$$

here, Q_n and Q_s −is the amount of oil and water in the LM.

It is known that the flow measurement in the Separator (S) is determined by the following expressions:

$$Q_n = \frac{24V}{\tau}(1-\alpha)\rho_n\, g, \tag{30}$$

$$Q_s = \frac{24V}{\tau}\alpha\rho_s\, g; \tag{31}$$

here, V −the total volume of LM in S is determined as follows: $V = V_1 + V_2$; $V_1 = \pi r_1^2 \cdot h_1$; $V_2 = \pi(r_2 - r_1)^2 \cdot h_2$,$\tau$ −time period of LM filling to the S, α −coefficient indicating the amount of water in LM, ρ_n and ρ_s −oil and water densities, respectively, g − is acceleration of free fall.

In expressions (29) - (31) the density of water and oil in LM will be determined by the binary system as follows:

$$\rho_{MQ} = \alpha\rho_s + (1-\alpha)\rho_n\,, \tag{32}$$

If adding to the S a vertical tube filled with a special antifreeze liquid according to the law of communicating vessels (Fig. 2), the following expression can be written:

$$\rho_{MQ} = \alpha\rho_s + (1-\alpha)\rho_n + \rho_a - \rho_a\,, \tag{33}$$

here, ρ_a −is antifreeze density.
The following expression can be written for the LM volume in both separator capacities:

$$\rho_{MQ} = \rho_n \frac{V_1}{V} + \rho_s \frac{V_2}{V}, \quad (34)$$

According to the law of communicating vessels the following expression can be written:

$$\rho_n h_1 = \rho_s h_2, \quad (35)$$

From (35) the oil density is determined as follows:

$$\rho_n = \frac{h_2}{h_1} \rho_s . \quad (36)$$

When the LM level in the S is equal to the antifreeze level in the vertical pipe (h_2), the differential pressure transmitter (DPT) measures the difference in steady pressure (Δp) and the following expression is obtained:

$$\Delta p = (\rho_a - \rho_{MQ}) g h_2, \quad (37)$$

From (37) the following expression for ρ_{MQ} is obtained:

$$\rho_{MQ} = \rho_a - \frac{\Delta p}{g h_2}, \quad (38)$$

When the appropriate conversions of the above expressions are performed, the following formula is obtained to determine the amount of water contained in the LM set in the S:

$$\alpha = \frac{\rho_a - \rho_n - \frac{\Delta p}{g h_2}}{\rho_s - \rho_n}. \quad (39)$$

The principle of operation and algorithm of the TMS are outlined in the dissertation.
As can be seen from formula (39), the main control parameters are the measured pressure differences and liquid densities. Thus, from the above formulas obtained the following general expression for the flow rate of wells:

$$Q_n = \frac{24V}{\tau} \left(1 - \frac{\rho_a - \rho_n - \frac{\Delta p}{g h_2}}{\rho_s - \rho_n} \right) \rho_n \, g, \quad (40)$$

Automated Emulsifier System:
To speed up the oil separation process and make it more efficient, special chemical reagents is needed to be mixed into the fluid flow at a defined distance in inlet manifold of the S. The amount (dose) of mixed reagents is determined according to the LM flow rate in the inlet manifold. For this purpose, an Automated Emulsifier System (AES) was developed to provide high-precision measurement of flow rate and reagent dosage [28].
The flow resistance coefficient is used as an integral indicator characterizing the flow process:

$$\lambda = \frac{2d\Delta p}{l \cdot \rho_{MQ} \cdot \vartheta^2}, \tag{41}$$

here, d −inlet pipe diameter; Δp −pressure drop between measuring points in the inlet pipe; l −the distance between the points selected to measure the pressure difference in the inlet pipe; ρ_{MQ} − LM density in the inlet pipe; ϑ −the velocity of the LM flowing in the inlet pipe.

The LM flow rate in the inlet pipe is determined as follows:

$$\vartheta = \frac{Q_{MQ}}{S}, \tag{42}$$

here, Q_{MQ} −is LM flow rate in the inlet pipe; S −cross-sectional area of the pipe

The amount of LM in the flow in the result of joint operation of transmitters is determined by the following formula [10, 25]:

$$Q_a = p_a\left(1 - \frac{\mu_0}{\mu_i}\right)\left(\frac{\lambda_D \cdot \rho_{NQ}}{2}\vartheta^2 + \frac{48 \cdot \frac{b}{a} \cdot \mu \cdot l}{S^2} + \Delta p_0\right), \tag{43}$$

here, p_a −coefficient determining the range of the meter; μ_0 −the dynamic viscosity of the flowmeter under the flow condition $Q_a = 0$;μ_i −dynamic viscosity during flow control; ρ_{MQ} −LM density; μ −dynamic viscosity in the control flow; λ_D −coefficient of resistance of the circulating fluid flowing from the rotating working body of the flowmeter; S_a −the operating cross-sectional area determined in relation to the cross-sectional area of the pipe of the a and b chambers of the device; l −the distance between the points of the hydraulic line assumed to measure the pressure difference; Δp_0 −pressure loss at the sensitivity limit of the device.

Putting together formulas (41) - (42), the following analytical expression for determining the amount of LM passing through the cross section of the inlet pipe per day is obtained:

$$Q_a = p_a\left(1 - \frac{\mu_0}{\mu_i}\right)\left\{\frac{[\alpha \cdot \rho_S + (1-\alpha)\rho_N]\vartheta^2 \cdot \lambda_D}{2} + \frac{48 \cdot \frac{b}{a} \cdot \mu \cdot l}{S^2} + \Delta p_0\right\}. \tag{44}$$

The structural diagram of the Automated Emulsifier System is as follows.

The dissertation presents an algorithm of operation, block diagram and software of the AES.

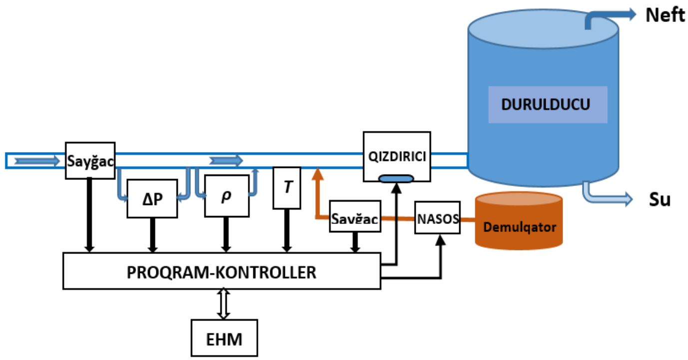

Figure 3. Automated Emulsifier System

The Third Chapter deals with the principle and algorithms of development of testing measuring devices for high-precision measurement of oil parameters in the flow [4, 9, 14, 16]. In this case, Fisher for high flows and Brooks and other brands' flowmeter devices for weak flows were studied to determine the amount of oil.

As the flow is a dynamic process, existing flow meters cannot measure the amount of oil with fiscal accuracy. For this purpose, the measurement of flow rate, density, pressure and temperature under real operating conditions was studied. TMS performed with hybrid testing based on smart transmitters and measurement algorithms were developed to ensure high precision measurement [25, 30].

Since the examined research facilities have complex natural conditions, the MP of the primary measuring instruments used in these facilities deteriorates sharply. At the same time, the measurement parameters are constantly subject to drastic changes. Therefore, these conditions put severe circumstances on the developed IMS.

The amount of fluid in the flow is determined directly or indirectly. In this case, the determination of the amount of oil on the basis of the requirements of the relevant state standard is becoming more serious and legalized at the level of fiscal metering. By volume-weight method, the amount (mass) of the product is determined by the following formula[2]:

$$m = V \cdot \rho \cdot (1 + \beta\delta_t)(1 + \gamma\delta_p), \qquad (45)$$

here, m -product weight, kg;V -product volume, m^3; ρ -product density,

[2] GOST R 8.903-2015. State system for ensuring the unity of measurements. Mass of oil and petroleum products. Measurement techniques (methods). Moscow, Standardinform, 2015, p. 36

$\frac{kq^3}{m}$; β -the volume-expansion coefficient of the product, $\frac{1}{}^0 S$; $\delta_t = (t_\rho - t_V)$ -temperature change when measuring density and volume, $1/^0S; \gamma$ -the degree of compression of the product from the pressure; $\delta_p = (p_V - p_\rho)$ - is pressure difference in measuring volume and density.
The error of the measurement method is determined by the following formula:

$$\Delta m = \pm 1{,}1\sqrt{\Delta V^2 + \Delta\rho^2 + \left(\beta \frac{\Delta\delta_i}{1+\beta\Delta\delta_i}\cdot 100\right)^2 + \Delta M^2}, \quad (46)$$

here, ΔM - is relative calculation error.
In the tested measurement process, the errors of temperature and pressure difference ($\Delta\delta_t, \Delta\delta_p$) are also reduced repeatedly, as the accuracy of the measurement is loaded several times. At the same time, due to the very small expansion and compression coefficients of the oil volume, the close proximity of the density meter and the flow meter, δ_t and δ_p errors are very small. Thus, from formula (46) the following general expression is obtained:

$$\Delta m = \pm 1{,}1\sqrt{\Delta V^2 + \Delta\rho^2}\,, \quad (47)$$

As can be seen from the expressions, the accuracy of determining the amount of liquid fuel in the flow depends on the accuracy of measurement in the conditions of the meter, density, pressure and temperature transmitter and throughout the measurement range.
Flow rate measurement diagram. The metering system is installed on a low-flow pipeline parallel to the oil pipeline (OP) and is called an oil metering unit (OMU), and it combines flow rate, density, pressure, temperature, viscosity, etc. transmitters, as well as enforcement mechanisms
Tested measurement method of oil consumption in the flow:
The amount of oil in the flow is measured in meters with different principles of impact [9]. As already mentioned, the complexity of the measuring medium, flow dynamics, mixed fluid composition, unstable temperature, and other reasons increase the measurement error of the meters. The dissertation developed hybrid test algorithms to reduce and correct errors and improve measurement accuracy.
Adequate models were generated as a result of tests conducted using test algorithms. In this case, the transmitters CF were studied in the form of quadratic and cubic equations, and the following expression was obtained for the dependence of the measurement error on the fluid flow [9]:

$$\delta = a_o + a_1 Q + a_2 Q^2 + a_3 Q^3 \tag{48}$$

here, a_0, a_1, a_2, a_3 - are the coefficients of CF.

