Automated Modeling Verification Complex of the Intelligent Instrument System

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Abstract

Automated Model Verification Complexes are an important tool for research, testing, and verification of information and measuring instrument control systems, navigation, mechanical engineering, and other branches of technology. The model of the automated verification and simulation complex of the instrument system was developed based on the method of calibrated signals using a software-controlled measure. The calculation of the mathematical methodical error and the mean square deviation of the methodical error during quantization of the sum of input influences and additive interference are given.

Keywords

Model, instrument system, simulation, calibration, signal, measure, error, software-controlled measure.

1. Introduction

The most important role in ensuring the quality and reliability of high-tech products is played by control and measurement equipment and instrument systems, in which the means of measuring and controlling the functional parameters of these products occupy a special position.

In the majority of scientific works, attention is mainly paid to measuring systems of various types. They allow for obtaining and accumulating information about the parameters of a complex technical system with more accurate characteristics of a middle-class measuring instrument system, with the use of computer error correction, process data storage, and measurement results. However, the requirements for the accuracy of measurement by remote instrument systems lead to the need to improve the methods and means of measuring the stress-strain state in order to obtain reliable models of the obtained values, taking into account the operating conditions.

Therefore, in current conditions, the question of creating highly intelligent instrument systems that contain, unlike classical instrument information and measurement systems, a database, a knowledge base, a computing and measurement complex with automated verification units, etc., is acute.

Automated Model Verification Complexes (AMVC) are an important tool for research, testing, and verification of information and measuring instrument control systems, navigation, mechanical engineering, and other branches of technology. On the basis of AMVC, natural studies of various characteristics and parameters of similar real systems can be conducted using mathematical and physical models. In comparison with mathematical modeling, natural studies provide a much higher degree of reliability [1, 2, 3, 4, 5, 6] of estimates of system parameters, than the effects simulated in AMVC are closer to operational ones.

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2. Methods and Techniques

The connection of the system under study with software in full-scale simulation is carried out using physical models and stands for the implementation of environmental influences and processor modules for generating and processing signals [3]. The combination of various mathematical and physical models, as well as the variety of systems or their components determines the diversity of the content of natural states has the form:

$$\frac{dz(t)}{dt} = f\{z(t), u(t), \psi(t)\},$$

$$y(t) = g\{z(t), u(t), v(t)\}, \quad (1)$$

where f, g - are function vectors; y - is the vector of unmeasured perturbations (noise) acting on the system under study; v - is the vector of observation and signal processing noise.

