Розроблено і запропоновано метод прогнозування відмов апаратних засобів мікропроцесорних систем залізничної автоматики, що дозволяє визначити ймовірність відмови пристрою з певної групи із використанням розподілу Стьюдента, методів максимальної правдоподібності та нерівноточних спостережень. На відміну від існуючих підходів до прогнозування, запропонований метод враховує обмежений обсяг статистичних даних про функціонування мікропроцесорних систем керування на залізничному транспорті

Ключові слова: мікропроцесорні системи, залізнична автоматика, розподіл Стьюдента, метод максимальної правдоподібності, мікростатистика

Разработан и предложен метод прогнозирования отказов аппаратных средств микропроцессорных систем железнодорожной автоматики, который позволяет определить вероятность отказа устройства определённой группы с использованием распределения Стьюдента, методов максимального правдоподобия и неравноточных наблюдений. В отличие от существующих подходов к прогнозированию, предложенный метод учитывает ограниченный объём статистических данных о функционировании микропроцессорных систем управления на железнодорожном транспорте

Ключевые слова: микропроцессорные системы, железнодорожная автоматика, распределение Стьюдента, метод максимального правдоподобия, микростатистика

PREDICTING A TECHNICAL CONDITION OF RAILWAY AUTOMATION HARDWARE UNDER CONDITIONS OF LIMITED STATISTICAL DATA

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1. Introduction

One of the key problems that arise in the implementation of microprocessor systems of railway automation is the realization of effective technical diagnosis and control in the process of operation. Solving it is an important component of the confirmation and ensuring the required level of reliability and functional safety of the specified systems [1–3].

This problem appears to be the most acute in terms of the timely detection of dangerous failure in separate channels of reserved information-control systems. This is due, above all, to the absence of manifestation of a dangerous failure in the separate channels of a reserved technical unit from the point of view of direct impact on the controlling elements. Only reliable technical diagnosis can promptly detect and warn of such dangerous failures [3].

One of the priority tasks in technical diagnosis and control is the assessment of permissibility and feasibility of further operation of equipment taking into account results of the prediction of technical condition when detecting a defect in hardware. Such a task is defined in line with a number of national (DSTU 2389-94, DSTU 3021-95, DSTU 4178-2003), European (EN 1330-9, EN 13848-5, EN 13261:2009) and international (ISO/IEC 17020, ISO 9001-94, IEC 300-1/ISO 9000-4) standards, results of scientific research and methodological recommendations. Significant contribution into the formation of results of the aforementioned prediction is made by statistical methods based on taking the identified defects into account, as well as failures of technical devices in the process of operation [4–10].

However, using the classical methods of mathematical statistics is significantly complicated for microelectronic devices of the systems of railway automation by a number of factors, the main of which are [11–13]:

1. Relatively limited experience of operating the microprocessor systems of management and control at the railway transport of Ukraine, under conditions of low volume of the implementation, which limits the size of statistical samples and their representativeness.

2. Limited access to information on the statistics of failures in the process of operating the microprocessor systems of railway automation in foreign countries. This complicates the formation of objective statistical picture, which would have allowed the use of classical methods for its evaluation.

3. The realized strict requirements on reliability and safety in the operation of such systems, when the cases of failures and defects are an extremely rare phenomenon, which, when applied to a general shortage of statistical data, makes the classical processing of results of observations practically impossible.

It should be noted that the analytical prediction of failure rate of hardware devices is essential to ensure high reliability and safety when using railway automatics [8, 9, 11, 13]. Therefore, it is a relevant issue to devise such methods of forecasting, for which limited statistical volume is sufficient.

2. Literature review and problem statement

Over the last decade, the problem of forecasting the technical condition of means of management and control has been addressed in a significant number of studies. The majority of relevant scientific publications in the field of railway automation are aimed at improving the methods and means of detection and prevention of failures in its micro-electronic equipment.

The research indicated considers software and hardware design of information-control systems, and thus forecasting a condition of equipment is mainly based on the use of software testing. In particular, article [14] proposes to perform the prediction of failures in a computing device based on two main parameters: information message and a time interval between information messages, created by software. A similar approach, but complemented with the use of statistical methods, limited in application to only the means with the installed UNIX-operating systems (OS), is described in paper [15]. In the given study, a failure is defined as a discrete random magnitude, and, in order to detect a probable onset of a pre-failure state of a device, authors employ an analysis of the histogram of its distribution.

The method of predicting that implies an analysis and grouping of diagnostic information, recorded by software to the file of system errors, was proposed in the copyrighted document (patent) [16]. According to the method, each message from an appropriate file is compared with a specific template. In the case when results of the comparison match, a failure of a particular hardware element is localized in space and time with a certain probability. This localization takes place considering the groups of messages or their totality.

The method of prediction that does not use continuous or periodic software and hardware testing of equipment but is based on an analysis of statistical data is proposed in article [17]. According to it, the prediction is performed in two stages. The first is to calculate a prediction for mathematical expectation and variance of the detected diagnostic attribute at a specified point of time over a certain range. The second is to calculate, using the determined values, a probability of failure-free operation or a failure in equipment. In this case, underlying the calculations is a hypothesis about the provisions of a random process matching the non-random time functions. A similar procedure, but based on mathematical description of the ratio of operating parameters and diagnostic signal and the extrapolation of experimental data over time, is outlined in paper [18].

An analysis of relevant problems in diagnosis, including forecasting the technical condition of devices of railway automatics, taking into account the peculiarities of functioning, is given in article [19]. The study employed a stepwise procedure for technical diagnosis, based on the consistent determining of the state of parameters of a controlled object in discrete time moments over a certain interval. Processing of observation results is performed using the classic apparatus of probability theories and mathematical statistics.