In measurements using test algorithms, CF coefficients are replaced by reference tests, in which case the error of the meter is reduced to $\Delta\rho$, the meansquare deviation does not exceed 0.15%.

In this case, the number of measurement cycles is four, and the following system equation is obtained:

$$\begin{cases} \delta_1 = a_o + a_1 Q_1 + a_2 Q_1^2 + a_3 Q_1^3 \\ \delta_2 = a_o + a_1 Q_2 + a_2 Q_2^2 + a_3 Q_2^3 \\ \delta_3 = a_o + a_1 Q_3 + a_2 Q_3^2 + a_3 Q_3^3 \\ \delta_4 = a_o + a_1 Q_4 + a_2 Q_4^2 + a_3 Q_4^3 \end{cases} \tag{49}$$

here, $Q_1,\dots,Q_4$ -value of relevant consumption; $\delta_1,\dots,\delta_4$ -value of relevant errors.

To determine the empirical form of the mathematical model in (49), the following model is proposed under the conditions a <0, b <0 and as a result of the analysis of experimental data:

$$\delta = \frac{a}{Q} + bQ + c \tag{50}$$

Model (50) is considered to be more universal for different types of meters, and to determine the coefficients of the mathematical model the following system of equations is obtained and solved:

$$\begin{aligned} \delta_1 &= \frac{a}{Q_1} + bQ_1 + c \\ \delta_2 &= \frac{a}{Q_2} + bQ_2 + c \\ \delta_3 &= \frac{a}{Q_3} + bQ_3 + c \end{aligned} \tag{51}$$

here, $\delta_1,\ \delta_2, \delta_3$ -the relative error of the meters; $Q_1,\ Q_2, Q_3$ -are value of flow rate measured accordingly.

The values of the model parameters will be calculated using the following formulas:

$$a = \left[\frac{\delta_1 - \delta_2}{Q_1 - Q_2} - \frac{\delta_2 - \delta_3}{Q_2 - Q_3}\right] \frac{Q_1 Q_2 Q_3}{Q_1 - Q_3}$$

$$b = \left[\frac{\delta_1 - \delta_2}{Q_2 - Q_1} Q_1 - \frac{\delta_2 - \delta_3}{Q_3 - Q_2} Q_3\right] \frac{1}{Q_3 - Q_1} \tag{52}$$

$$c = \frac{\frac{\delta_1 Q_1 - \delta_2 - Q_2}{Q_1^2 - Q_2^2} - \frac{\delta_2 Q_2 - \delta_3 Q_3}{Q_2^2 - Q_3^2}}{\frac{1}{Q_1 + Q_2} - \frac{1}{Q_3 + Q_2}}$$

Thus, more economic mathematical models are chosen to determine the tare of the meter, the number of BTE is reduced to 3 and a nonlinear approximation is performed.

Tested method for measuring oil density in the flow:

Due to the lack of reliable automatic density metering (DM) devices with high precision in real flow conditions, the density of the product in the oil facilities is still determined under laboratory conditions.

The first automated DM with vibration-frequency principle was designed at "Neftgazavtomat" SPA (Scientific Production Association) in Azerbaijan, is mass-produced and used at oil facilities of the former USSR. The informative parameters of this device, named АИП-2М, are based on measuring the period of the output signal. In the dissertation , the АИП-2М was upgraded, and a Tested Density Meter (TDM) with hybrid tests was developed to improve its MP. In this case, the system also modulates the frequency of the output signals, it also identifies conversion characteristics (CC) and evaluates error components (EC).

The operation of the TSM is based on the dependence of the frequency of specific vibrations of mechanical resonators on the density of the fluid flowing from the sensitive element of the transmitter. With this type of sensor, a metal pipe, which acts as a sensitive element in the density measurement, is connected to the fluid flow, while another pipe is filled with a reference fluid. Both pipes are equipped with a resonator [9].

The nonlinearity of CC of the TMS is described by the following formula:

$$f = f_o(1 + b_1 x + b_2 x^2 + b_3 x^3 + ...) \tag{53}$$

here: f -transmitter output frequency; f_o ,b_1,b_2,b_3 - parameters and coefficients of CF of transmitter; x -measured value, here LM is density (ρ).

If the parameters included in the CF when measuring oil density in the flow with TMS, then the following equation analogous to function (55) can be written:

$$f = a_0 + a_1\rho + a_2\rho^2 + a_3\rho^3 \tag{54}$$

here: $a_0 = f_0$; $a_1 = f_0 b_1$; $a_2 = f_0 b_2$; $a_3 = f_0 b_3$.

CC of TMS is taken as a square trinomial, in which case the number $n = 3$ of measurement cycles and the optimal set of tests will be as follows.

In formula (54) measurement quantity ρ_x are determined in the form of additive test ($\rho_x + \rho_{et}$), multiplicative ($2\rho_x$) and combined tests ($2\rho_x + \rho_{et}$) according to optimal density values. Then the Basic Test Equations (BTE) of the TMS will be in the form of the following system of equations:

$$\begin{cases} f_0 = b_0 + b_1\rho_x + b_2\rho_x^2 \\ f_1 = b_0 + b_1(\rho_x + \rho_{et}) + b_2(\rho_x + \rho_{et})^2 \\ f_2 = b_0 + b_1 2\rho_x + b_2(2\rho_x)^2 \\ f_3 = b_0 + b_1(2\rho_x + \rho_{et}) + b_2(2\rho_x + \rho_{et})^2 \end{cases} \quad (55)$$

Solving this system of equations, the following CF is obtained:

$$\rho_x = \frac{(f_1 - f_2) + (f_0 - f_3)}{(f_0 - f_3) - (f_1 - f_2)} \cdot \rho_{et}, \quad (56)$$

here, f_0, f_1, f_2 and f_3 -are the measurement values of the TMS output quantity in the relative measurement cycles.

The approximation error of the CF of TMS was investigated, and the following BTEs were obtained taking into account the measurement errors (55) in the system of equations significant for each measurement cycle:

$$\begin{cases} f_0 + \Delta_0 = b_{1s} + b_{2s}\rho_x + b_{3s}\rho_x^2 \\ f_1 + \Delta_1 = b_{1s} + b_{2s}(\rho_x + \rho_{et.}) + b_{3s}(\rho_x + \rho_{et.})^2 \\ f_2 + \Delta_2 = b_{1s} + b_{2s} 2\rho_x + b_{3s}(2\rho_x)^2 \\ f_3 + \Delta_3 = b_{1s} + b_{2s}(2\rho_x + \rho_{et.}) + b_{3s}(2\rho_x + \rho_{et.})^2 \end{cases} \quad (57)$$

here, $\Delta_0,...,\Delta_3$ – are the values of the errors of the measurement cycle brought to the output of the TMS.

If a system of equations (57) is solved, the following expression for TMS is obtained:

$$\frac{\rho_x + \rho_{et.}}{\rho_x - \rho_{et.}} = \frac{(f_0 - f_3) + (\Delta_0 - \Delta_3)}{(f_1 - f_2) + (\Delta_1 + \Delta_2)}, \quad (58)$$

Since (58) considers measurement cycle errors, the difference between the static error and these expressions will produce the TMS error:

$$\Delta_T = [\rho_x + \rho_{et.}](\Delta_1 - \Delta_2) + [\rho_x - \rho_{et.}](\Delta_3 - \Delta_0). \quad (59)$$

Since expression (59) is a function determining the final error of TMS, the following mathematical model of the whole EC is obtained by substituting the values of additive and multiplicative tests and $\Delta_0,...,\Delta_3$ errors:

$$\Delta_T = \rho_{et.}[(\Delta_1 - \Delta_2) - (\Delta_3 - \Delta_0)] + \rho_x[(\Delta_1 - \Delta_2) + (\Delta_3 - \Delta_0)]. \quad (60)$$

For the absolute error brought to the TMS input, the following expression is obtained:

$$\Delta_{gir.} = f_T^{-1}\left[f_T(x) + \Delta_T\right] - x = \frac{\Delta_{TT}}{f_T^1(x)}, \tag{61}$$

here, $f_T(x) = (y_0 - y_0)(\rho_x - \rho_{et.}) + (y_2 - y_1)(\rho_x + \rho_{et.})$.

By differentiating the expression (61) by x, the following value is obtained for $f_T'(x)$:

$$f_T'(x) = [(y_0 - y_3) - (y_1 - y_2)]. \tag{62}$$

If replace (59) and (62) in (61), the following expression is obtained:

$$\Delta_{gir.} = \frac{\rho_{et.}[(\Delta_1 - \Delta_2) - (\Delta_3 - \Delta_0)] + \rho_x[(\Delta_1 - \Delta_2) + (\Delta_3 - \Delta_0)]}{2\rho_{et.}(b_{2SH} + b_{3SH}(\rho_x + \rho_{et.}))}. \tag{63}$$

If the real CF of the initial MS is partially nonlinearly approximated in the form of third-degree polynomials, then this is implemented by the corresponding algorithm in the CF identification, and the error $\Delta^*_{Tgir.}$ brought to the output of the system is as follows:

$$\Delta^*_{Tgir.} = \frac{\Delta^*_T}{f_T'(x)} = \frac{(\Delta_0 + \Delta_2 + \Delta_3 + \Delta_5 - 2\Delta_1 - \Delta_4)\rho_x}{2\rho_{et}^2\{2b_{3s} + 3b_{4s}[3\rho_x + 2\rho_{et.}]\}} + \frac{(\Delta_2 - \Delta_0 + \Delta_3 - \Delta_5)}{2\rho_{et.}\{2b_{3s} + 3b_{4s}[3\rho_x + 2\rho_{et.}]\}}, \tag{64}$$

here,

$$\Delta^*_T = (\Delta_0 + \Delta_5)(2\rho_x - \rho_{et.}) + (\Delta_2 + \Delta_3)(2\rho_x + \rho_{et.}) - 4\rho_x(\Delta_1 + \Delta_4). \tag{65}$$

As seen, errors Δ_i of measurement cycle are the result of a large number of random factors

Δ_T, Δ^*_T, $\Delta^*_{Tgir.}$ and errors $\Delta_{gir.}$ are random values, and the distribution laws are defined as the sum of the distributions of random values Δ_i. To fully describe them, it is necessary to determine M_Δ -mathematical expectation and D_Δ -dispersion.