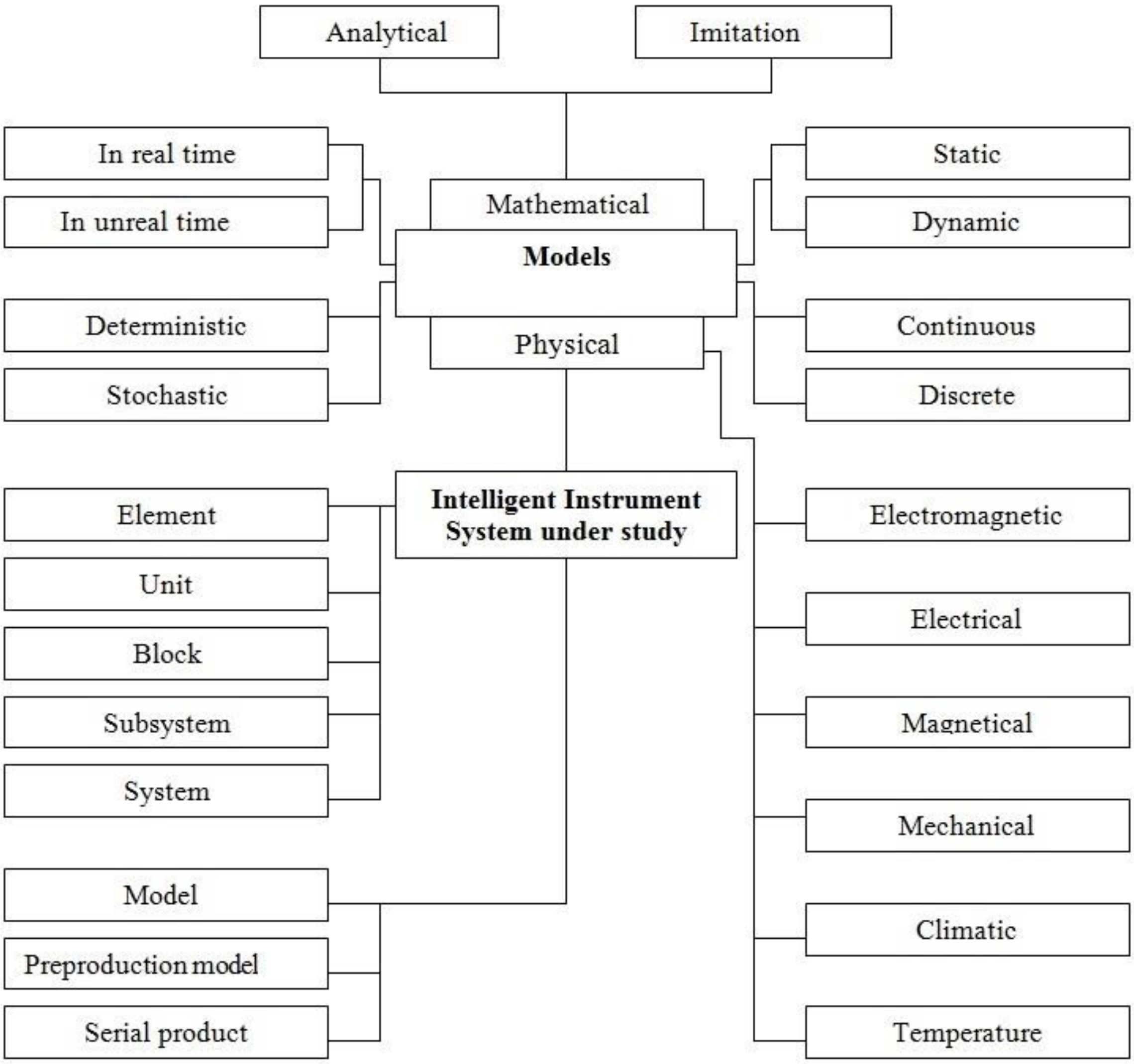

Figure 1: The structure of research objects during testing

After a series of experimental tests, as a result of which an assessment of the state of the system under study is determined, the parameters of the latter can be optimized in accordance with its objective function. In Fig.1. the structure of research objects during testing is presented.

3. Results and Discussion

The impact in a complex of immeasurable disturbances and noise leads to measurement errors, the magnitude of which decreases with an increase in the number of experiments, i.e. with an increase in the time interval of research Statistical properties of the state vector $\hat{z}(t)$ of the system are described by a posteriori probability distribution density:

$$w_1\left(\frac{z}{y}\right) = \frac{w_0(z) w_n(\frac{y}{z})}{w_y}, \tag{2}$$

where $w_0(z)$ - is the a priori probability density of the vector z; $w_n(\frac{y}{z})$ - is multidimensional likelihood function; w_y - distribution density of the observation vector.

In Fig.2. the model of the verification complex of the instrument system is presented.

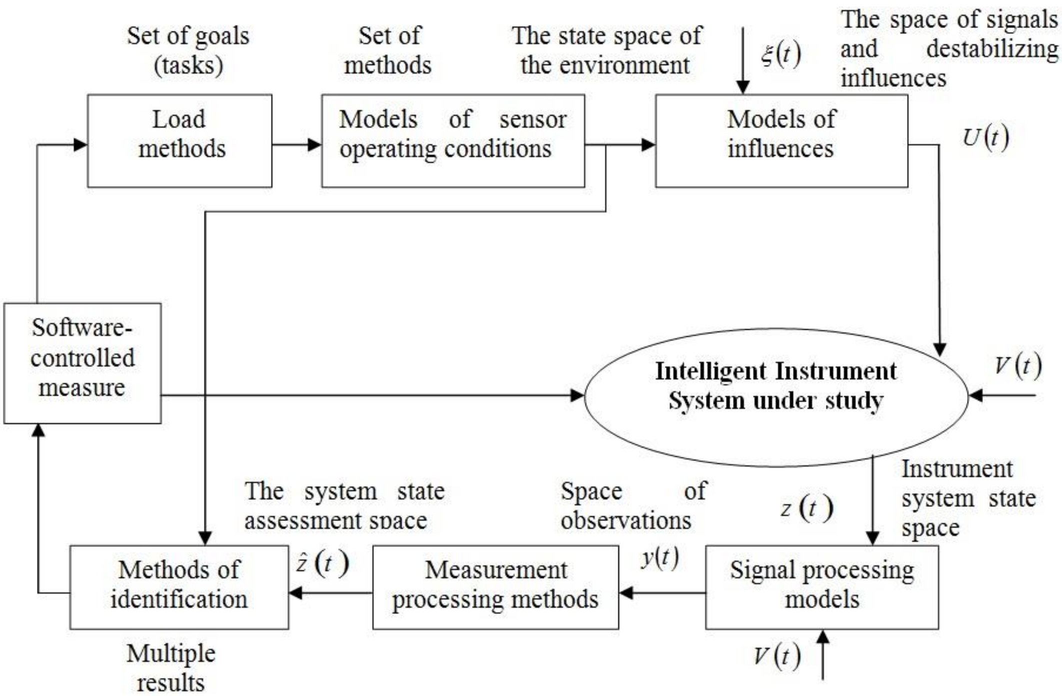

Figure 2: The model of the verification complex of the instrument system

In the case of automated verification of measuring devices, the method of calibrated signals is most often used. The highest level of automation of verification using calibrators is achieved when using a software-controlled measure. As shown in Fig. 2, a test signal from a PC-controlled measure is applied to the measuring instrument. The signal observed at the output of the tester is converted into a digital code and compared with the code of the test signal. Based on the comparison of the codes, the error at a certain point of the measurement range is determined. The procedure, according to which the processing of measurement results is carried out according to a certain software algorithm, is repeated at each reliable point of the scale of the measuring instrument.

Verification of the methods of standard instruments consists of the fact that an uncalibrated signal is applied to the verification instrument system, the value of which is automatically set by the measuring device of the instrument system to the verification mark of the scale. This signal value is measured by a reference measuring device. The value of the signal from the measuring device and the sample is processed using a PC in order to calculate the metrological characteristics of the calibration device.

Measuring transducers can also be trusted in such an installation. Signals specified in the regulatory documentation are sent to the input of the converter to the trusted converter. The optimal method of verification will be when the quality of verification of measuring instruments will increase while the costs of verification are reduced.

The minimization of errors in the evaluation of the vector z is connected with the determination of the center of gravity $\hat{z}$ of the function $w_1\left(\frac{z}{y}\right)$ at the obtained value of the vector of observations y.

The a posteriori integral estimation error of the state vector I_1 (uncertainty of the system state) depends on the hyper volume of the body, calculated at $w_1 = const$, the value of which is equal to:

$$I_1 = C_1 \prod_{i=1}^{k} \sigma_{1i} \ , \qquad (3)$$

where C_1 - the proportionality coefficient; σ_{1i} - the mean squared error of measurements of the I component of the vector z, k - the number of components of the vector.