Variants of the automation of forecasting procedures of technical condition of devices of railway automatics are proposed in paper [20]. The essence of variants comes down, in particular, to the machine processing of results of testing the systems using a classic apparatus of the probability theory.

Article [21] considers a comparative approach to predicting and diagnosing a technical condition. Under such conditions, a comparison is performed of the managing and controlling information in each channel of a multichannel device. Based on comparative data, a numerical probabilistic assessment is made of a pre-failure state of the device. A similar approach, but based on a multistage comparison of information-governing data from different channels, is proposed in paper [22]. As a result, the accuracy of execution of the specified probabilistic assessment increases substantially.

A generalized overview of prospects for the development of methods and means of technical diagnosis and prognostication of technical equipment of railway automatics is given in article [23]. Special attention in this case is paid to the issues of improving the reliability of prediction results. Authors also considered the aspects related to the missing initial data for mathematical processing of results of experimental research.

However, a common shortcoming of most of the known methods for predicting in the field of railway automation is the orientation towards a considerable amount of statistical data (results of observations, tests, etc.). Such approach is not acceptable under conditions of relatively insignificant experience in the operation of microprocessor information-control systems at railway transport. Solving the specified problem was initiated in paper [24] in terms of establishing the reliability of test results of the system of microprocessor centralization. The study took into account that the results of experimental research into separate examined samples have a limited application for technical analogs. In addition, verification article [25] stated a fundamental possibility of applying this approach to calculation determining of the probability of a failure of technical means over a certain period of operation.

Paper [26] developed and proposed methods and technical means for testing the technical tools of railway automatics on the example of microprocessor centralization. The methods and means are based on the combined simulation of technological processes when performing diagnostic procedures.

Data obtained in article [24] are expedient to accept as a basis for developing the methods for the prediction of microprocessor technical equipment of railway automatics in the process of operation. In this case, we should consider the procedure in experimental methodology, given in paper [26], which tackles execution of the required diagnostic tests.

3. The aim and tasks of research

The aim of present research is to develop a progressive method of forecasting the technical condition of microelectronic means of railway automation. It should provide for determining the probability of failure of a certain functional node in the information-control system of railway transport under conditions of limited statistical data on its operation.

To accomplish the set aim, the following tasks have to be solved:

– to establish criteria, which are used to predict technical condition of microprocessor devices of railway automation;

– to substantiate apparatus of mathematical statistics, which is to be applied to carry out effective and reliable processing of limited data from observations (operational, laboratory, testing, etc.);

– to develop mathematical models, on which a method of predicting the technical condition of microprocessor devices are based;

– to construct analytical and graphic patterns associated with the prediction of technical condition of microprocessor devices.

4. Materials and methods for improving the procedure of predicting the equipment of railway automation

4. 1. The use of the principle of equivalence of identical elements

Underlying the research is the principle of identity of microprocessor controllers (MPC). MPCs are thus combined in a single equivalence class by structural-functional attribute. This allows using limited statistical data on reliability of microprocessor devices within the framework of research [24, 26].

In order to apply the appropriate methods, the whole set L of MPC of a certain level of control system is divided into n equivalence classes $L_i \subset L$, only identical MPC are within the limits of each class.

In accordance with the principle of equivalence, results of testing, tests or other studies, executed relative to a separate element of equivalence class l_j, are L_i, are applicable to the whole set L_i. Based on the theory of relations, results of studies, performed relative to the system of representatives of all equivalence classes are applicable for the entire set L [10].

Dissemination of research results over the system of representatives on all relevant equivalence classes directly follows from the transitivity of the given relationship. However, a deviation in the parameters of a particular MPC l_{def} is L_i leads to the group L_i ceasing to be an equivalence class. Such a deviation may be a consequence of damage, production defect or other failure of a technical device. Instead, the class of equivalence in this case is the set $L_i / \left(L_i^{def} = \left\{ l_{def} \right\} \right)$. Then results of research into MPC l_{def} cannot apply to the entire set of identical elements.

Thus, from the point of view of the theory of relations, forecasting the technical condition of MPC can be reduced to determining the probabilistic indicators of manifestation of set L_i^{def} [10, 24], which is the basis of the study, which is considered in the present article.

4. 2. Probabilistic approach with the use of a Lyapunov theorem

If it was not for the well-organized industrial initial or other inspection control of MPC, there is always a set of unaccounted factors whose influence leads to occasional mistakes, the result of which is the set $L_i^{err} = \left\{ l_{err} \right\}$ of MPC with unidentified deviations from technical parameters, operation of which leads to hardware failures. Thus, the prediction of technical state of MPC is determined by the probability of membership of element $l \in LL_i$, arbitrarily chosen from the whole totality of MPC, to the class of equivalence $L_i^e = L_i / L_i^{err}$: $P(E: l \in L_i^e)$ [10].

The specified random errors are interpreted by the corresponding number of products. Their inspection control (in production, at a maintenance-technological station, etc) did not detect any flaws (defects, etc.). Quantitative estimation of random errors is determined by their ratio to the total number of products in a relevant group. If one has statistical data on the specified quantity from several sites of the implementation of MPC, then the probability P(E) can be calculated based on statistical methods.

Random errors are naturally considered as a result of impact from a large number of various reasons. Each one of them contributes with a very small error. None of them is dominant. If one detects dominant errors, then such errors should be attributed to the systematic ones and should be accounted for by appropriate adjustment.

According to Lyapunov theorem, there is a reason to believe that random errors are distributed according to the normal law. Then normally distributed are also magnitudes $\omega = \omega_{jh} = (N_{err}/N_{com}) \times 100\,\%$ that represent such errors. N_{err} here is the number of defective goods of a particular type detected during inspection. Parameter N_{com} specifies a total number of such products. This justifies the application of methods associated with this type of distribution, relative to the defect percentage magnitudes ω, obtained in the course of observations at previous sites of MPC operation (defects, failures).