Thus, the study of MP of the TMS shows that the following components have the greatest influence on the measurement error of such systems:

–the components of the error caused by the use of constant components of additive and multiplicative tests;

– Uncorrelated TMS static error components;

– The component of the dynamic error of TMS ;

– Error component caused by the inadequacy of the accepted mathematical model of the real CF of TMS.

The developed test algorithms were tested on the laboratory stand on the AIP-2M sample and the adequacy of the results was confirmed.

The tested method of measuring the pressure of oil in the flow.

It is known that the accuracy of measuring the amount of oil in the flow also depends on the accuracy of measuring the pressure drop it creates in the pipeline. For this purpose, differential pressure transmitters (DPT) Sapphire-22DD were used, more than 50 samples were tested on the laboratory stand [1, 10]. It appeared that the dependence of DPT on the temperature of the CC does not correspond to any law and there was a large temperature error. TMS was developed to correct the error.

CC of the DPT was taken in the following square trinomial:

$$i = b_0 + b_1 p_x + b_2 p_x^2, \tag{66}$$

here, i-DPT output signal; b_0, b_1 and b_2 - CC coefficients of DPT; p_x – is measurement value, pressure.

Thus, in the process of tested measurement, the following BTE was compiled using one reference additive test ($p_{et.}$), multiplicative ($2p_x$) and combined tests ($2p_x + p_{et.}$):

$$\begin{cases} i_0 = b_0 + b_1 p_x + b_2 p_x^2 \\ i_1 = b_0 + (p_x + p_{et.})[b_1 + b_2(p_x + p_{et.})], \\ i_2 = b_0 + b_1 2p_x + b_2(2p_x)^2, \\ i_3 = b_0 + (2p_x + p_{et.})[b_1 + b_2(2p_x + p_{et.})], \end{cases} \tag{67}$$

here, i_0, i_1, i_2, i_3 - values for the output signals according to the corresponding DPT measurement cycles; b_0, b_1, b_2 -the coefficioents of CC; p_x-measurement quantity, pressure; $p_{et.}$- is the reference pressure connected to the differential input of DPT.

Thus, substituting the values of real measurement results in the system equation (67) and solving the system of equations with respect to p_x, the following result is obtained:

$$p_x = \frac{N_{i_3^*} + N_{i_2^*} - N_{i_1^*} - N_{i_0^*}}{N_{i_3^*} - N_{i_2^*} + N_{i_1^*} - N_{i_0^*}} \cdot p_{et.} \tag{68}$$

This mathematical model is implemented according to the following functional scheme, thus the CC of the transmitter is identified with high precision, and the current measurement operations are performed with high accuracy.

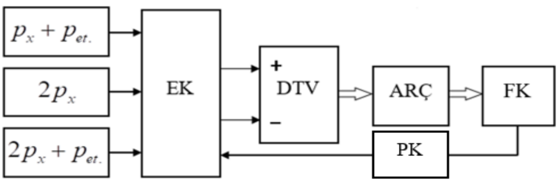

Figure 6. Functional diagram of the TMS.

here, EC-Electronic Commutator; DPT-Differential Pressure Transmitter; ADC- Analog-to-digital Converter; SC - Software Controller; PC-is Personal Computer.

The statistical evaluation reveals that as a result of the tested measurement algorithm (68) based on the accepted mathematical model (66), the value of uncorrelated components of static errors is $s_{ad.gir.} \approx 0{,}02\%$ and this figure is very small compared to the DPT data sheet - the permissible error of measurement is 0.25%.

The dissertation presents a block diagram and software of the TMS measurement algorithm.

Tested temperature measurement system in the flow

Constant control and accurate measurement of the liquid fuel (LF) temperature in the flow is required. Since the temperature varies over a wide range in actual measuring conditions, temperature-dependent errors need to be corrected when determining the product quantity. Due to the fact that the measurement process is carried out under harsh climate conditions, platinum heat gauges (PHG) with a large measuring range and reliability were used [9]. The TMS and algorithm were developed to continuously identify the CC of PHG, specify the mathematical model, and ensure stability.

The CC of PHG reflects the functional dependence between the thermal resistance R_t and the temperature of the measured medium:

$$R_t = R_0\left(1 + at + bt^2\right), \tag{69}$$

here, R_0 -Resistance of PHG brought to 0°S, a and b -are the relevant CC coefficients under normal PHG conditions.

The formula (69) can be written as the following quadratic polynomial:

$$R_t = b_0 + b_1 t + b_2 t^2 , \tag{70}$$

here, $b_0 = R_0;\ b_1 = R_0 a;\ b_2 = R_0 b$ - are the relevant coefficients of the polynomial.

The BTEs generated from simple temperature measurement tests will take the form of the following system equation:

$$\begin{cases} R_{t_0} = b_0 + b_1 t_x + b_2 t_x^2 \\ R_{t_1} = b_0 + (t_x + t_{et.})[b_1 + b_2 (t_x + t_{et.})], \\ R_{t_2} = b_0 + b_1 2t_x + b_2 (2t_x)^2, \\ R_{t_3} = b_0 + (2t_x + t_{et.})[b_1 + b_2 (2t_x + t_{et.})], \end{cases} \tag{71}$$

here, $R_{t_0}, R_{t_1}, R_{t_2}, R_{t_3}$ - values of relevant output parameters by heat gauge measurement cycle, t_x-temperature measurement quantity, $t_{et.}$- is reference value thermal resistance.
For the output signal values obtained from the actual measurements of the tested heat gauge, the measurement value is (t_x) determined from (71) and the following expression for the conversion function is obtained:

$$t_x = \frac{(R_{t_3^*} - R_{t_1^*}) + (R_{t_2^*} - R_{t_0^*})}{(R_{t_3^*} + R_{t_1^*}) - (R_{t_2^*} + R_{t_0^*})} \cdot t_{et.} \qquad (72)$$

The tested measurement operation is based on BTE (71) and CF (72). The block diagram and software of the TMS algorithm are provided in the dissertation.
The Chapter Four deals with the development of tested commercial metering system (CMS) for oil storage tanks (reservoirs). Here, basically, two methods of measurement (volume-weight and piezometric) were studied, and their effectiveness was justified.
New structures based on test algorithms are developed.
The first tested CMS was based on an acoustic radar level meter (Fig. 7).

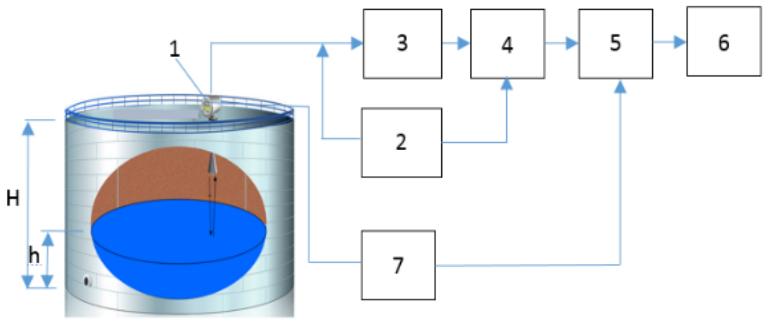

Figure 7. Acoustic level meter system

here, 1-acoustic transducer, 2-generator, 3-amplifier, 4-timer, 5-transducer, 6-program controller, 7-temperature regulator.

An ultrasonic vibration source and receiver, as well as a special piezo element as an acoustic radar device were used in the system. Signals from generators 2 are generated in the form of ultrasonic pulses, which excite the piezoelectric element of the acoustic transducer 1 and are connected to the timer circuit 4. The ultrasonic pulses sent and reflected from the liquid surface reach the piezo element after a certain time t, and as a result the distance from the liquid surface to the piezo element is determined. The parameters are defined according to the difference (Δr) between the incident and returned radar beams:

$$\Delta r = R_1 - R_2 = 0{,}5c\frac{t_1 - t_2}{t_1 \cdot t_2}, \quad (73)$$

here, Δr-the measured depth of the wave generated at the liquid surface, R_1,R_2 -the distances of the incident and returning waves, respectively, t_1,t_2 - period of the incident and returning waves, respectively, c - is radar wave velocity.

In the dissertation, this method is used to evaluate free waving - measurement error on the surface of the oil in the tanks.

This dissertation presents level measurement system by continuous frequency-modulated emission (FME) method and flowchart for measurement algorithm.

Piezometric system for measuring the density of liquid fuel.

It is known that the density of liquid fuel in the tank is piezometrically determined by the following expression:

$$\rho = \frac{\Delta p}{g \cdot \Delta H}, \quad (74)$$

here, Δp -the difference between the hydrostatic pressure generated by the liquid columns between two points of the tank, $\Delta H = h_1 - h_2$ -the distance between the two points of the tank, g - is acceleration of free fall.

The density of the product is determined in laboratory conditions when applying the system of commercial fuel metering in tanks on the basis of the volume-weight method. This operation is considered inefficient because it is performed manually. Therefore, for the purpose of full automation in the case of dissertation, the TMS (Fig. 8) and a measurement algorithm based on the piezometric measurement of density LF in the tank:

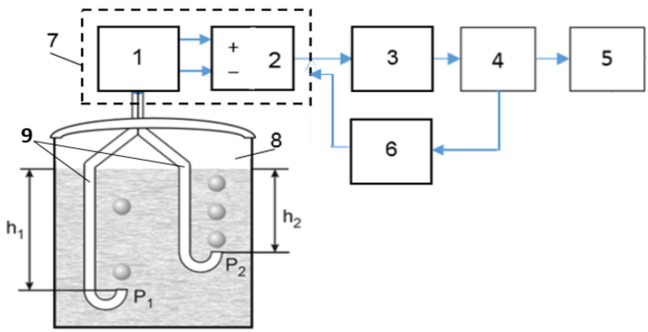

Figure 8. Piezometric measurement system of fluid density

In Figure 8, 7 measurement and control device (MCD) consists of 1 a compressor and pneumatic unit (CPU) and 2 a differential pressure transmitter (DPT) and is located on top of 8 the oil tank (OT). The difference in hydrostatic pressures (Δp) created by 9 the air and impulse tubes (AIT) at heights h_1 and h_2 of the LF is converted by the DPC into a nominal electrical output signal and in 3 the analog-to-digital converter (ADC) it is converted into a digital code and transmitted to 4 the program-controller (PC), and from there to 5 the computer (C). On the basis of the formula (74) of the results, the density ρ is determined by the distance $\Delta H = h_1 - h_2$ between points h_1 and h_2 of the LF and the pressure difference Δp between these points.
Thus, the tested measurement algorithm based on the formula (74) is as follows:

$$\rho = \frac{p_{et.}}{g \cdot \Delta H} \frac{(i_4 - i_1) + (i_3 - i_2)}{(i_4 - i_1) - (i_3 - i_2)}, \quad (75)$$

here, i_1,i_2,i_3 and i_4 - are DPC output signals from test combinations, $p_{et.}$ - is an applicable standard.
The measuring system of liquid density has a mobile design and can be placed on the roof of any OT. In this case, the centralized exchange of information on the warehouse is carried out via Wi-Fi.
A block diagram of the TMS algorithm is presented in the dissertation.
Automated calibration system for oil tanks.
The individual calibration chart (ICC) for each tank is used to determine the amount of LF in the oil tanks [1]. The preparation (methodology) of ICC is regulated by the relevant state standard[3]. Since the calibration procedure is mostly carried out geometrically and manually, the measurement results are inaccurate and require a lot of effort and time. Therefore, a method of automated calibration (grading) of OT and TMS (Fig. 9) was developed in the dissertation work [20].