Considering the fact that there is a priori uncertainty of the system state

$$I_0 =_0 \prod_{i=1}^{k} \sigma_{0i} \ ,$$

let's introduce an indicator of the effectiveness of field studies:

$$E = \frac{I_0}{I_1} = C \prod_{i=1}^{k} \frac{\sigma_{0i}}{\sigma_{1i}} .$$

It is obvious that for an effective set of tests $E > 1,\ E_i = \frac{\sigma_{0i}}{\sigma_{1i}} \geq 1.$

When designing AMVC, it is necessary to be guided by a number of basic principles. One of them is the principle of a system approach, which determines the creation of flexible hardware and software tools for automating the control of test technologies in accordance with the criteria for the functioning of the simulation complex. In addition, the principle of adaptability and development is important, which allows adapting the configuration of the AMVC for conducting research on a specific system, which ensures the further development of the complex, which is related to the modernization and updating of test tasks. And, finally, the principle of unification and modularity reduces the nomenclature of the component parts of the AMVC, which provides flexibility in the preparation and testing processes, which as a result reduces the cost of the complex.

The experience of development and experimental operation shows that the main characteristics of the AMVC functioning are five indicators: the adequacy of the signal and impact models, the accuracy of the assessment of the parameters of the state of the system under study, the system research time, the reliability of the complex, the cost of the AMVC.

The adequacy of the models determines the hardware and software complexity of the AMVC, which means that it affects its reliability and cost, and together with the assessment accuracy indicator, characterized by the vector of root mean square errors of the measurement of the state vector z of the system, establishes the degree of reliability of semi-natural studies.

The system research time t_i includes the full time from preparation to the end of the system research and determines the complexity and thus the cost of AMVC. The components of the indicator t_i are: t_p - time of preparation of the experiment, t_c - time of conducting the experiment, and t_0 - time of processing experimental data, i.e. $t_i = t_p + t_c + t_0$.

The experiment at AMVC is conducted in real-time. Therefore, the parameter t_e cannot be unreasonably reduced or increased and is determined by a sufficient amount of statistics about the studied system, necessary for its identification.

In the software-hardware verification complex of full-scale simulation, the time for preparing the experiment is calculated as [6, 7, 8, 9, 10]:

$$t_n = \sum_{i=1}^{m}(t_{si} + t_{ai} + t_{li}) + t_c \, , \tag{4}$$

where t_{si} - the time of creating the file and signal values; t_{ai} - the time of attestation of the signal parameters, t_{li} - the time of loading the file into the signal generator, m - the total number of simultaneously generated signals, t_c - the time of entering the output data for modeling.

The file generation time is proportional to the number of counts in the file. The time of attestation t_{ai} of signal parameters i depend on the parameter estimation method. In the general case, for random signals, it is necessary to use correlation-spectral analysis [8, 11, 12, 13, 14]. Then the certification time is proportional to the square of the number of readings in the file and is the most capacious value in the expression for the time to prepare the experiment t_n. The reduction t_n is due to the full hardware implementation of the signal shaper. At the same time, the process of generation of readings, as well as attestation of parameters proceeds in parallel in the real-time scale of the experiment, therefore $t_n = t_c$. Another reduction solution t_n is to create a library of typical certified signals that are used for system testing.

The time of experimental data t_0 processing to is determined by the time of calculation t_p of diagnosed system parameters and output (documentation) of information. The calculation of diagnosed parameters with the high performance of a specialized processing processor can proceed in parallel with the experiment, then $t_p = 0$. Otherwise, the calculation is performed after the end of the experiment and the value of t_p are proportional to the time of the experiment t_c.

When developing AMVC, there is a natural desire to achieve the best values of each of the indicators of the complex. However, the improvement of one of the indicators can cause the deterioration of a number of other indicators due to countervailing relationships. The AMVC optimization criterion [15, 16, 17, 18, 19] deserves attention when two main indicators are distinguished:

- technical one, which determines the usefulness of the system;
- economic one or utility fee (cost of AMVC).

Optimization of the system is carried out by choosing the most acceptable option according to these two indicators while limiting other indicators of the complex.

Of the five named indicators of AMVC, the concept of usefulness is most satisfied by such an indicator as system research time. The simulation complex is designed to replace the time- and material-intensive full-scale tests with semi-full-scale tests. Therefore, the smaller the t_i, is the higher the utility of AMVC. However, as t_i decreases, the cost of achieving its value and the cost of the complex increase. The latter depends not only on the main parameter t_i, but also on the adequacy parameters, as well as on the errors of estimating the parameters of the studied system. Optimization of the complex is related to the best combination of software and hardware within the framework of the described optimization criterion [20-24].

The complex implemented in accordance with Fig. 2 solves the following main tasks of testing and checking the instrument system:

- simulation of sensor dynamics with an arbitrary position of the measurement object with different levels of simulation;
- formation of an adequate electromagnetic environment (signals and disturbances);
- modeling of the signal propagation environment;
- operational change of initial data, dynamic management of the testing process in real-time;
- collection and processing of current values of system sensor parameters and display in real-time;
- spectral correlation analysis and documentation of research results.

The complex includes an IBM PC for modeling dynamic parameters of the environment and influences, an IBM PC for fixing and processing the states of the system under test, a specialized electronic block for forming electromagnetic influences and collecting information about the system state, and software. The electronic unit contains digital elements, including signal processors, analog nodes for system operation as part of the instrument system, information converters, and connections. The software is open, allows expansion, and is built according to the modular principle, with the possibility of software reconfiguration of the complex for the study of a specific system [25, 26, 27, 28, 29].