Event E can be regarded as a simultaneous occurrence of two events. The first is when the defect percentage ω of specific MPC from the entire totality N_{com} does not exceed some value $\omega_{max}(\omega \le \omega_{max})$. The second comes down to selecting MPC from the totality $N_{com} - N_{err}(\omega_{max})$ of well-functioning devices. The second event is dependent on the first one and occurs in the case of its emergence. Then, in accordance with the rule of finding the probability of occurrence of dependent events:

$$P(E) = P(\omega \le \omega_{max}) \times P_{\omega \le \omega_{max}} (ll \in LL_{ij}^e). \tag{1}$$

Given that, from all N_{com} possible outcomes of choosing MPC, a workable controller is matched with $N_{com} - N_{err}$ results, then, according to the classical determining of probability, conditional probability $P_{\omega \le \omega_{max}} (ll \in LL_{ij}^e)$ is determined as:

$$P_{\omega \le \omega_{max}} (ll \in LL_{ij}^e) = \frac{N_{com} - N_{err}^{max}}{N_{com}} = 1 - \frac{N_{err}^{max}}{N_{com}} = 1 - \frac{\omega_{max}}{100\,\%}, \tag{2}$$

where N_{err}^{max} is the absolute number of defective MPC that corresponds to magnitude ω_{max}.

Thus, formula (1) takes the following form:

$$P(E) = P(\omega \le \omega_{max}) \times \left(1 - \frac{\omega_{max}}{100\,\%} \right) =$$
$$= \frac{P(\omega \le \omega_{max}) \times (100\,\% - \omega_{max})}{100\,\%}. \tag{3}$$

Thus, as follows from expression (3), the probability P(E) is a function of parameter ω_{max}, determining which is actually what the problem of forecasting comes down to.

Given the fact that the percentage of defects cannot be negative, it is possible to perform the following equivalent transformations over interval $\omega \le \omega_{max}$:

$$(\omega \le \omega_{max}) \equiv (0 \le \omega \le \omega_{max}) \equiv (\omega_o - \Delta\omega = 0 \le \omega \le \omega_o + \Delta\omega = \omega_{max}) \equiv$$
$$\equiv (-\Delta\omega \le \omega - \omega_o \le +\Delta\omega). \tag{4}$$

The values of magnitudes ω_o and $\Delta\omega$ are determined from the following system of equations:

$$\begin{cases} \omega_o - \Delta\omega = 0; \\ \omega_o + \Delta\omega = \omega_{max}; \end{cases} \rightarrow \begin{cases} \omega_o = \Delta\omega; \\ 2\Delta\omega = \omega_{max}; \end{cases} \rightarrow \omega_o = \Delta\omega = \frac{\omega_{max}}{2}. \quad (5)$$

According to formula (4), there has to be equality:

$$P(\omega \leq \omega_{max}) = P(-\Delta\omega \leq \omega - \omega_o \leq +\Delta\omega),$$

that justifies determining the confidence probabilities and confidence intervals to compute the given probability and value ω_{max}. Taking into account result (5), the value of $P(\omega \leq \omega_{max})$ is determined through the integrals of probability and Laplace:

$$P(\omega \leq \omega_{max}) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\frac{\omega_{max}}{2}}^{+\frac{\omega_{max}}{2}} e^{\frac{\left(\omega - \frac{\omega_{max}}{2}\right)^2}{2\sigma^2}} d\left(\omega - \frac{\omega_{max}}{2}\right) =$$

$$= \sqrt{\frac{2}{\pi}} \int_0^{\chi} e^{\frac{\chi^2}{2}} d\chi = 2\Phi(\chi), \quad (6)$$

where σ is the root-mean-square deviation (RMSD) of random magnitude ω;

$$\chi = \frac{\omega - \frac{\omega_{max}}{2}}{\sigma} = \frac{2\omega - \omega_{max}}{2\sigma}.$$

is the parameter that interprets a probability integral into the Laplace integral; $\Phi(\chi)$ is the Laplace function (integral).

At the known value of RMSD σ, one can determine probability $P(\omega \leq \omega_{max})$ at the assigned valid ω_{max} or vice versa – the value of ω_{max} at the assigned permissible (confidence) probability $P(\omega \leq \omega_{max})$ by the reference data that determine the value of function $\Phi(\chi)$ in any point χ.

However, in most cases, the magnitude σ is not known, and its calculation is impossible because of missing data on the specific values of distribution function of random magnitudes ω. In order to solve this problem, according to the classical theory of errors, one can employ the method of maximum likelihood and the Bessel formula, according to which the magnitude σ is replaced with the mean value of selective standard s_{mean}, which is its approximated value:

$$\sigma \rightarrow s_{mean} = \sqrt{\frac{1}{\rho(\rho-1)} \sum_{h=1}^{\rho} \left(\omega_{jh} - \omega_{mean}\right)^2},$$

$$\omega_{mean} = \frac{1}{\rho} \sum_{h=1}^{\rho} \omega_{jh}, \quad (7)$$

where ω_{mean} is the mean value of parameter ω_{jh} – the point estimation of this parameter; ρ is the number of observations of magnitude ω_{jh} (experimental objects of transport infrastructure where statistical data are collected).

Results (1)–(7) with a certain modification for use under conditions of limited statistical data, which is the process of research, laid the foundation for the developed method for the prediction of technical condition.

5. Results of development of a method for the prediction of technical condition

5. 1. The method of prediction for a separate class of equivalence

Direct application of formulas (6) and (7) is limited by a number of factors. Decisive among these is the shortage of statistical data, as well as a probable uneven accuracy of observations for each object. Though uneven accuracy is related to the types of MPC that are close in characteristics, but they are not quite identical. It is also affected by differences in the technology of operation, which could lead to different manifestations of a defect.