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[3] GOST 8.346-2000. Horizontal cylindrical steel tanks. Verification methodology. Interstate Council for Standardization, Metrology and Certification. Minsk, 2001, p. 21.

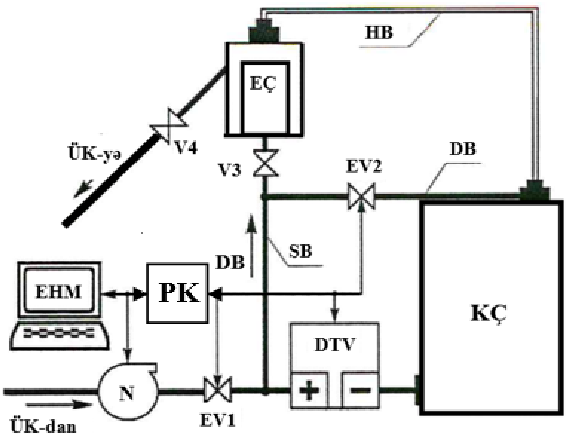


Figure 9. Block diagram of the Automated Calibration System

here, ECM -electronic computing machine, PC program controller, DPT -differential pressure transmitter, RT -reference tank, CT -calibration tank, CM -common manifold, P -pump, EV -electronic valve, V -valve, FT -filling pipe, VP -vertical pipe, AP -air pipe.

The system compiles the ICC based on the results by measuring (the measurement continues until the CT is full) the difference in hydrostatic pressures of liquids settling in both the reference (RT) and calibrated tanks (CT) simultaneously.

The algorithm of the calibration system (CS) is as follows:

1st measurement: LF is filled from CM to RT, EV1 is closed after the RT is fully filled, the total hydrostatic pressure ($p_{RT1} + p_{VP}$) created by the settling of the LF mass in the RT and VP is measured in the "+" DPT chamber and LF is emptied from RT to CT by opening EV2.

The difference $\Delta p_1 = p_{VP} - p_{KT1}$ is measured by transferring the LF mass settled in the CT to the "-" DPT chamber. After the measurement process, the output signal of DPT is transmitted to the PC and entered into the ECM as a digital code, and the weight of the LF is calculated according to the following formula:

$$m_1 = (\Delta p_1 - p_{VP}) S_{or1} / \mathrm{g}, \qquad (76)$$

2nd measurement: Again RT is filled by LF in the previous sequence, pressure difference is measured in the "+" chamber of the DPT, EV2 is opened and LF empties from RT to CT, the weight of LF is calculated by measuring the hydrostatic pressure difference of LF settled in VP and CT.

$$m_2 = (\Delta p_2 - p_{VP}) S_{or2} / \mathrm{g}, \qquad (77)$$

This process is repeated until the CT is full. Thus, the following expression is obtained for the current measurement result:

$$m_i = (\Delta p_i - p_{VP}) S_{ori}/\mathrm{g}, \quad (78)$$

here, i - are the number of LF columns filled in the CT.

Thus, the ICC is obtained for OT of any geometric size and shape, and the following formula is derived from this ICC for determining the cross-sectional area of CT:

$$S_{CT}^{i}(h) = \frac{p_{RT}}{p_{CT}^{i}} S_{RT}(h), \quad (79)$$

here, $S_{CT}^{i}(h)$ −average cross-sectional area of $i$column of CT at value p_{CT}^{i} and height h , p_{RT} and p_{CT}^{i} − are values of the hydrostatic pressure generated by LF in RT and CT, respectively.

The Fifth Chapter – deals with the mathematical modeling of processes of product receiving to oil storage tanks, storage and release. The time dependence of the amount of fluid in each OT during long-term circulation of LF was studied as a random process and the dynamics of motion were modeled [5-8, 10, 17].

The purpose of modeling is to control the process of sedimentation and crystallization during long-term operation of the OT. As the amount of sludge in the OT increases, losses occur, tank capacity decreases and the metering process deteriorates. With time, crystallization occurs in the OT, which leads to serious complications, makes it difficult to clean the OT and even destroys the tank.

To eliminate this problem, it is important to control the state of sedimentation and crystallization created by LF in each OT over time and keep statistical records. As can be seen, the process is quite time-consuming and complex, requiring numerous measurements and statistical evaluations.

In the dissertation, mathematical and statistical modeling based on process automation, precise measurements and management were performed, resulting in mathematical equations for determining the initial sedimentation and crystallization time. Based on accurate statistics, crystallization can be avoided by applying special chemical reagents as a preventive measure, and by liquefying it, it is cleaned and removed from the tank by means of pumps.

Receiving, storing, and releasing fluid from each tank is a random stochastic process, its minimum and maximum levels have been accepted as upper and lower screens. The speed of filling and discharging liquid fuel

from the oil tank over a long period of time, constant level time form the parameters of the mathematical model.
The purpose of the modeling is to determine the sample mean and sample correlation functions of the stochastic process, which, respectively, changes continuously between the screens. An analytical expression of the process and the distribution of its main boundary function were determined, mathematical expectation and correlation function were evaluated. The amount of fluid corresponding to a continuous stochastic process varies between two "b" and "a" $(a > b > 0)$ screens under positive and negative angles α and β (α , $\beta \in (0°, 90°)$), respectively.
Mathematical formulation of the issue: Suppose that $(\Omega, F, P(\cdot))$ has the same distribution in the probability space. However, the sequence of independent four-dimensional positive random variables $\{\xi_\kappa^+(\omega), \eta_\kappa^+(\omega); \xi^-(\omega), \eta_\kappa^-(\omega)\}$, $\kappa = 1, \infty$, α and β, $0° \le \alpha \le 90°$, $0° \le \beta \le 90°$ angles are presented. According to these numbers, the mathematical description of the random process will be as follows:

$$X^{--}(t,\omega) = \begin{cases} [t - \sum_{i=1}^{k-1} \eta_i^-(\omega) & \text{if} \quad \sum_{i=1}^{k-1} [\xi_i^-(\omega) + \eta_i^-(\omega)] < t < \sum_{i=1}^{k-1} [\xi_i^-(\omega) + \eta_i^-(\omega)] + \xi_k^-(\omega), \\ \sum_{i=1}^{k} \xi_i^-(\omega & \text{if} \quad \sum_{i=1}^{k-1} [\xi_i^-(\omega) + \eta_i^-(\omega)] + \xi_k^-(\omega) < t < \sum_{i=1}^{k} [\xi_i^-(\omega) + \eta_i^-(\omega)], \end{cases}$$

$$X^{++}(t,\omega) = \begin{cases} [t - \sum_{i=1}^{k-1} \eta_i^+(\omega)] & \text{if} \quad \sum_{i=1}^{k-1} [\xi_i^+(\omega) + \eta_i^+(\omega)] < t < \sum_{i=1}^{k-1} [\xi_i^+(\omega) + \eta_i^+(\omega)] + \xi_k^+(\omega), \\ \sum_{i=1}^{k} \xi_i^+(\omega) & \text{if} \quad \sum_{i=1}^{k-1} [\xi_i^+(\omega) + \eta_i^+(\omega)] + \xi_k^+(\omega) < t < \sum_{i=1}^{k} [\xi_i^+(\omega) + \eta_i^+(\omega)], \end{cases}$$

(80)

$$X^{0-}(t,\omega) = \begin{cases} [t - \sum_{i=1}^{k} \eta_i^-(\omega)] & \text{if} \quad \sum_{i=1}^{k-1} [\xi_i^-(\omega) + \eta_i^-(\omega)] + \eta_k^-(\omega) < t < \sum_{i=1}^{k} [\xi_i^-(\omega) + \eta_i^-(\omega)], \\ \sum_{i=1}^{k-1} \xi_i^-(\omega) & \text{if} \quad \sum_{i=1}^{k-1} [\xi_i^-(\omega) + \eta_i^-(\omega)] < t < \sum_{i=1}^{k-1} [\xi_i^-(\omega) + \eta_i^-(\omega)] + \eta_k^-(\omega), \end{cases}$$

$$X^{0+}(t,\omega)=\begin{cases}[t-\sum_{i=1}^{k}\eta_i^{+}(\omega)] & \text{if} \quad \sum_{i=1}^{k-1}[\xi_i^{+}(\omega)+\eta_i^{+}(\omega)]+\eta_k^{+}(\omega)<t<\sum_{i=1}^{k}[\xi_i^{+}(\omega)+\eta_i^{+}(\omega)], \\ \sum_{i=1}^{k-1}\xi_i^{-}(\omega) & \text{if} \quad \sum_{i=1}^{k-1}[\xi_i^{+}(\omega)+\eta_i^{+}(\omega)]<t<\sum_{i=1}^{k-1}[\xi_i^{+}(\omega)+\eta_i^{+}(\omega)]+\eta_k^{+}(\omega).\end{cases}$$

here $t>0,\ k\geq 1$.

The following markings are made in the mathematical expressions of the random process:

$A^{--}=\{X^{--}(t,\omega)$ 0 momentum of process occurrence$\}$;

$A^{0-}=\{X^{0-}(t,\omega)$ process start-up from 0 momentum$\}$;

$A^{++}=\{X^{++}(t,\omega)$ starting the process with a rise from 0 momentum$\}$;

$A^{0+}=\{X^{0+}(t,\omega)$ process starts from 0 momentum$\}$.