The basics of using simulation modeling to determine the values of error characteristics stem from the structure of the measurement procedure and the methods of determining errors and their characteristics. When developing the principles of the application of simulation modeling in metrology, the experience accumulated in related fields of technology, in particular in automatic control, measuring technology, radio technology, etc., was used.

According to [20, 25], simulation modeling should be understood as "a method of mathematical modeling in which direct substitution of numbers simulating external influences, parameters and variables of processes into mathematical models of processes and equipment is used", that is, a method based on reproducing the procedure measurements in numerical form using a PC. Thus, for simulation modeling of the measurement process, it is necessary to have a software system, which includes programs for reproducing input effects, analog measurement transformations, analog-to-digital transformations, processor-based measurement transformations, as well as programs for processing simulation results.

Calculation of the mathematical methodical error and the mean square deviation of the methodical error when quantizing the sum of input influences and additive interference.

Let x_j and n_j be the input influence and interference in the j- th measurement experiment, respectively. The amount $x_j + n_j$. is received at the input of the Analog-Digital Converter (ADC). Then the adopted algorithm (measurement equation) will look like this:

$$x_j^* = \left[\left[x_j + n_j\right]_{\Delta_{н}x}[m_x]_0\right]_0$$

Since the true value of x_j is determined by the equation:

$$x_j = \left[\left[x_j\right]_0[m_x]_0\right]_0$$

then the methodological error will be:

$$\Delta_{м}x_j^* = \left[\left[x_j + n_j\right]_{\Delta_{н}x}[m_x]_0\right]_0 - \left[\left[x_j\right]_0[m_x]_0\right]_0 = \Delta_n^{м}x_j^* + \Delta_{к}^{м}x_j^*,$$

where

$$\Delta_n^{м}x_j^* = \left[\left[x_j + n_j\right]_0[m_x]_0\right]_0 - \left[\left[x_j\right]_0[m_x]_0\right]_0$$

$$\Delta_{к}^{м}x_j^* = \left[\left[x_j + n_j\right]_{\Delta_{н}x}[m_x]_0\right]_0 - \left[\left[x_j + n_j\right]_0[m_x]_0\right]_0.$$

The first component is equal to n_j and its characteristics correspond to the characteristics of the disturbance, i.e.:

$$M\left[\Delta_n^{м}x_j^*\right] = M\left[n_j\right]; \quad D\left[\Delta_n^{м}x_j^*\right] = D\left[n_j\right].$$

The second component is due to the quantization of the sum of two random variables: $z = x + n$. Accordingly, to determine the characteristics of $\Delta_{к}^{м}x_j^*$, it is necessary to establish the type of density of the probability distribution $w(z)$. In the general case, the density of the probability distribution of the sum of two random variables will be determined as follows:

w(z)=(dF(z))/dz ,

where

$$F(z) = \iint_{x+n<z} w(x)\, w(n)\, dx\, dn.$$

We specify the properties of input influence and interference. We accept:

$$w(x) = \begin{cases} \frac{1}{X_{max}} & при\ x \in [0, X_{max}] \\ 0 & при\ x \notin [0, X_{max}] \end{cases},$$

$$w(n) = \begin{cases} \frac{1}{\Delta n} & при\ x \in \left[-\frac{\Delta n}{2}, \frac{\Delta n}{2}\right] \\ 0 & при\ x \notin \left[-\frac{\Delta n}{2}, \frac{\Delta n}{2}\right] \end{cases}.$$

Then:

$$w(z) = \begin{cases} \frac{2}{X_{max}\Delta n} + \frac{1}{2X_{max}} & at\ z \in [-\frac{\Delta n}{2}, \frac{\Delta n}{2}) \\ \frac{1}{X_{max}} & at\ z \in [\frac{\Delta n}{2}, X_{max} - \frac{\Delta n}{2}) \\ -\frac{2}{X_{max}\Delta n} + \frac{2}{X_{max}\Delta n}\left(X_{max} + \frac{\Delta n}{2}\right) & at\ z \in [\,X_{max} - \frac{\Delta n}{2}, X_{max} + \frac{\Delta n}{2}) \\ 0 & at\ z \notin [-\frac{\Delta n}{2}, X_{max} + \frac{\Delta n}{2}] \end{cases}$$

Accordingly, when $\Delta n > \Delta_к x$ we will have:

$$w\left(\Delta_к^м x_j^*\right) = \begin{cases} \frac{\Delta_к x_j^*}{X_{max}\Delta n} + \frac{1}{X_{max}\Delta n}\left(\Delta_н x + \frac{\Delta n}{2}\right) \\ at\ \ \Delta_к x_j^* \in [-\frac{\Delta n}{2} - \Delta_н x, -\frac{\Delta_н x}{2}) \\ \frac{p}{\Delta_н x} \\ at\ \ \Delta_к x_j^* \in \left[-\frac{\Delta_н x}{2}, \frac{\Delta_н x}{2}\right) \\ -\frac{\Delta_к x_j^*}{X_{max}\Delta n} + \frac{1}{2X_{max}} \\ at\ \ \Delta_к x_j^* \in \left[-\frac{\Delta_к x}{2}, \frac{\Delta n}{2}\right) \\ 0 \\ at\ \ \Delta_к x_j^* \notin [-\frac{\Delta n}{2} - \Delta_н x, \frac{\Delta n}{2}] \end{cases}$$

where $\Delta_к x = \frac{X_{max}}{2q}$ – is the quantization interval це інтервал квантування (q – is the bit rate of the ADC);

$$p = 1 - \int_{-\frac{\Delta n}{2}\Delta_н x}^{-\frac{\Delta_к x}{2}} \frac{1}{X_{max}\Delta n}\left(y + \Delta_к x + \frac{\Delta n}{2}\right) dy - \int_{\frac{\Delta_к x}{2}}^{\frac{\Delta n}{2}} \left(-\frac{1}{X_{max}\Delta n} + \frac{1}{2X_{max}}\right) dy$$