Solving the first problem is achieved by using the Student distribution, widely applied in the statistics of small samples (microstatistics). Based on formulas of the Student distribution [10], and taking into account expressions (5)–(7) and accepted assumptions (in particular, $\sigma \rightarrow s_{mean}$), it is possible to write the following intermediate value of probability:

$$P(\omega \leq \omega_{\textbf{p}max}) = P\left(-t \leq u = \frac{\omega_{mean} - \frac{\omega_{max}}{2}}{s_{cp}^p} \leq +t\right) =$$

$$= P\left(-t_p s_{mean} \leq \omega_{mean} - \frac{\omega_{max}}{2} \leq +t_p s_{mean}\right) =$$

$$= P\left(\omega_{mean} - t_p s_{mean} \leq \frac{\omega_{max}}{2} \leq \omega_{mean} + t_p s_{mean}\right) =$$

$$= P\left(2\omega_{mean} - 2t_p s_{mean} \leq \omega_{max} \leq 2\omega_{mean} + 2t_p s_{mean}\right) =$$

$$= \int_{-t_p}^{+t_p} \left[\frac{\Gamma\left(\frac{\kappa+1}{2}\right)}{\sqrt{\pi\kappa}\Gamma\left(\frac{\kappa}{2}\right)}\left(1 + \frac{u^2}{\kappa}\right)\right] du =$$

$$= 2\int_{0}^{+t_p} \left[\frac{\Gamma\left(\frac{\kappa+1}{2}\right)}{\sqrt{\pi\kappa}\Gamma\left(\frac{\kappa}{2}\right)}\left(1 + \frac{u^2}{\kappa}\right)\right] du = S(t_p, \kappa), \quad (8)$$

where $\Gamma(z) = \int_0^{+\infty} e^{-x} x^{z-1} dx$ is the gamma function: the Euler integral of the second kind (x=Re(z)>0); $\kappa = \rho - 1$ is the Student coefficient, which determines the number of degrees of freedom for the eponymous distribution.

The values of the Student function $S(t_p, \kappa)$ are determined at different values of parameters t_p and κ using the reference tables [10]. The function determines the probability that a deviation of the arithmetic mean value of defect percentage ω_{mean} from the true value ω does not exceed $\Delta_p = t_p s_{mean}$. In this case, as follows from expression (8), this function also determines the probability of finding permissible defect percentage over some interval

$$\omega_{max} \in [2\omega_{mean} - 2t_p s_{mean}; 2\omega_{mean} + 2t_p s_{mean}],$$

whose separate elements, as shown below, can be less than zero. Considering that the defect percentage cannot be negative, a negative value of parameter ω_{max} is impossible, that is $P(\omega_{max}<0)=0$. Therefore, taking into account possible loss of coverage of segment $[0; 2\omega_{cp}-2t_p s_{mean}]$, which is possible only at $2\omega_{cp}-2t_p s_{cp} \geq 0$, provided the permissible defect value

is at the level of $\omega_{max}=2\omega_{mean}+2t_p s_{mean}$, we can assume that probability $S(t_p, \kappa) \leq P(\omega < \omega_{max})$, hence, it follows:

$$P(E') = P(E) - P(\Delta E) = P(\omega_{min} \leq \omega \leq \omega_{max}) \times$$
$$\times P_{\omega_{min} \leq \omega \leq \omega_{max}}(ll \in LL_{ij}^e) \leq P(E), \qquad (9)$$

where ΔE is the event that implies that the defect percentage of MPC of the appropriate type matches the interval $[0; \omega_{min}]$, is incompatible with the event E': $P(\Delta E)=P(\omega < \omega_{min})$; $\omega_{min}=2\omega_{mean}-2t_p s_{mean}$ is the conditional minimum estimated value of parameter ω.

According to the obtained inequality, it is possible to use, instead of the probability $P(E)$, the probability $P(E')$, which is not larger than that. Then the acceptable value of $P(E')$ enhances the result of prediction. In this case, possible loss of values on the probability $P(\Delta E)$ is the cost of using microstatistics. Here, in the case when $\omega_{min}<0$, true is the expression $P(\Delta E)=P(\omega_{min}<0)=0$, which implies: $P(E')\Delta_{E=\{\omega_{min}<0\}} = =P(E)$. That is, the accuracy of prediction improves; in this case, the appropriate indicators of probability get better.

To resolve the second problem related to the uneven accuracy of observations, it is possible to use the weighing method proposed in article [10].

The method implies that each observation is assigned with its weight, which is an integer. The least reliable observations receive the least weight while others are assigned with the weight depending on the accuracy of observations. In this case, weight m_{jh} is regarded as a multiplication of an observation, that is, it is considered that an observation with weight m_{jh} is equivalent to m_{jh} observations with a unit weight, which corresponds to the reduction in the mean error by $\sqrt{m_{jh}}$ times. In this case, the corresponding expressions in formula (9) for ω_{mean} and s_{mean} take the following form:

$$\omega_{mean} = \frac{1}{\sum_{h=1}^{\kappa+1} m_{jh}} \sum_{h=1}^{\kappa+1}\left[m_{jh}\left(\omega_{jh}-a\right)\right]+a, \qquad (10)$$

$$s_{mean} =$$
$$= \sqrt{\frac{1}{\kappa(\kappa+1)}\left\{\sum_{h=1}^{\kappa+1}m_{jh}\left(\omega_{jh}-a\right)^2 - \frac{1}{\sum_{h=1}^{\kappa+1}m_{jh}}\left[\sum_{h=1}^{\kappa+1}\left(\omega_{jh}-a\right)\right]^2\right\}}, \quad (11)$$

where a is an arbitrary number, similar in value to ω_{mean}, determined according to (6).