Then the mathematical description of the random process will be as follows:

$$X^{\pm}(t,\omega)=\begin{cases}X^{\pm\pm}(t,\ \omega), & A^{++}(A^{--} \text{ if occurs,} \\ X^{0\pm}(t,\omega), & A^{0+}(A^{0-}) \text{ if occurs}\end{cases}$$

here, consider the process $X_1(t,\omega)=X^{+}(t,\omega)-X^{-}(t,\omega)$ and $X_1(t,\omega)$ as a continuous stochastic process at positive and negative angles α and β (α, $\beta\in(0°, 90°)$), respectively.

$X_1(t,\omega)$ process varies between screens $b\ (b>0)$ and $a\ (a>b)$, and by denoting the processes with $X_b(t,\omega)$ and $X(t,\omega)$, the following is received:

$$X_b(t,\omega)=X_1(t,\omega)-\inf_{0\leq s\leq t}(b,X_1(s,\omega)) \tag{81}$$

$$X(t,\omega)=X_b(t,\omega)-\sup_{0\leq s\leq t}(0,X_b(t,\omega)-a).$$

here, $X(t,\omega)$ will be called a continuous stochastic process between positive and negative angles α and β (α, $\beta\in(0°, 90°)$) and between two delaying screens a and $b\ (a>b>0)$.

The main goal here is to model the process $X(t,\omega)$ and find its sample mean and sample correlation functions.
If denote the sample function of the process $X(t,\omega)$ in a given interval (0, T) as $x(t)$, then the value of mean sample at point t_j is as follows:

$$EX(t_j,\omega) \approx \bar{x}(t_j) = \frac{\sum_{i=1}^{n} x_i(t_j)}{n}, \quad (82)$$

here, n - is number of trajectories in the range (0, T) of the process $X(t,\omega)$.
The sample correlation function of the process at points t_j and t_l is determined by the following formula:

$$K(t_j,t_l) \approx k(t_j,t_l) = \frac{\sum_{i=1}^{n} [x_i(t_j) - \bar{x}(t_j)][x_i(t_l) - \bar{x}(t_l)]}{n-1}, \quad (83)$$

Consider the modeling of LF circulation in OT with a semi-Markov process [8, 10, 17].
Here we assume that in the probability plane $(\Omega, F, P(\cdot))$, the random variables $\{\xi_k;\eta_k;\zeta_k\}, k = \overline{1,\infty}$ are given in a three-dimensional sequence independent of each other and referring to these random variables, the mathematical-statistical description of semi-Markov random "walk" process will be expressed as follows [17].

$X_1(t,\omega)$ process will be defined by the following general formula:

$$\bar{X}(t) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{k} X_i(t_j)}{kn}, \quad (84)$$

A visual representation of the computer modeling of the process is shown in Figure 10 below:

(86)

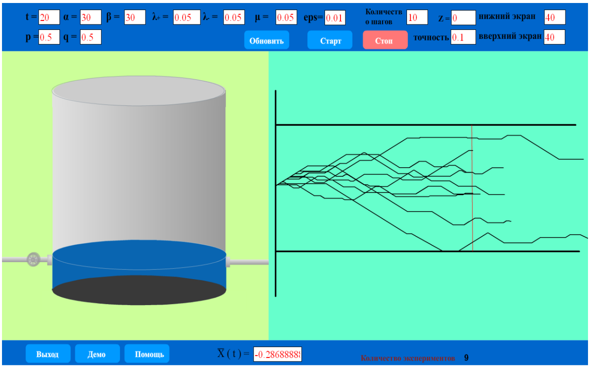


Figure 10. Results of test processes

Finally, a general integral equation for the average calculation of the temporal distribution of the amount of LF in the OT is obtained.

In the Chapter Six, errors of tested measurement systems were studied, uncorrelated static error, dynamic components of error, inadequacy error and total error of mathematical model of conversion function were analyzed, correctional test equations for error components were obtained.

The metrological performance (MP) of the IMS depends mainly on the stability and sensitivity of the conversion functions (CF) of the primary measuring systems included in its structure. Their high-precision identification in the measurement process depends on the accuracy of the selected tests and the choice of optimal values. Therefore, strict conditions are imposed on the conversion functions of MS operating in complex metrological conditions.

As mentioned above, the real conversion functions of MS are non-linear, and each interval of approximation in the form of a square trinomial is sufficient for their high-precision identification [27]:

$$y = b_0 + b_1 x + b_2 x^2, \tag{85}$$

here, b_0, b_1, b_2 -are the coefficients of the conversion functions of MS.

The conversion functions for TMS are defined as follows [32]:

$$y_0 = \frac{(y_1 - y_2)[x(k-1) + \theta] + y_3(xk - x - \theta)}{x(k-1) - \theta}, \tag{86}$$

The value of the MS input quantity is determined as follows:

$$x_{hes.} = \frac{(y_1 - y_2) + (y_0 - y_3)}{(y_0 - y_3) - (y_1 - y_2)} \cdot \frac{\theta}{(k-1)}, \tag{87}$$

The absolute error of TMS will be as follows:

$$\Delta_T = [x(k-1)+\theta](\Delta_1 - \Delta_2) + [x(k-1)-\theta](\Delta_3 - \Delta_0). \qquad (88)$$

Given that the relative error of TMS is determined by expression (88), then the following formula for all error components is obtained by substituting the corresponding values of the absolute errors generated by the additive and multiplicative tests in each measurement cycle (MC):

$$\Delta_T = \theta[\Delta_1 - \Delta_2 - (\Delta_3 - \Delta_0)] + x(k-1)\cdot[\Delta_1 - \Delta_2 + (\Delta_3 - \Delta_0)]. \qquad (89)$$

For the absolute error $\Delta_{gir.}$ brought to the TMS input:

$$\Delta_{gir.} = \frac{\Delta_T}{f'_T\,(x)}, \qquad (90)$$

is obtained. Here:

$$f_T(x) = (y_0 - y_3)[x(k-1)-\theta] + (y_2 - y_1)[x(k-1)+\theta]. \qquad (91)$$

When expression (91) is differentiated by x, the following is obtained for $f'_T\,(x)$:

$$f'_T\,(x) = (k-1)[(y_0 - y_3) - (y_1 - y_2)]. \qquad (92)$$

Considering expressions (89) and (91) in (90), the following expression for absolute error $\Delta_{gir.}$ brought to the TMS input is obtained:

$$\Delta_{gir.} = \frac{\{\theta[(\Delta_1 - \Delta_2) - (\Delta_3 - \Delta_0)] + x(k-1)[\Delta_1 - \Delta_2 + (\Delta_3 - \Delta_0)]\}}{(1-k)2\theta\{b_1 + b_2[(k-1)x+\theta]\}}. \qquad (93)$$

Thus, for the absolute error dispersion, the following expression is obtained if the measurement cycles of the TMS are not dependent on each other:

$$\sigma^2_{\Delta T} = \sigma^2_{\Delta_0}[z-\theta]^2 + \theta^2_{\Delta_1}[z+\theta]^2 + \sigma^2_{\Delta_2}[z+\theta]^2 + \sigma^2_{\Delta_3}[z-\theta]^2; \qquad (94)$$

here, $\sigma_{\Delta i} -$ is mean square deviations of the relevant MC errors.

As a final result, the following formula is obtained for the absolute error brought to the initial MS input:

$$\Delta_{gir\cdot T} = \frac{\Delta_M}{k-1} - \frac{\Delta_\theta}{\theta}. \qquad (95)$$

An important conclusion from expression (95) is that the components of the total error $\Delta_{gir\cdot T}$ of TMS, operating on the measurement algorithm (86), do not depend on the values of the CF coefficients of MS during the realization of the optimal set of tests.

Errors Δ_θ and Δ_M are usually continuous random variables that are not correlated with each other and have a normal distribution law. Consequently, the relative error ($\delta_{gir\cdot T}$) brought to the TMS input is in turn a continuous random variable and is characterized by mathematical expectation (M_{δ_T}) and dispersion ($\sigma^2_{\delta_T}$).

The mathematical expectation is defined by the following expression:

$$M_{\delta_T} = \frac{M[\Delta_M]}{k-1} - \frac{M[\Delta_\theta]}{\theta}, \tag{96}$$

here, $M[\Delta_M]$ and $M[\Delta_\theta]$ – are the mathematical expectations of random variables Δ_M and Δ_θ, respectively.

The dispersion $\sigma^2_{\delta_T}$ is determined by the following formula:

$$\sigma^2_{\delta_T} = \frac{\sigma^2_{\Delta_M}}{(k-1)^2} + \frac{\sigma^2_{\Delta_\theta}}{\theta^2}, \tag{97}$$

here, σ_{Δ_M} and σ_{Δ_θ} – mean square deviations of random variables Δ_M and Δ_θ, respectively.

Thus, comparing the calculated dispersion values $\sigma^2_{[\delta_T]}$ and $\sigma^2_{[\delta^*_T]}$, we observe that the TMS realised with the optimal set of additive, multiplicative, and hybrid tests has small dispersion value in terms of total error components than analogous TMS with simple additive and multiplicative tests. No additional time is required if the TMS conversion characteristic is square trinomial and the basic test equations (BTE) are solved.