When $\Delta n \le \Delta_{\kappa} x$ we have:

$$w(\Delta_{\kappa} x_j^*) = \begin{cases} \frac{\Delta_{\kappa} x_j^*}{X_{max}\Delta n} + \frac{1}{X_{max}\Delta n}\left(\Delta_{\text{н}} x + \frac{\Delta n}{2}\right) \\ at\ \Delta_{\kappa} x_j^* \in \left[-\frac{\Delta n}{2} - \Delta_{\text{н}} x, -\frac{\Delta_{\kappa} x}{2}\right) \\ \frac{p}{\Delta_{\kappa} x} \\ at\ \Delta_{\kappa} x_j^* \in \left[-\frac{\Delta_{\kappa} x}{2}, \frac{\Delta_{\kappa} x}{2}\right) \\ 0 \\ at\ \Delta_{\kappa} x_j^* \notin \left[-\frac{\Delta n}{2} - \Delta_{\kappa} x, \frac{\Delta n}{2}\right] \end{cases},$$

and $p = 1 - \int_{-\frac{\Delta n}{2} - \Delta_{\text{н}} x}^{-\frac{\Delta_{\text{к}} x}{2}} \frac{1}{X_{max}\Delta n}\left(y + \Delta_{\text{к}} x + \frac{\Delta n}{2}\right) dy.$

The systematic methodical error will be:

$$M[\Delta_n x_j^*] = M[\Delta_n^{м} x_j^*] + M[\Delta_{\text{к}}^{м} x_j^*].$$

Since $M[\Delta_n^{м} x_j^*] = 0$, then we have:

$$M[\Delta_n\, x_j^*] = M[\Delta_{\text{к}}^{м} x_j^*] = \int_{-\frac{\Delta n}{2} - \Delta_{\text{н}} x}^{+\frac{\Delta_{\text{к}} x}{2}} \Delta_n\, x_j^* w(\Delta_{\text{к}}^{м} x_j^*) d\Delta_{\text{к}} x_j^* .$$

and when $\Delta n \le \Delta_{\kappa} x$ we will have:

$$M[\Delta_n x_j^*] = \int_{-\frac{\Delta n}{2} - \Delta_{\text{н}} x}^{-\frac{\Delta_{\text{к}} x}{2}} \frac{1}{X_{max}\Delta n}\left(y + \frac{\Delta n}{2} + \Delta_{\kappa} x\right) dy$$

and when $\Delta n > \Delta_{\kappa} x$ we will have:

$$M[\Delta_n x_j^*] = \int_{-\frac{\Delta n}{2} - \Delta_{\text{н}} x}^{-\frac{\Delta_{\text{к}} x}{2}} \frac{1}{X_{max}\Delta n}\left(y + \frac{\Delta n}{2} + \Delta_{\kappa} x\right) dy + \int_{-\frac{\Delta_{\text{н}} x}{2}}^{\frac{\Delta n}{2}} \left(-\frac{y}{X_{max}\Delta n} + \frac{1}{2X_{max}}\right) dy.$$

The mean square deviation of the methodological error is determined using the following ratio:

$$D[\Delta_{\text{м}} x_j^*] = [D[\Delta_n^{м} x_j^*] + D[\Delta_{\text{к}}^{м} x_j^*] + 2M[\Delta_n^{м} x_j^* \Delta_{\text{к}}^{м} x_j^*]]$$

where $\Delta_{\text{к}}^{м} x_j^*$ - the centered values of the methodological error components $\Delta_n^{м} x_j^*$ *and* $\Delta_{\text{к}}^{м} x_j^*$.

In accordance with the type of distribution $w(\Delta_n^{м} x_j^*) = w(n_j)$ we have:

$$D[\Delta_n^{м} x_j^*] = \frac{\Delta_{\kappa}^2 n}{12}.$$

Considering $w(\Delta_n^{м} x_j^*)$ when $\Delta n \le \Delta_{\kappa} x$, we have:

$$D[\Delta_n^{м} x_j^*] = \int_{-\frac{\Delta n}{2} - \Delta_{н} x}^{-\frac{\Delta_{\kappa} x}{2}} \frac{1}{X_{max}\Delta n}\left(y - M[\Delta_n^{м} x_j^*]\right)^2 \times \left(y + \frac{\Delta n}{2} + \Delta_{\kappa} x\right) dx + \frac{p^2 \Delta_{\kappa}^2 x}{12},$$

and when $\Delta n > \Delta_{\kappa} x$ will be:

$$D\left[\Delta_n^{м} x_j^*\right] = \int_{-\frac{\Delta n}{2}-\Delta_{н}x}^{-\frac{\Delta_{к}x}{2}} \frac{1}{X_{max}\Delta n}\left(y - M\left[\Delta_n^{м} x_j^*\right]\right)^2 \times \left(y + \frac{\Delta n}{2} + \Delta_{к} x\right) dx + \frac{p^2\Delta_{к}^2 x}{12} +$$

$$+ \int_{\frac{\Delta_{к}x}{2}}^{\frac{\Delta n}{2}} \left(\frac{y}{X_{max}\Delta n} + \frac{1}{2X_{max}}\right)\left(y - M\left[\Delta_n^{м} x_j^*\right]\right)^2 dy.$$