By combining formulas (3), (5)–(11), it is possible to obtain the following expression for finding the probability $P(E')$:

$$P(E') = 4\left(\frac{\sum_{h=1}^{\kappa+1}m_{jh}\left(\omega_{jh}-a\right)}{\sum_{h=1}^{\kappa+1}m_{jh}} + \sqrt{\frac{1}{\kappa(\kappa+1)}\left\{\sum_{h=1}^{\kappa+1}m_{jh}\left(\omega_{jh}-a\right)^2 - \frac{1}{\sum_{h=1}^{\kappa+1}m_{jh}}\left[\sum_{h=1}^{\kappa+1}\left(\omega_{jh}-a\right)\right]^2\right\}}+a\right)\times$$

$$\times\int_0^{+t_p}\frac{\left(t_p-\kappa\right)\Gamma\left(\frac{\kappa+1}{2}\right)\sqrt{\frac{1}{\kappa(\kappa+1)}\left\{\sum_{h=1}^{\kappa+1}m_{jh}\left(\omega_{jh}-a\right)^2 - \frac{1}{\sum_{h=1}^{\kappa+1}m_{jh}}\left[\sum_{h=1}^{\kappa+1}\left(\omega_{jh}-a\right)\right]^2\right\}}}{\kappa\sqrt{\pi\kappa\Gamma\left(\frac{\kappa}{2}\right)}}dt_p. \qquad (12)$$

Given that parameters κ, m_{jh}, ω_{jh} and a do not depend on t_p, it is possible to displace the appropriate constant part beyond the sign of integral in equation (12). Upon computing integral

$$\int_0^{+t_p}\left(t_p-\kappa\right)dt_p = \int_0^{+t_p}t_p\,dt_p - \kappa\int_0^{+t_p}dt_p = \frac{t_p^2}{2}-\kappa t_p = t_p\left(\frac{t_p}{2}-\kappa\right),$$

accepting in this case

$$a = \frac{1}{\kappa+1}\sum_{h=1}^{\kappa+1}m_{jh},$$

expression (12) for determining $P(E')$ is written as follows:

$$P(E') = \frac{4\kappa^2 t_p\left(\frac{t_p}{2}-\kappa\right)\Gamma\left(\frac{\kappa+1}{2}\right)}{\sqrt{\pi(\kappa+1)\Gamma\left(\frac{\kappa}{2}\right)}}\times$$

$$\times\sqrt{\frac{\left(\sum_{h=1}^{\kappa+1}m_{jh}\right)^2\sum_{h=1}^{\kappa+1}m_{jh}\left(\omega_{jh}-\frac{\sum_{h=1}^{\kappa+1}m_{jh}}{\kappa+1}\right)^2 - \left[\sum_{h=1}^{\kappa+1}\left(\omega_{jh}-\frac{\sum_{h=1}^{\kappa+1}m_{jh}}{\kappa+1}\right)\right]^2}{\sum_{h=1}^{\kappa+1}m_{jh}}}\times$$

$$\times\left(\frac{\sum_{h=1}^{\kappa+1}m_{jh}\left(\omega_{jh}-\frac{\sum_{h=1}^{\kappa+1}m_{jh}}{\kappa+1}\right)}{\sum_{h=1}^{\kappa+1}m_{jh}} + \right.$$
$$+ \sqrt{\frac{\left(\sum_{h=1}^{\kappa+1}m_{jh}\right)^2\sum_{h=1}^{\kappa+1}m_{jh}\left(\omega_{jh}-\frac{\sum_{h=1}^{\kappa+1}m_{jh}}{\kappa+1}\right)^2 - \left[\sum_{h=1}^{\kappa+1}\left(\omega_{jh}-\frac{\sum_{h=1}^{\kappa+1}m_{jh}}{\kappa+1}\right)\right]^2}{\kappa(\kappa+1)\sum_{h=1}^{\kappa+1}m_{jh}}} +$$
$$\left.+ \frac{\sum_{h=1}^{\kappa+1}m_{jh}}{\kappa+1}\right). \qquad (13)$$

Direct computation of $P(E')$ using the obtained formula is cumbersome and requires determining in advance the Euler integral of the second kind. It is therefore more appropriate to indirectly determine this integral based on tables of values of functions $S(t_p, \kappa)$, given in article [10], which is multiplied by value

$$P_{\omega_{min} \leq \omega \leq \omega_{max}}(ll \in LL_{ij}^e)$$

according to formulas (1), (3). Preliminary, in this case, parameters ω_{max}, ω_{mean} and s_{mean} are found by formulas (8), (10) and (11).

Determining the weight coefficients of m_{jh} can be conduct-

ed by any acceptable method, in particular, by the method of expert estimations.

In this case, the value of function $S(t_p, \kappa)$ is determined according to Table 1 [10].

Table 1

Tabulated values of function $S(t_p, \kappa)$

t_p	Values of $S(t_p, \kappa)$ at values of κ					
	1	2	3	4	7	11
0.1	0.063	0.071	0.073	0.075	0.078	0.07966
0.2	0.126	0.140	0.146	0.149	0.155	0.15852
0.5	0.295	0.333	0.349	0.356	0.373	0.38292
1.0	0.500	0.577	0.609	0.626	0.661	0.68269
2.0	0.705	0.817	0.861	0.884	0.926	0.95450
3.0	0.795	0.905	0.942	0.960	0.988	0.99730
5.0	0.874	0.962	0.985	0.992	0.999	0.99999

Computed directly by formula (13) or indirectly by formulas (9)–(12), the value of P(E') preliminary determines the reliability of test-diagnostic studies (laboratory or performance tests, testing of dependences, etc.) relative to the entire respective set L_i.

5. 2. Generalization of results of the prediction over a full set of control system equipment

By applying formula (13), we determine the value of probability of the absence of defective MPC within the same equivalence class. However, these values are not sufficient in terms of dissemination of the results over other samples that are included in the composition of other classes. In addition, the value of probability may prove to be insufficient from the point of view of the possibilities of operating a system under specific technical conditions.