As an example, if we take a set of tests x, $x+\theta_1$, $x+\theta_2$, kx for the full measurement period of TMS, the measurement result (MR) will have the corresponding output values $y_0, ..., y_3$, and the following BTE will be obtained:

$$\begin{cases} y_0 = b_0 + b_1 x + b_2 x^2 \\ y_1 = b_0 + b_1(x+\theta_1) + b_2(x+\theta_1)^2 \\ y_2 = b_0 + b_1(x+\theta_2) + b_2(x+\theta_2)^2 \\ y_3 = b_0 + b_1 kx + b_2 (kx)^2 \end{cases} \tag{98}$$

If errors caused by inaccuracies in the TMS measurement cycles are taken into account, then the following expressions are obtained:

$$\begin{aligned} \Delta_{T1} &= [b_2 + 2b_3(x+\theta_1)] \cdot \Delta_{\theta_1}, \\ \Delta_{T2} &= [b_2 + 2b_3(x+\theta_2)] \cdot \Delta_{\theta_2}, \\ \Delta_{T3} &= [b_2 + 2b_3 kx] \cdot \Delta_M \cdot x. \end{aligned} \tag{99}$$

If the conversion characteristic of TMS is in the form of a polynomial of degree $n = 3$, the following expression is obtained for the MS conversion function when it is written and solved in the initial BTE expressions:

$$y_0 = \frac{y_1 x(k-1)\theta_2[x(k-1)-\theta_2] - y_2 x(k-1)\theta_1[x(k-1)-\theta_1] + y_3\theta_2\theta_1(\theta_2-\theta_1)}{[x(k-1)-\theta_1][x(k-1)-\theta_2](\theta_2-\theta_1)}. \quad (100)$$

Thus, from expressions (99) and (100) for the absolute error of TMS the following expression is obtained:

$$\Delta_T^* = x(k-1)\theta_2[b_2 + 2b_3(x+\theta_1)][x(k-1)-\theta_2]\Delta_{\theta_1} - x(k-1)\theta_1[b_2+2b_3(x+\theta_2)]\times \quad (101)$$

$$\times[x(k-1)-\theta_1]\Delta_{\theta_2} + x[b_2+2b_3kx)]\theta_2\theta_1(\theta_2-\theta_1)\Delta_M.$$

According to expression (90), the following mathematical model for the relative error brought to TMS input is obtained:

$$\delta^*_{gir.} = \frac{[x(k-1)-\theta_2][b_2+2b_3(x+\theta_1)]}{(b_2+2b_3kx)(\theta_1-\theta_2)}\cdot\frac{\Delta_{\theta_1}}{\theta_1} - \frac{[x(k-1)-\theta_1][b_2+2b_3(x+\theta_2)]}{(b_2+2b_3kx)(\theta_1-\theta_2)}\cdot\frac{\Delta_{\theta_2}}{\theta_2} + \frac{\Delta_M}{k-1}. \quad (102)$$

For the mathematical expectation and dispersion of the relative error $\delta^*_{gir.}$ of the TMS, the following expressions are obtained, respectively:

$$M_{[\delta^*_{gir.}]} = 0;$$

$$\sigma^2_{[\delta^*_{gir.}]} = \frac{[x(k-1)-\theta_2]^2[b_2+2b_3(x+\theta_1)]^2}{(b_2+2b_3kx)^2(\theta_1-\theta_2)^2}\cdot\frac{\delta^2_{\Delta_{\theta_1}}}{\theta_1^2} + \quad (103)$$

$$+\frac{[x(k-1)-\theta_1]^2[b_2+2b_3(x+\theta_2)]^2}{(b_2+2b_3kx)^2(\theta_1-\theta_2)^2}\cdot\frac{\delta^2_{\Delta_{\theta_1}}}{\theta_2^2} + \frac{\delta^2_{\Delta_{\theta_1}}}{(k-1)^2}$$

As can be seen from expressions (97) and (103), by using the multiplicative test, the weights of the other components are exactly equal in value and do not depend on the parameters of the conversion functions of MS. However, when using additive tests, they do not match in accuracy, and the weight ratios differ qualitatively. From these two expressions it is clear that even if the weighting factor in the first expression is equal to one, in the second expression the coefficients in front of these components depend on both values of the parameters of conversion function of MS and the relation between the values of additive and multiplicative tests.

Thus, the above proves the advantage of the measurement method, which takes place in the implementation of both tests and their optimal set.

Analysis of uncorrelated static error of TMS.

Errors caused by the instability of parameters of MS conversion functions can be divided into two frequency spectra: low and high frequencies:

$$\Delta b_i(t) = \overline{\Delta} b_i(t) + \overset{\circ}{\Delta} b_i(t). \quad (104)$$

In general, the error brought to TMS input can be shown in the following two summands:

$$\Delta_{gir.}(t) = \overline{\Delta}_{gir.}(t) + \overset{\circ}{\Delta}_{gir.}(t), \tag{105}$$

here, $\overline{\Delta}_{gir.}(t) -$ is correlatedcomponents of measurement error, $\overset{\circ}{\Delta}_{gir.}(t) -$ are uncorrelated components of measurement error.

Consider, uncorrelated components of measurement error (MR) derived from the application of algorithms (86) or (100) obtained for TMS. Considering, uncorrelated error components (EC) in test measurement processes, the BTE describing the relationship between applied tests and MR can be as follows:

$$\begin{cases} y_0 + \Delta_{qk}(t_1) = b_0 + b_1 x + b_2 x^2 \\ y_1 + \Delta_{qk}(t_2) = b_0 + b_1(x+\theta) + b_2(x+\theta)^2 \\ y_2 + \Delta_{qk}(t_3) = b_0 + b_1 xk + b_2(xk)^2 \\ y_3 + \Delta_{qk}(t_4) = b_0 + b_1(kx+\theta) + b_2(kx+\theta)^2. \end{cases} \tag{106}$$

here, $\Delta_{qk}(t_1), \Delta_{qk}(t_2), \Delta_{qk}(t_3), \Delta_{qk}(t_4) -$ represents the uncorrelated EC generated in the corresponding measurement cycles.

Given the expressions (104) and (105) in (106), the following system of equations for uncorrelated XT of measurement cycles is obtained:

$$\begin{cases} \Delta_{qk}(t_1) = \overset{\circ}{a}_1(t_1) + \overset{\circ}{a}_2(t_1)\, x + \overset{\circ}{a}_3(t_1) x^2 \\ \Delta_{qk}(t_2) = \overset{\circ}{a}_1(t_2) + \overset{\circ}{a}_2(t_2)\,(x+\theta) + \overset{\circ}{a}_3(t_2)(x+\theta)^2 \\ \Delta_{qk}(t_3) = \overset{\circ}{a}_1(t_3) + \overset{\circ}{a}_2(t_3) xk + \overset{\circ}{a}_3(t_3)(xk)^2 \\ \Delta_{qk}(t_4) = \overset{\circ}{a}_1(t_4) + \overset{\circ}{a}_2(t_4)\,(kx+\theta) + \overset{\circ}{a}_3(t_4)(kx+\theta)^2. \end{cases} \tag{107}$$

From expressions (90) and (107), the following expression for the uncorrelated components of the absolute error brought to the MS input:

$$\Delta_{gir.qk} = \begin{Bmatrix} \Delta_{qk}(t_2)\cdot[\theta + x(k-1)] - \Delta_{qk}(t_1)\cdot[x(k-1)-\theta] - \\ - \Delta_{qk}(t_3)\cdot[x(k-1)+\theta] - \Delta_{qk}(t_4)\cdot[x(k-1)-\theta] \end{Bmatrix} \times \frac{1}{2\theta(1-k)[b_2 + b_3(kx+x+\theta)]}, \tag{108}$$

For uncorrelated components of the relative error of TMS the following expression is obtained:

$$\delta_{gir\cdot qk} = \begin{Bmatrix} [x(k-1)-\theta]\cdot[\Delta_{qk}(t_4) - \Delta_{qk}(t_1)] + \\ + [x(k-1)+\theta]\cdot[\Delta_{qk}(t_2) - \Delta_{qk}(t_3)] \end{Bmatrix} \cdot \frac{1}{(1-k)x2\theta[b_2 + b_3(kx+x+\theta)]}. \tag{109}$$

For uncorrelated components of the additive (θ) error of TMS realized on the basis of algorithm (83), the following expression is obtained:

$$\Delta_{gir.qk_{ad.}} = \frac{[\theta + x(k-1)][\overset{\circ}{b}_1(t_2) - \overset{\circ}{b}_1(t_3)]}{(1-k)2\theta[b_2 + b_3(kx + x + \theta)]} + \frac{[x(k-1) - \theta][\overset{\circ}{b}_1(t_4) - \overset{\circ}{b}_1(t_1)]}{(1-k)2\theta[b_2 + b_3(kx + x + \theta)]}. \quad (110)$$

Given that the mathematical expectation of a random variable is zero, the following expressions are obtained for the expectation and dispersion of the additive EC from the expression (110):

$$M_{\Delta_{gir.q\kappa.ad.}} = 0;$$
$$\sigma^2_{\Delta_{gir.q\kappa.ad.}} = \frac{\sigma^2_{\overset{\circ}{a}_1}}{[a_{2N} + a_{3N}(kx + x + \theta)]^2}\left[\frac{x^2}{\theta_2} + \frac{1}{(1-k)^2}\right]. \quad (111)$$

For the coefficient of amplification ($K^*_{\sigma_{ad.}}$) reflecting the comparison of the mean square deviations (MSD) of uncorrelated components of the additive error of the single measurement in the TMS with MSD of uncorrelated error ($\Delta_{gir.qk.ad.}$) the following expression is obtained:

$$K^*_{\sigma_{ad.}} = \frac{b_2 + b_3 2x}{b_2 + b_3(kx + x + \theta)}\sqrt{\frac{x_2}{\theta_2} + \frac{1}{(1-k)^2}}. \quad (112)$$

Accordingly, for uncorrelated components of the multiplicative error of single measurement in the TMS the following expression is obtained:

$$K^*_{\sigma_{M1}} = \sqrt{\frac{[x(k-1)+\theta]^2 \cdot [(kx)^2 + (x+\theta)^2] + [x(k-1)-\theta]^2 \cdot [x^2 + (kx+\theta)^2]}{4\theta^2 x^2 (k-1)^2}} \times \quad (113)$$
$$\times \frac{b_2 + b_3 \cdot 2x}{\{b_2 + b_3[x(k+1)+\theta]\}},$$

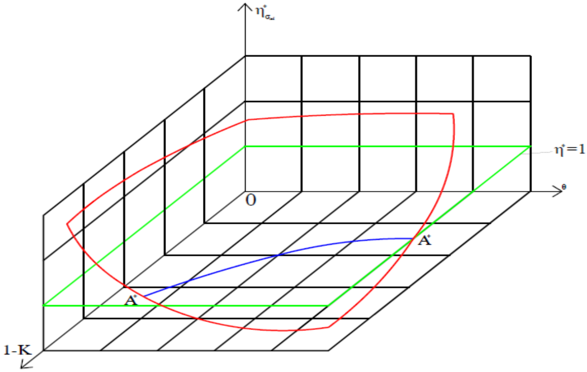
$$K^*_{\sigma_{M2}} = \sqrt{\frac{[x(k-1)+\theta]^2 \cdot [(kx)^4 + (x+\theta)^4] + [x(k-1)-\theta]^2 \cdot [x^4 + (kx+\theta)^4]}{4\theta^2 x^2 (k-1)^2}} \times \quad (114)$$
$$\times \frac{b_2 + b_3 \cdot 2x}{\{b_2 + b_3[x(k+1)+\theta]\}},$$

As can be seen, the uncorrelated components of the additive error generally prevail, so the coefficient $K^*_{\sigma_{ad.}}$ depends on the values of the additive and multiplicative tests.