Then we will have:

$$M\left[\dot{\Delta}_n^{м} x_j^* \dot{\Delta}_{к}^{м} x_j^*\right] = \int_{-\frac{\Delta n}{2}}^{+\frac{\Delta n}{2}} \int_{-\frac{\Delta n}{2}-\Delta_{к}x}^{+\frac{\Delta n}{2}} \dot{\Delta}_n^{м} x_j^* \dot{\Delta}_{к}^{м} x_j^* w\left(\dot{\Delta}_n^{м} x_j^*, \dot{\Delta}_{к}^{м} x_j^*\right) d\dot{\Delta}_n^{м} x_j^* d\dot{\Delta}_{к}^{м} x_j^*.$$

Since the two-dimensional probability distribution function can be represented in the form of an expression:

$$w\left(\dot{\Delta}_n^{м} x_j^*, \dot{\Delta}_{к}^{м} x_j^*\right) = \left(\dot{\Delta}_n^{м} x_j^*\right) w\left(\dot{\Delta}_{к}^{м} x_j^* / \dot{\Delta}_n^{м} x_j^*\right),$$

$$w\left(\dot{\Delta}_{к}^{м} x_j^* / \dot{\Delta}_n^{м} x_j^*\right) = \begin{cases} \frac{p_1}{\Delta_{к} x} \ \ at\ \dot{\Delta}_{к}^{м} x_j^* \in \left[-\frac{\Delta_{к}x}{2}, \frac{\Delta_{к}x}{2}\right) \\ \frac{1}{X_{max}} at\ \dot{\Delta}_{к}^{м} x_j^* \in \left[-\frac{\Delta_{к}x}{2}, -n_j\right), \\ 0 \quad at\ \dot{\Delta}_{к}^{м} x_j^* \notin \left[-\frac{\Delta_{к}x}{2}, -n_j\right] \end{cases}$$

If $\dot{\Delta}_n^{м} x_j^* < -\frac{\Delta_{к}x}{2}$, then:

$$w\left(\dot{\Delta}_{к}^{м} x_j^* / \dot{\Delta}_n^{м} x_j^*\right) = \begin{cases} \frac{p_2}{\Delta_{к} x} \ \ at\ \dot{\Delta}_{к}^{м} x_j^* \in \left[-\frac{\Delta_{к}x}{2}, \frac{\Delta_{к}x}{2}\right) \\ \frac{1}{X_{max}} at\ \dot{\Delta}_{к}^{м} x_j^* \in \left[-\Delta_{к}\ x \ \ - n_j, -\frac{\Delta_{к}x}{2}\right), \\ 0 \quad at\ \dot{\Delta}_{к}^{м} x_j^* \notin \left[-\Delta_{к}\ x \ \ - n_j, \frac{\Delta_{к}x}{2}\right] \end{cases}$$

If $\dot{\Delta}_n^{м} x_j^* \geq \frac{\Delta_{к}x}{2}$, then:

$$p_1 = \int_{\frac{\Delta_{к}x}{2}}^{-n_j} \frac{dy}{X_{max}}$$

and

$$p_2 = 1 - \int_{-\Delta_{к}x-n_j}^{-\frac{\Delta_{к}x}{2}} \frac{dy}{X_{max}}$$

It should be borne in mind that the conditional density of the probability distribution $w\left(\dot{\Delta}_{к}^{м} x_j^* / \dot{\Delta}_n^{м} x_j^*\right)$ will be obtained if:

$$w\left(\dot{\Delta}_{к}^{м} x_j^*\right) = \begin{cases} \frac{1}{\Delta_{к} x} \ \ при\ \dot{\Delta}_{к}^{м} x_j^* \in \left[-\frac{\Delta_{к}x}{2}, \frac{\Delta_{к}x}{2}\right] \\ 0 \quad при\ \dot{\Delta}_{к}^{м} x_j^* \notin \left[-\frac{\Delta_{к}x}{2}, \frac{\Delta_{к}x}{2}\right] \end{cases}$$

This assumption is valid under the condition $\Delta n \leq x_{max}$, since this condition is always fulfilled in practice.

As a result, we have:

$$M\left[\dot{\Delta}^{\text{м}}_{\text{к}}x_j^*\dot{\Delta}^{\text{м}}_{n}x_j^*\right] = \int_{-\frac{\Delta n}{2}}^{-\frac{\Delta_{\text{к}} x}{2}} \dot{\Delta}^{\text{м}}_{n}x_j^* \left(\int_{-\frac{\Delta_{\text{к}} x}{2}}^{+\frac{\Delta_{\text{к}} x}{2}} \frac{p_1\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{\Delta_{\text{к}} x\Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^* + \int_{\frac{\Delta_{\text{к}} x}{2}}^{-n_j} \frac{\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{X_{max}\Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^*\right) d\dot{\Delta}^{\text{м}}_n x_j^* +$$

$$+\int_{-\frac{\Delta_{\text{к}} x}{2}}^{+\frac{\Delta n}{2}} \dot{\Delta}^{\text{м}}_n x_j^*\left(\int_{-\Delta_{\text{к}} x-n_j}^{-\frac{\Delta_{\text{к}} x}{2}} \frac{\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{X_{max}\Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^* + \int_{-\frac{\Delta_{\text{к}} x}{2}}^{+\frac{\Delta_{\text{к}} x}{2}} \frac{p_2 \dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{\Delta_{\text{к}} x \Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^*\right) d\dot{\Delta}^{\text{м}}_n x_j^* =$$

$$= \int_{-\frac{\Delta n}{2}}^{-\frac{\Delta_{\text{к}} x}{2}}\int_{\frac{\Delta_{\text{к}} x}{2}}^{-n_j} \frac{\dot{\Delta}^{\text{м}}_n x_j^* \dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{X_{max}\Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^*\, d\dot{\Delta}^{\text{м}}_{\text{к}} x_j^* + \int_{-\frac{\Delta_{\text{к}} x}{2}}^{+\frac{\Delta n}{2}}\int_{-\Delta_{\text{к}} x-n_j}^{-\frac{\Delta_{\text{к}} x}{2}} \frac{\dot{\Delta}^{\text{м}}_n x_j^* \dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{X_{max}\Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^*\, d\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*.$$

Thus, we have defined all the components included in the ratio for $D^{1/2}\left[\Delta_{\text{м}} x_j^*\right]$.