Solving the problem is to conduct several cycles of studies within the framework of prediction over various MPC of a certain group by the same technique. For this purpose, for each cycle, we select an individual system of representatives, equivalent to the rest.

In order to disseminate research results, it is enough when at least one examined sample of MPC belongs to a class of equivalence (it had no defects). Events that imply simultaneous choosing a few representatives are independent, and the choice of at least one MPC without defects is the combination of the given events. Then, in accordance with the formula of finding the probability of combination of a finite number of independent events, total probability $P(E_{com})$ of the correct distribution of results of the observations over the entire batch will reach [10]:

$$P(E_{com}) = P\left(\bigcup_{k=1}^{n} E_k\right) = \sum_{k=1}^{n} P(E_k) - \sum_{1 \leq i < j \leq n} P(E_i \cap E_j) +$$

$$+ \sum_{1 \leq i < j < k \leq n} P(E_i \cap E_j \cap E_k) - \dots + (-1)^{n+1} P(E_1 \cap E_2 \cap E_3 \cap \dots \cap E_n), \quad (14)$$

where n is the number of testing cycles and the corresponding systems of MPC representatives; E_1, E_2,..., E_n are the events that imply selecting a system of representatives without defects.

According to the properties of independent events and previous considerations on the random selection of MPC, events E_1, E_2,..., E_n are equiprobable [10]:

$$P(E_1) = P(E_2) = P(E_3) = \dots = P(E_n) = P(E), \quad (15)$$

hence, the following form of formula (14) for this case:

$$P(E_{com}) = C_n^1 P^1(E) - C_n^2 P^2(E) +$$

$$+ C_n^3 P^3(E) - \dots + (-1)^{n+1} C_n^n P^n = \sum_{k=1}^{n} (-1)^{k+1} C_n^k P^k(E). \quad (16)$$

When deriving the formula (16), we considered the rule of finding a probability of the intersection of independent events:

$$P\left(\bigcap_{k=1}^{n} E_k\right) = \prod_{k=1}^{n} P(E_k), \ [10].$$

In addition to probabilities $P_j(E_{com}) = P(E_{com}^j)$, for separate types of MPC, very important is also the probability $P(D_{com})$, which implies the absence of defects in the entire chosen system of representatives. Events that imply the selection of representatives from different groups are independent, which is why

$$D_{com} = \bigcap_{j=1}^{m} E_{com}^j,$$

hence, it follows

$$P(D_{com}) = \prod_{j=1}^{m} P_j(E_{com}),$$

where m is the number of groups of MPC.

Thus, by generalizing the data obtained for a control system to all similar systems, we can assume that the probability $P(D_{com})$ in a general case depends on each value of $P_j(E_{com})$, the number of groups m and the number of testing-diagnostic cycles n and, according to formula (16), it is determined as [10]:

$$P(D_{com}) = \prod_{j=1}^{m} \sum_{k=1}^{n} (-1)^{k+1} C_n^k P_j^k(E) =$$

$$= \sum_{k=1}^{n} \left[(-1)^{k+1} C_n^k \prod_{j=1}^{m} P_j^k(E) \right] = \sum_{k=1}^{n} \left[(-1)^{k+1} C_n^k P^k(D) \right], \quad (17)$$

where D is the absence of any defective MPC per one cycle.

When comparing the last expressions in formulas (16) and (17), one observes their isomorphism relative to the operations over variables P(X), where X=E∨D. Note the equality that follows from equality (15):

$$P(D) = P(D_1) = P(D_2) = P(D_3) = \dots = P(D_n) = \sum_{k=1}^{n} \prod_{j=1}^{m} P_j(E),$$

where D_1, D_2, ..., D_n are the events that imply choosing appropriate systems of representatives for different appropriate testing cycles; $P_j(E)$ is the probability of choosing a defect-free MPC from the j-th group.

Then the character of dependence $P(X_{com}) = f[P(X), n]$, where $X_{com} = E_{com} \vee D_{com}$ is the same for X=E and X=D, that is, determined by the resulting P(X) only (Fig. 1).

The graph in Fig. 1 determines the values of parameters $P(E_{com})$, $P(D_{com})$. They do not depend on the technique used to obtain corresponding initial parameters P(E) or P(D). Therefore, the graph is the generalization of the prediction

procedure on any systems of control with an arbitrary character of the distribution of random magnitudes, similar to ω.
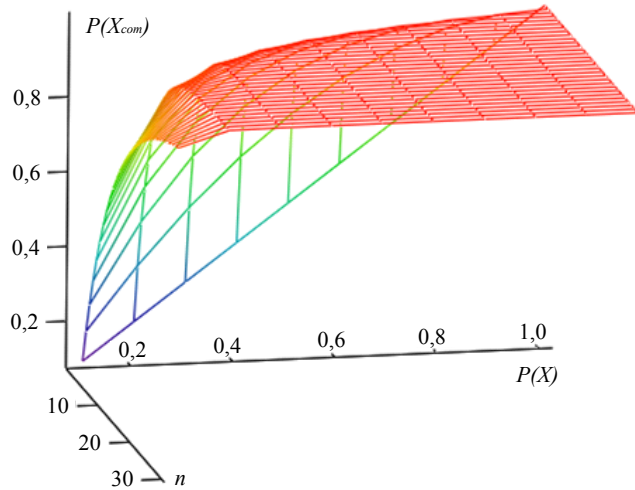

Fig. 1. Surface graph of dependence of P(X$_{com}$) on the values of P(x) and n

It follows from Fig. 1 that even at insignificant probabilities P(X) with sufficient values of the number of testing-diagnostic cycles, the resultant reliability of prediction P(X$_{com}$) reaches rather high values (over 90 %). Given this, we can draw a conclusion about the universality of the proposed method for all control systems in railway automation.