Clarify, the dependence of the coefficient $K^*_{\sigma_{ad.}}$ on the values of additive and multiplicative tests: as can be seen from expression (114), the detected correlation relation (CR) between the measured value, additive, and multiplicative test parameters is visually reflected by the presence of their values in the area A_0.

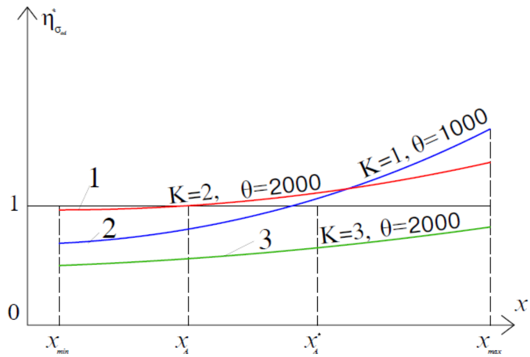
As a result of the application of algorithm (87), the uncorrelated components of the additive error of the TMS measurement result do not increase, at least because of the interrelation of the same error components. Graph 1 describes the dependence of $K^*_{\sigma_{ad.}}(\theta,k)$ in case of $x = x_0$.

As can be seen from the Graph, the dependence $K^*_{\sigma_{ad.}}(\theta,k)$, a given range of values of additive and multiplicative tests, is located behind the line intersecting with the points $A^* A^*$ on the the single-level plane $K^*_{\sigma_{ad.}}$.



Graph 1. Dependency graph $K^*_{\sigma_{ad.}}(\theta,k)$

Graph 2 illustrates the dependence of $K^*_{\sigma_{ad.}}(x)$ on the given values of the additive and multiplicative tests selected from area A_0. When the x values of areas θ and k are given, the additive components of the measurement error occurring during the execution of algorithm (90) do not increase compared to the analogous IMS error, are limited to values x_A, x^*_A and .The curve 3 corresponding to the θ and k values define the all IMS measurement range in this area.



Graph 2. Dependency graph $K^*_{\sigma_{ad.}}(x)$

here, 1 – dependency $K^*_{\sigma_{ad.}}(x)$, in case of $k=2,\quad \theta=2000$; 2 – dependency $K^*_{\sigma_{ad.}}(x)$, in case of $k=3,\quad \theta=1000$; 3 – dependency $K^*_{\sigma_{ad.}}(x)$, in case of $k=3,\quad \theta=2000$.

It should be noted that in the application of TMS, the selection of the values of θ and k parameters from the area A_0 was practically limited to real technical possibilities. The values of θ and k were searched at the boundary of area A_0, so the increase in the accuracy of measurements as a result of the implementation of test algorithms was accompanied by an increase in the correlation components of the measurement error. As a result, the number of measurement cycles increased indefinitely, complicating the measurement process and increasing the time required.

At present, TMS and intellectual information provision developed with the combined use of modern transmitters, software controllers and a personal computer can be implemented at a high level, autocorrection of measurement errors is performed, and the adequacy of the test algorithms is confirmed.

Quantization error in TMS.

When calculating the error of the measurement results and the values of the error components in the TMS, the following corresponding expressions for the quantization error were obtained:

$$\delta_{HQ_{gir.}} = \frac{\theta(\Delta_{1HQ}-\Delta_{2HQ}-\Delta_{3HQ}+\Delta_{0HQ})+x(k-1)(\Delta_{1HQ}-\Delta_{2HQ}+\Delta_{3HQ}-\Delta_{0HQ})}{2x\theta(1-k)\left[b_2+b_3(kx+x+\theta)\right]}. \quad (115)$$

$\delta_{HQ_{gir.}}$ - mathematical expectation and dispersion will be as follows:

$$M_{\Delta_{HQ_{gir.}}} = \frac{[x(k-1)+\theta]-[x(k-1)-\theta]-[x(k-1)+\theta]+[x(k-1)-\theta]}{(1-k)2\theta[a_{2N}+a_{3N}(kx+x+\theta)]}\cdot M_{\Delta_{HQ}}=0; \quad (116)$$

$$\sigma^2_{\Delta_{HQ_{gir.}}} = \frac{\Delta\tau^2}{12}\cdot\frac{\theta^2+x^2(k-1)^2}{(1-k)^2\theta^2\left[b_2+b_3(kx+x+\theta)\right]^2}, \quad (117)$$

here, Δ_{0HQ}, ..., Δ_{3HQ} -are calculated values of static error brought to the input of the MS on the appropriate cycle; $\Delta\tau$ – are individual quantization levels.

Analysis of dynamic error components of TMS

In the operation of the TMS, an additional summand is generate, which is specific for this method in dynamic error components in the measurements of time cycle. In the test measurement method, the tests and their combinations are connected to the TMS input with x along all measurement cycles. Therefore, the time change of the measurement quantity in a series of measurement processes consisting of an appropriate number of unknown parameters in the measurement cycles of the conversion function of the initial MS leads to the occurrence of the following components of the dynamic error. Then the BTE describing the connection between the tests given to the input of the initial MS based on the algorithm (85) and the measurement results will be as follows:

$$\begin{cases} y_0 = b_0 + b_1 x(t_0) + b_2 [x(t_0)]^2 \\ y_1 = b_0 + b_1 [x(t_1) + \theta] + b_2 [x(t_1) + \theta]^2 \\ y_2 = b_0 + b_1 [kx(t_2)] + b_2 [kx(t_2)]^2 \\ y_3 = b_0 + b_1 [kx(t_3) + \theta] + b_2 [kx(t_3) + \theta]^2, \end{cases} \quad (118)$$

here, $x(t_0),\ x(t_1),\ x(t_2),\ x(t_3)$ -value of the quantity measured x in the relevant measurement cycle.

If to solve the system equation (118) according to the value obtained by x measured at time t_0, the following expression is obtained:

$$x(t_0) = \frac{[x(t_1) - x(t_0)](y_3 - y_0)}{(1-k)[(y_2 - y_1) - (y_3 - y_0)]} - \frac{k[x(t_2) - x(t_0)](y_3 - y_0)}{(1-k)[(y_2 - y_1) - (y_3 - y_0)]} + \\ + \frac{\theta[(y_3 - y_0) + (y_2 - y_1)]}{(1-k)[(y_2 - y_1) - (y_3 - y_0)]} + \frac{k[x(t_3) - x(t_0)](y_2 - y_2)}{(1-k)[(y_2 - y_1) - (y_3 - y_0)]}. \quad (119)$$

At the same time, if we take into account that the value of the MQ calculated by the formula (118) remains unchanged in the series of measurements, then the corresponding MR can be attributed to any time moments $t_0,\ t_1,\ t_2,\ t_3$.

If the result of any measurement coincides in time t_0, the difference between expressions (83) and (118) takes the following expression of component $\Delta_{din.}(t_0)$ for the final value of the dynamic error determined by the change in the measured value of the measured quantity x.

$$\Delta_{din.}(t_0) = C_1[x(t_1) - x(t_0)] - C_2[x(t_2) - x(t_0)] + C_3[x(t_3) - x(t_0)], \quad (120)$$

here,

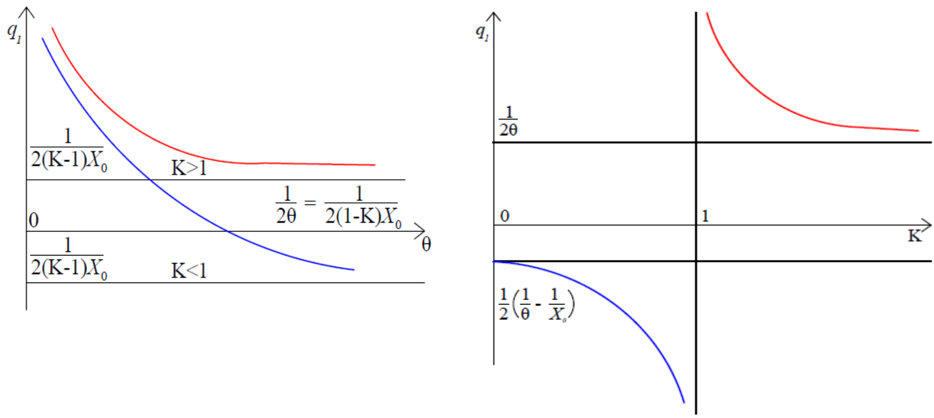
$$C_1 = \frac{y_3 - y_0}{[(y_3 - y_0) - (y_2 - y_1)]} = \frac{x}{2\theta} + \frac{1}{2(k-1)};$$
$$C_2 = \frac{k(y_3 - y_0)}{(k-1)[(y_3 - y_0) - (y_2 - y_1)]} = \frac{kx}{2\theta} + \frac{k}{2(k-1)}; \quad (121)$$
$$C_3 = \frac{k(y_2 - y_1)}{(k-1)[(y_3 - y_0) - (y_2 - y_1)]} = \frac{kx}{2\theta} + \frac{k}{2(k-1)}.$$

For the relative error the following expression is obtained:

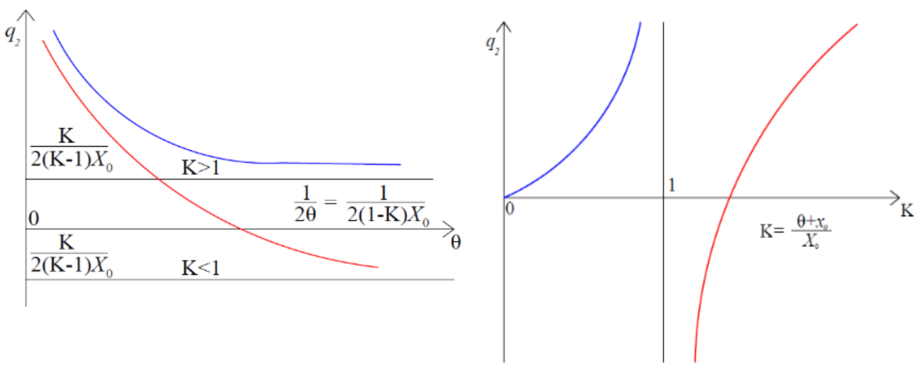
$$\delta_{din.}(t_0)=q_1[x(t_1)-x(t_0)]-q_2[x(t_2)-x(t_0)]+q_3[x(t_3)-x(t_0)], \qquad (122)$$

here, $q_1=\frac{1}{2\theta}+\frac{1}{2x(k-1)}$; $q_2=\frac{k}{2\theta}+\frac{k}{2x(k-1)}$; $q_3=\frac{k}{2\theta}-\frac{k}{2x(k-1)}$, are weight ratios, respectively.