Under the condition $\Delta n \leq \Delta_{\text{к}} x$, we have:

$$D^{1/2}\left[\Delta_{\text{м}} x_j^*\right] = \left[\frac{\Delta_{\text{к}}^2 n}{12} + \int_{-\frac{\Delta n}{2}-\Delta_{\text{к}} x}^{-\frac{\Delta_{\text{к}} x}{2}} \frac{1}{X_{max}\Delta n}\left(\Delta_{\text{м}} x_j^* - M\left[\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*\right]\right)^2 \times\right.$$

$$\times\left(\dot{\Delta}^{\text{м}}_{\text{к}} x_j^* + \frac{\Delta n}{2} + \Delta_{\text{к}} x\right) d\dot{\Delta}^{\text{м}}_{\text{к}} x_j^* + \frac{p_2\Delta_{\text{к}}^2 x}{12} + + \int_{-\frac{\Delta n}{2}}^{-\frac{\Delta_{\text{к}} x}{2}}\int_{\frac{\Delta_{\text{к}} x}{2}}^{-n_j} \frac{\dot{\Delta}^{\text{м}}_n x_j^* \dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{X_{max}\Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^*\, d\dot{\Delta}^{\text{м}}_{\text{к}} x_j^* +$$

$$\left. + \int_{-\frac{\Delta_{\text{к}} x}{2}}^{+\frac{\Delta n}{2}}\int_{-\Delta_{\text{к}} x-n_j}^{-\frac{\Delta_{\text{к}} x}{2}} \frac{\dot{\Delta}^{\text{м}}_n x_j^* \dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{X_{max}\Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^*\, d\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*\right]^{1/2},$$

And under the condition $\Delta n > \Delta_{\text{к}} x$, we have:

$$D^{1/2} = \left[\Delta_{\text{м}} x_j^*\right] = \left[\frac{\Delta_{\text{к}}^2 n}{12} + \int_{-\frac{\Delta n}{2}-\Delta_{\text{к}} x}^{-\frac{\Delta_{\text{к}} x}{2}} \frac{1}{X_{max}\Delta n}\left(\Delta_{\text{м}} x_j^* - M\left[\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*\right]\right)^2 \times\right.$$

$$\times\left(\dot{\Delta}^{\text{м}}_{\text{к}} x_j^* + \frac{\Delta n}{2} + \Delta_{\text{к}} x\right) d\dot{\Delta}^{\text{м}}_{\text{к}} x_j^* + \frac{p_2\Delta_{\text{к}}^2 x}{12} + \int_{\frac{\Delta_{\text{к}} x}{2}}^{\frac{\Delta n}{2}} \left(-\frac{\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{X_{max}\Delta n} + \frac{1}{2X_{max}}\right)\left(\Delta_{\text{м}} x_j^* - M\left[\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*\right]\right)^2 d\dot{\Delta}^{\text{м}}_{\text{к}} x_j^* +$$

$$\left. + \int_{-\frac{\Delta n}{2}}^{-\frac{\Delta_{\text{к}} x}{2}}\int_{\frac{\Delta_{\text{к}} x}{2}}^{-n_j} \frac{\dot{\Delta}^{\text{м}}_n x_j^* \dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{X_{max}\Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^*\, d\dot{\Delta}^{\text{м}}_{\text{к}} x_j^* + \int_{-\frac{\Delta_{\text{к}} x}{2}}^{+\frac{\Delta n}{2}}\int_{-\Delta_{\text{к}} x-n_j}^{-\frac{\Delta_{\text{к}} x}{2}} \frac{\dot{\Delta}^{\text{м}}_n x_j^* \dot{\Delta}^{\text{м}}_{\text{к}} x_j^*}{X_{max}\Delta n}\, d\dot{\Delta}^{\text{м}}_n x_j^*\, d\dot{\Delta}^{\text{м}}_{\text{к}} x_j^*\right]^{1/2}.$$

4. Conclusions

The expediency of a new refined mathematical model, algorithms, and programs for calculating metrological characteristics during metrological certification of a new measured system was confirmed by Automated Model Verification Complexes (AMVC).

All the main conclusions made as a result of analytical studies were experimentally confirmed during the metrological certification of the system.

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References

[1] R. N. Bhatt, Stress dependence of the metal-insulator transition in doped semiconductors. Phys. Rev, 26 2 (1982) 1082-1085.

[2] P. Fisher Digital's Kompensation sverfahren zur Verbesserung von Messfuhlern. Erb. K. “Bulletin SEV/VSE”, 80 7 (1989) 365-368.

[3] National Instruments, SCXI Universal Strain Grade Input: SCXI-1540. URL: http://www.ni.com/pdf/products/us/4scxisc293_ETC_196.pdf.

[4] SCXI-1126. User Manual. Eight-Channel Isolated Frequency Input Module for Signal Conditioning. National Instruments Corporation, 2003.

[5] Field Wiring and Noise Considerations for Analog Signals. URL: http:// www.ni.com/white-paper/3344/en/

[6] K.B. Klassen Basis of measurements. Electronic methods and devices in measuring equipment. Postmarket, 2000.

[7] J. Uikzer, Connectivity: Intelligent Sensors or Intelligent Interfaces. Sensors and Systems, 10 (2002) 50-55.

[8] G. Rus, S. Y. Lee, S. Y. Chang, S. C. Wooh, Optimized damage detection of steel plates from noisy impact test. International Journal for Numerical Methods in Engineering, 68 7 (2006) 707-727. doi:10.1002/nme.1720.