5. 3. Example of using the method of prediction for microprocessor centralization

A successful application of the developed method was used for the system of microprocessor centralization MPC-S. Statistical data on which the present study is based are limited by the observations at four railway stations. Relevant data on MPC defects of five types are given in Table 2 [27].

It follows from Table 2 that the modules of input and output 1 did not demonstrate any defects during operation. This can be explained by limited batches of making these devices and the minimization of error during output control related to it. Excluding the given errors for the i/o modules (that is assuming a 100 % probability of detecting the defects during examination), they will not be considered in subsequent research.

For determining the weight coefficients m$_{jh}$ in formula (13) in accordance with Table 2, we conducted expert assessment among competent specialists from the enterprise that designed the system MPC-S. The result is the established values of coefficients for various MPC at the stations given in Table 2 [27]

$$\left\| m_{jh} \right\| = \begin{Vmatrix} m_{11}=3 & m_{12}=1 & m_{13}=4 & m_{14}=2 \\ m_{21}=2 & m_{22}=1 & m_{23}=3 & m_{24}=1 \\ m_{31}=4 & m_{32}=2 & m_{33}=4 & m_{34}=2 \end{Vmatrix}.$$

Evaluation of weight parameters is performed by means of a questionnaire survey among fifteen experts with equal influence using a five-point scale.

The calculation of probability P(E') for the hardware of the system MPC-S using the data given in Table 2 was performed in software application E (applied programming environment MathCAD 15). In this case, the values of function $S\left(t_p,\kappa\right)$ are determined according to Table 1.

The values of parameters that determine the accuracy of distribution of experimental data for three types of MPC over the entire examined set (within a station), computed by the software, are given in Table 3.

As follows from calculation results, all values of ω$_{min}$ are negative. Therefore, in accordance with calculations under formula (9), in this case, P(E')=P(E).

According to expression (16), based on consolidated data in Table 3, Fig. 2 shows constructed graphs of dependence of probability P(E$_{com}$) depending on the number of diagnostic tests. They take into account appropriate parameters for the three types of controllers, given in Tables 2, 3.

Table 2

Data on MPC defects detected during experimental operation of the system MPC-S

No. j	Type of MPC	Quantitative characterisitcs	Number h and name of the station			
			1	2	3	4
			Post Pivdenny	Napivgirky	Peredacha-Donetsk	Tranzitna
1	Traffic light controller	Quantity	58	23	54	18
		Quantity of defects	1	1	1	0
		Defect percentage	1.72 %	4.35 %	1.86 %	0 %
2	Switch controller	Quantity	19	10	31	10
		Quantity of defects	0	0	1	0
		Defect percentage	0 %	0 %	3.23 %	0 %
3	Controller of rail pickups (RP)	Quantity	98	50	130	42
		Quantity of defects	2	1	3	1
		Defect percentage	1.04 %	2.0 %	2.31 %	2.38 %
4	Input controller	Quantity	2	2	6	2
		Quantity of defects	0	0	0	0
		Defect percentage	0 %	0 %	0 %	0 %
5	Output controller	Quantity	2	2	6	2
		Quantity of defects	0	0	0	0
		Defect percentage	0 %	0 %	0 %	0 %

Table 3

Results of computation of parameters for predicting the equipment of the system MPC-S

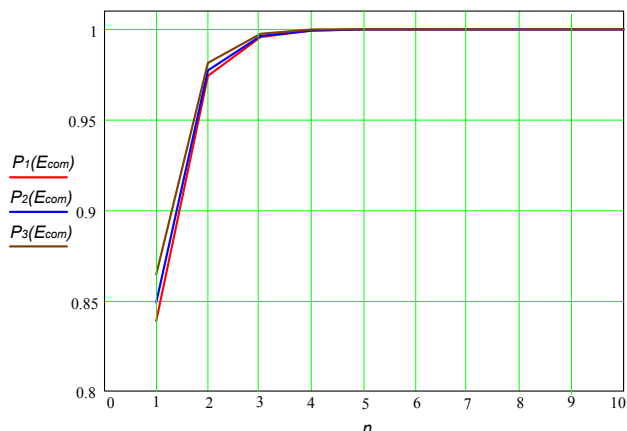| Type of MPC	Intermediate and final parameters of prediction							
	ω_{mean}	s_{mean}	t_p	ω_{max}	ω_{min}	$S(t_p,\kappa)$	$P(E')$	$P_\%(E')$
Traffic lights	1.695	1.257	3	10.931	−4.151	0.942	0.839	83.903
Switches	1.384	1.183	3	9.866	−4.329	0.942	0.849	84.906
RP	2.180	0.789	5	12.249	−3.529	0.985	0.864	86.435

Fig. 2. Dependences of $P(E_{com})$ on the number of testing cycles of the system MPC-S

In Fig. 2, probabilities $P_1(E_{com})$, $P_2(E_{com})$, $P_3(E_{com})$ define the accuracy of prediction for MPC of traffic lights, switches and RP, respectively.

It directly follows from matching the graphs in Fig. 1, 2 that the reliability of forecasting improves with the number of diagnostic tests.

Similarly, it is possible to apply the developed method for other devices in railway automation. It is also possible to use given method in related fields of industrial automation.

6. Discussion of the proposed method for prediction

Based on results of the present study, the developed and proposed method for the prediction establishes the following basic implementation procedures:

1. Direct application of formulas (9)−(13) and Table 1 to assess a statistical probability of failure (defect) among MPC that are included in a certain class of equivalence under conditions of limited statistical data on the reliability of operation.