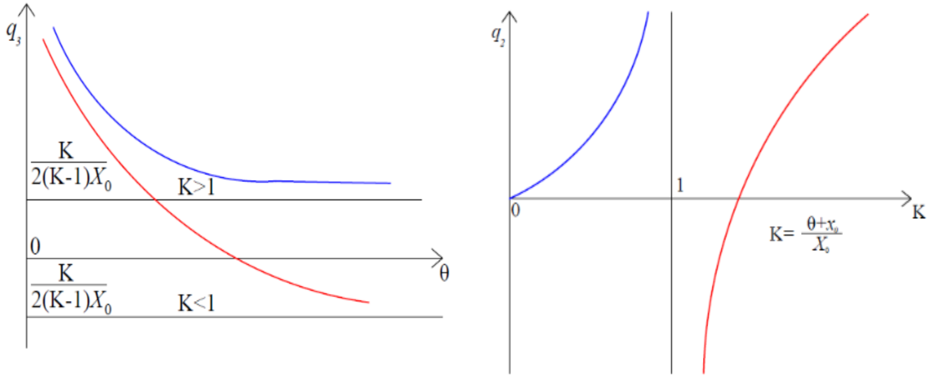
Graphs 3 and 5 show dependence diagram of weight coefficients (q_1, q_2, q_3) on values of additive and multiplicative tests (θ, k) according to the distribution law of the measured quantity x along the working range $\frac{x_{\max}}{x_{\min}}<10$.



Graph 3. Dependencies of the weight functions $q_1(\theta)$ and $q_1(k)$



Gaph 4. Dependencies of the weight functions $q_2(\theta)$ and $q_2(k)$



Graph 5. Dependencies of the weight functions $q_3(\theta)$ and $q_3(k)$

Considering that the measured quantity x varies linearly in the range $x(t_3)-x(t_0)$ and $\delta_{din.}(t_0)$ equals to zero, then the required terms is obtained from the expressions (120). For this purpose, by dividing the function $x(t)$ by a Taylor series as two limit values and considering expressions (120), following equation is obtained for the relative error:

$$\delta_{din.}(t_0)=q_1[x'(t_0)\tau]-q_2[x'(t_0)2\tau]+q_3[x'(t_0)3\tau]. \qquad (123)$$

Reducing this expression to zero, results in the following formula:

$$q_1-2q_2+3q_3=0. \qquad (124)$$

If we use the values of the weight coefficients q_1, q_2, q_3 in expression (124) and take into account that $k>0, x>0, \theta>0$, we obtain the required term as follows:

$$\theta-\frac{(k^2-1)}{5k-1}=0. \qquad (125)$$

This expression allows to determine the existing relationship between x, k and θ, meeting the condition $\delta_{din.}(t_0)=0$ and from the obtained expressions it can be seen that the value $\delta_{din.}(t)$ will change depending on the time the measurement result is taken.

Analysis of the total error of the TMS.

Given that the components of the measurement error of TMS are not related to each other, the error of the MR can be expressed by their sum:

$$\Delta_{yek.} = \Delta_T + \Delta_{QK} + \Delta_{HQ} + \Delta_g + \Delta_{QA} \quad (126)$$

here, Δ_T - absolute error of BTE of TMS; Δ_{QK} - uncorrelated absolute error; Δ_{HQ} - absolute error of the computing device; Δ_g - absolute error; Δ_{QA} - is inadequacy error of mathematical model.

To completely describe the total error ($\Delta_{yek.}$) in the expression (126), it is necessary to know its one-dimensional distribution law, which is defined as the accumulation of the distribution laws of the errors that make up this sum. Describing the total error, the joint probability distribution, is almost impossible with the definition of a law, as it leads to time-consuming and difficult research. It is known that according to the law of distribution, at the same time, the normalized error can be replaced by the first two normalized moments without losing the necessary information about the its zone.

The zone in which the specified error does not occur with a given probability $p^*_{yek.}$ is defined under the following conditions: the total error $\Delta_{yek.}$ has a single-mode distribution law, which is typical for TMS, and is not affected by "backlash" and hysteresis.

This zone is defined by the following inequality:

$$M[\Delta_{yek.}] - k\sigma[\Delta_{yek/}] \leq \Delta_{yek.} \leq M[\Delta_{yek.}] + k\sigma_{[\Delta_{yek.}]}, \quad (127)$$

here, k - is a known function depending on p^*, if the form of the probability characteristic of the law of one-dimensional distribution of error $\Delta_{yek.}$ is known; $M[\Delta_{yek.}]$ -mathematical expectation of the total error; $\sigma[\Delta_{раз.}]$ - is MSD of total error.

It should be noted that to estimate this zone, in addition to the coefficient k, it is necessary to know the values $M[\Delta_{yek.}]$ and $\sigma[\Delta_{yek.}]$. Which depends on the reliability of the assessment ($P^* = 0{,}95$), the error $\Delta\sigma^2[\Delta_{yek.}] \approx 50\%$ and the number of tests (100).

Thus, there is no need to determine the value of the coefficient k with great accuracy, and this will not cause a noticeable increase in the precision of the zone designation. At the same time, the error values generated by the measuring devices are added to the evaluation criteria $\hat{M}[\Delta_{yek}]$ and $\hat{\sigma}[\Delta_{yek}]$.

It follows from the above that without determining the distribution law of these errors, on a given reliability $p_{yek.}$ and expression (126), it is possible to find exactly the place of the error $\Delta_{yek.}$, zone - sufficient for the experiment, only by their mathematical expectation and SD. At the first moment of the TE, the ECs ($\Delta_T, \Delta_{QK}, \Delta_{HQ}, \Delta_g, \Delta_{QA}$) are calculated within the uncorrelation condition using the following expressions:

$$M[\Delta_{yek}] = M_{\Delta_T} + M_{\Delta_g} + M_{\Delta_{QA}}, \tag{128}$$

$$\sigma^2[\Delta_{yek}] = \sigma^2_{\Delta_T} + \sigma^2_{\Delta_{QK}} + \sigma^2_{\Delta_{HQ}} + \sigma^2_{\Delta_{QA}}, \tag{129}$$

here, $M_{\Delta_{QA}}$ and $\sigma^2_{\Delta_{QA}}$ - is the mathematical expectation and dispersion of the EC inadequacy of multi-channel TMS.

Considering the above values of mathematical expectation and dispersion of EC in (128) and (129), at the same time, assuming that this prevails in uncorrelated additive error, the following expressions for the mathematical expectation $M[\Delta_{yek.}]$ and dispersion $\sigma^2[\Delta_{yek.}]$ of the total error are obtained:

$$M[\Delta_{yek.}] = \left(\frac{M_{\Delta_M}}{K-1} - \frac{M_{\Delta_\theta}}{\theta}\right)x + v\tau\left[\frac{1+k}{2\theta} - \frac{(sk-1)}{2x(k-1)}\right]x +$$

$$+\frac{\dfrac{R'''_{yek.}(x)}{3!}[x(k-1)+\theta][x(k-1)-\theta]x}{2\left[\dfrac{R'_{yek.}(x)}{1!} + \dfrac{R''_{yek.}(x)}{2!}[x(k-1)+\theta] + \dfrac{R'''_{yek.}(x)}{3!}\left\{[x(k-1)+\theta]^2 + \dfrac{x(k-1)}{2}[x(k-1)-\theta]\right\}\right]} + \tag{130}$$

$$+M_{\Delta_{QA}},$$

here, v - is the rate of change of the measured value;

$$\sigma^2[\Delta yek.] = \frac{\sigma^2_{\Delta_M}}{(k-1)^2}x^2 + \frac{\sigma^2_{\Delta_\theta}}{\theta^2}x^2 + \frac{\sigma^2_{b_1}\left[\dfrac{x^2}{\theta^2} + \dfrac{1}{(1-k)^2}\right]}{[b_{2N} + b_{3N}(kx + x + \theta)]^2} + \tag{131}$$

$$+\frac{\Delta\tau^2}{12}\left\{\frac{\theta^2 + x^2(k-1)^2}{(1-k)^2\theta^2[b_{2N} + b_{3N}(kx + x + \theta)]^2}\right\} + \sigma^2_{\Delta_{QA}}.$$

If considering expression (126) in (130) and (131), given the probability, we determine the zone where the last error $\Delta_{yek.}$ is located.

MAIN RESULTS

1. A concept has been presented for the development of information measurement and management complex with high metrological characteristics, combining the objects of the oil industry.
2. The group flow rate measuring device has been modernized, improving measurement accuracy, efficiency, technical and economic performance through the use of a hybrid testing algorithm.
3. The composition of the oil emulsion quantitative and qualitative indicators to determine the base model proposed, the process of separation the efficiency has been increased.
4. The system developed to determine the flow rate according to the filtration characteristics of the oil well layers realized the correction of the results.
5. A tested monitoring and measuring system for automatic mixing of chemicals in the separator inlet manifold has increased the speed and efficiency of the oil separation process.
6. A frequency oscillation device for measuring oil density in the flow was upgraded, and the application of the developed hybrid test algorithms improved the accuracy of the measurement.
7. The amount of oil in the flow by mechanical meters measurement process for tested measuring system and algorithm processed, measurement its accuracy was improved.
8. Mathematical model of nonlinear approximation of conversion characteristics of primary measuring systems (transmitters) was developed and measurement error was reduced.
9. A miniature structure and a high metrological characteristics based on complex measurement for oil tanks were developed.
10. An automated calibration system based on piezometric measurement for oil tanks of various geometric sizes and a method for designing individual calibration tables were developed [18, 20].
11. The processes of long-term storage and circulation of products in oil tanks were modeled, the corresponding Integral Equations were obtained, the non-formation and quantity of sediment was evaluated.
12. The developed measuring systems and their measurement errors were investigated and corrective algorithms were obtained.

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