[9] A. Schroder, J. Rautenberg, B. Henning, Evaluation of cost functions for FEA based transducer optimization. Physics Procedia, 3 1 (2010) 1003-1009. doi: 10.1016/j.phpro.2010.01.129.

[10] I. Korobiichuk, V. Mel'nick, V. Kosova, Z. Ostapenko, N. Gnateiko, K. Rzeplinska-Rykala, Mathematical Model of the Approximate Function as the Result of Identification of the Object of Automatic Control, in: Szewczyk, R., Zieliński, C., Kaliczyńska, M., Bučinskas, V. (eds) Automation 2023: Key Challenges in Automation, Robotics and Measurement Techniques. AUTOMATION 2023. Lecture Notes in Networks and Systems, vol 630. Springer, Cham, 2023. Doi:10.1007/978-3-031-25844-2_16

[11] J. Li, , P. Liu, H. Ding, W. Cao, Modeling characterization and optimization design for PZT transducer used in Near Field Acoustic Levitation. Sensors and Actuators A: Physical, 171 2 (2011) 260–265. doi: 10.1016/j.sna.2011.06.020

[12] J. Corcoran, K. Poulton, Analog to Digital Converters: 20 years of progress in Agilent oscilloscopes. Agilent Measurement J, 1 (2007) 35-40.

[13] S. Norsworthy, R. Schreirer, G. Temes, Delta Sigma Data Converters. Theory, Design, and Simulations. Edited by. IEEE Press, IEEE Order Number PC3954, 2020.

[14] M. Rakushev, S. Kovbasiuk, Y. Kravchenko, O. Pliushch, Robustness evaluation of differential spectrum of integration computational algorithms, in: 2017 4th International Scientific-Practical Conference Problems of Infocommunications. Science and Technology (PIC S&T), 2017, pp. 21-24.

[15] Y. Kravchenko, O. Starkova, K. Herasymenko, A. Kharchenko, Peculiarities of the IPv6 implementation in Ukraine, in: 2017 4th International Scientific-Practical Conference Problems of Infocommunications. Science and Technology (PIC S&T), 2017, pp. 363-368.
[16] E. Ozalevli, Lo Haw-Jing, P.E. Hasler, Binary-Weighted Digital-to-Analog Converter Design Using Floating-Gate Voltage References, IEEE Transactions on Circuits and Systems I: Regular Papers, 55 4 (2008) 990 – 998.
[17] L. Kuzmych, L. Volk, A. Kuzmych, S. Kuzmych, G. Voropay, V. Polishchuk, Simulation of the Influence of Non - Gaussian Noise During Measurement, in: 2022 IEEE 41st International Conference on Electronics and Nanotechnology (ELNANO), 2022, pp. 595-599. doi: 10.1109/ELNANO54667.2022.9927008.
[18] L. Kuzmych, G. Voropay, A. Kuzmych, V. Polishchuk, A. Kuzmych, Concept of creation of the automated system of remote deformation monitoring and control of the technical condition of engineering infrastructure, in: International Conference of Young Professionals «GeoTerrace-2022», Oct 2022, Volume 2022, p.1-5 DOI: https://doi.org/10.3997/2214-4609.2022590076.
[19] L. Kuzmych, M. Voloshin, A. Kuzmych, S. Kuzmych, V. Polishchuk. Experimental studies of deformation monitoring in metal structures using the electromagnetic method, in: international Conference of Young Professionals «GeoTerrace-2022», Oct 2022, Volume 2022, p.1 – 5. DOI: https://doi.org/10.3997/2214-4609.2022590078
[20] A. Rokochinskiy, I. Korobiichuk, L. Kuzmych, P. Volk, A. Kuzmych, The System Optimization of Technical, Technological and Construction Parameters of Polder Systems. AUTOMATION, 1140 (2020) 78-86. Doi:10.1007/978-3-030-40971-5_8.
[21] I. Korobiichuk, L.Kuzmych, V. Kvasnikov, The system of the assessment of a residual resource of complex technical structures, in MECHATRONICS 2019: Mechatronics 2019: Recent Advances Towards Industry 4.0, 2019, pp. 350-357. Doi:10.1007/978-3-030-29993-4_43.
[22] L. Kuzmych, Study of the durability of reinforced concrete structures of engineering buildings, Advances in intelligent systems and computing, 543 (2017) 659-663. DOI:10.1007/978-3-319-48923-0.
[23] K.J. Åström, T.Hägglund, Avanced PID Control. ISA-The Instrumentation, Systems and Automation Society, 2006.
[24] A. O’Dwyer, Handbook of PI and PID Controller Tuning Rules, 3rd edn. Imperial College Press, London (2009). 599 p.
[25] R. Zurawski, Integration Technologies for Industrial Automated Systems. Industrial information technology Series. CRC Press, Taylor & Francis Group, Boca Raton, 2007.
[26] M. Masum, Analytical Design of PID Controller for Enhanced Disturbance Rejection of Processes without Time Delay. Graduate School of Yeungnam University, 2010.
[27] M.A. Johnson, M.H. Moradi, PID Control. New Identification and Design Methods. Springer, London, 2005.
[28] T. Harada, N. Ishikawa, T. Kanda, K. Suzumori, Y. Yamada, K. Sotowa, Droplet generation using a torsional Langevin-type transducer and a micropore plate. Sensors and Actuators A: Physical, 155 1 (2009) 68-174. doi: 10.1016/j.sna.2009.08.007.
[29] S. Keil, Beanspruchungsanalyse mit Dehnungsmessstreifen. Stress analysis using strain gages – Cuneus Verlag, 1995.