2. The use of the combined approach. It implies certain experimental research (laboratory, operational) into MPC of a certain class of equivalence. Under conditions of such experiments, one determines and takes into account a probability of authenticity of the examined system of MPC representatives to the functional and workable elements. This probability is computed using formulas (14)−(17) and the graphic dependence related to them, shown in Fig. 1.

A significant disadvantage of the first variant is the excessive forced understatement of static parameters of MPC reliability, formed as initial data. Accordingly, the result of prediction may prove to be worse than the actual state of microelectronic equipment. Calculated reliability indicators will be lower than those regulated by technical specifications. In this case, the results obtained cannot substantiate operational working ability of respective MPC. The

indicated shortcoming is leveled off by the second variant, which, however, requires additional measures and special equipment to conduct experimental research (testing-diagnostic impacts). Thus, if the first variant of using the method should be considered solely as the estimated calculation, then the second variant – as the calculation-experimental. When employing the method, a significant limitation should be noted. It implies direct application of formulas (14)−(17) only under conditions of 100 percent positive results of experimental research. This is possible only when the research results confirm the stated reliability of the system of MPC representatives. Otherwise, it is necessary to establish additional correction whose scientifically substantiated determining requires a separate study.

In contrast to the drawbacks and limitations specified, the proposed method allows us to operate with minimal statistical data on the operation of microelectronic control systems. This was not possible when applying the previous methods. This, in the course of further improvement, will make it possible to widely use it in the technology of maintenance and repair of advanced systems of railway automation.

7. Conclusions

1. We defined a criteria, which is used to predict a technical condition of microprocessor devices in railway automation. We established as such a criterion determining the probability of manifestation of production defect or other failure of a microprocessor controller or a group of controllers that are operated as part of a particular control system. From a formalized point of view, the specified criteria is interpreted as a violation of equivalence relation by the faulty device to other identical devices of the corresponding class. The indicated principle allowed us to reduce the prediction procedure to a probabilistic assessment of the violation of integrity of the equivalence class of a particular type of controllers. This is achieved using a structural-functional attribute.

2. We substantiated the apparatus of mathematical statistics to process results under conditions of limited data. By applying a Lyapunov theorem, we justified expediency of employing the methods of unevenly accurate observations, maximal likelihood and the Student spread. The latter allows us to process microstatistical data when performing a probabilistic evaluation of the manifestation of a defect in controllers.

3. Mathematical models are constructed that implement the developed method of prediction in two variations. The first of these is based on the direct use of microstatistics. The second is based on its combination with additional experimental studies conducted in the course of implementation of forecasting.

4. Based on the developed models, we established common regularities in the application of the devised method.

The patterns hold both for the controllers of a separate class and for the systems of representatives of all equivalence classes of the entire set of micro-electronic equipment. The patterns were represented both analytically and graphically. These dependences make it possible to unify the approaches to single or multiple predictions when using the proposed method of forecasting.

Thus, we developed and proposed the method to predict technical condition of microelectronic equipment of railway automation that can be applied under conditions of limited statistical data on its operation at the infrastructure sites.

It should be noted that the developed method has some drawbacks and limitations. The drawbacks are associated primarily with the forced understatement of original operational reliability indicators of the examined equipment. Therefore, a subsequent complex of studies is required aimed at improving processing of microstatistic data. Based on this, promising are the appropriate modifications of the method for different microelectronic systems of railway automation.

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Обґрунтовується ефективність використання скремблерів в вузькосмугових системах зв'язку, що працюють в умовах низького відношення сигнал/завада. Оцінюється вплив кількості та порядку перестановки смуг на залишкову розбірливість скрембльованого сигналу. Досліджується стійкість скрембльованого сигналу до злому. Наводяться практичні рекомендації щодо розробки смугових скремблерів, що реалізують цифрову обробку мовних сигналів з використанням алгоритму швидкого перетворення Фур'є з ковзаючим вікном

Ключові слова: скремблювання, смуговий скремблер, швидке перетворення Фур'є, ковзаюче вікно, залишкова розбірливість

Обосновывается эффективность использования скремблеров в узкополосных системах связи, работающих в условиях низкого отношения сигнал/помеха. Оценивается влияние количества и порядка перестановки полос на остаточную разборчивость скремблированного сигнала. Исследуется устойчивость скремблированного сигнала к взлому. Приводятся практические рекомендации по разработке полосовых скремблеров, реализующих цифровую обработку речевых сигналов с использованием алгоритма быстрого преобразования Фурье со скользящим окном

Ключевые слова: скремблирование, полосовой скремблер, быстрое преобразование Фурье, скользящее окно, остаточная разборчивость

RESEARCH INTO THE USE OF SCRAMBLERS IN NARROWBAND COMMUNICATION SYSTEMS

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1. Introduction

Along with the development of computer technologies, methods and means for transmission of information, approaches to ensure information security are also being developed. Operation of information security systems which provide protection of transmitted voice messages is based on converting speech signal characteristics. As the result, the speech becomes unintelligible to eavesdroppers after interception of such messages.

Among the variety of voice communication systems narrowband systems occupy a special place. Due to the narrow bandwidth of individual channels the rational use of radio-frequency resource is achieved. These systems are characterized by low requirements to stability of communication channel characteristics and low-cost of equipment. Examples of narrowband communication systems are

general- and special-purpose wired telephone lines as well as special, operational-technological and amateur radio systems up to the VHF band. In such systems, along with the requirements of reliability and efficiency, issues of the information transmission security are also of importance.

There are two basic methods of converting speech signals for the purpose of protection against tapping: scrambling and digital encryption [1–5]. The main difference between scrambling and digital encryption is that scramblers are converting the frequency-time characteristics of the original analog speech signal transmitted over the communication channel. The signal after scrambling occupies the same frequency band as the original one. On the contrary, digital encryption devices are encoding bit sequence that is transmitted over the communication channel and determines the samples of the original speech signal [2, 5].