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DEVELOPMENT OF A DEVICE FOR THE OPTIMAL RECEPTION OF SIGNALS AGAINST THE BACKGROUND OF AN ADDITIVE THREE-COMPONENT INTERFERENCE

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Синтезовано оптимальний приймач кодових сигналів автоматичної локомотивної сигналізації. Сигнали спостерігаються на тлі адитивної трикомпонентної завади. Перша компонента завади – імпульсна, друга компонента – неперервна синусоїдна завада від лінії електропередач, третя компонента – гаусівський шум. В приймачі реалізовано метод сумісної оцінки параметрів сигналу та структурно детермінованих завад. Запропонований метод є гнучким до зміни параметрів завад. Рішення про вид прийнятого кодового сигналу приймається за критерієм мінімуму середнього квадрату похибки апроксимації. Під похибкою апроксимації мається на увазі різниця між величиною суми сигналу та структурно детермінованих компонент завади та величиною всієї напруги на вході приймача. На базі реалістичних припущень про статистичні взаємозв'язки сигналу та компонент завади показано: цільова функція являє собою взяту із зворотним знаком суму ізольованих логарифмів відношень правдоподібності та поправочних функцій. Дослідження були направлені перш за все на вивчення можливості ослаблення впливу структурно детермінованих завад. В підсумку розроблений пристрій здатен оперативно реагувати на зміни параметрів таких завад. Показано принципову можливість побудови оптимального приймача за модульним принципом. При цьому модулі можуть підключатися та відключатися відповідно до апріорно визначеного складу комплексу завад, а «бібліотека» модулів може поповнюватися по появі нових видів завад. Шляхом комп'ютерного моделювання показано, що в каналі, який відповідає формуванню вірного рішення, величина похибки апроксимації приблизно в 6 разів менше, ніж в інших двох каналах. Це співвідношення залишається справедливим, коли амплітуди імпульсної завади та завади від лінії електропередач мають багаторазову перевагу над амплітудою кодового сигналу. Розроблений пристрій забезпечує високу завадостійкість розрізнення коддових сигналів у широкому діапазоні параметрів завад. Це дозволить підвищити безпеку руху і точність дотримання графіка руху поїздів

Ключові слова: структурно детермінована завада, кодовий сигнал, оптимальне розрізнення, багатоекстремальна цільова функція

1. Introduction

Current communication systems operate under increasingly complex electromagnetic environment. This environment is formed due to the working and side emissions from third-party radio-electronic devices and technological installations. The number of such devices and installations has been steadily increasing over time. A series of natural processes is also accompanied by the formation of disturbing electromagnetic radiation. The undesired electromagnetic processes can also occur within communication systems. Typical causes are the uncontrolled fluctuations in the parameters of communication channels. The impact of listed factors is a prerequisite for a relative increase in the number of errors that a recipient makes while recognizing the received information signals. Such an increase may prove particularly unacceptable where a communication system is integrated into the overall system of a technological process safety system. The described situation occurs specifically during railroad transportation in the technological communication systems and subsystems that transfer signals from railroad automatics. As the saturation of industries, transport, and even households, with such integrated systems grows, solving the tasks on noise-resistant receival of information signals becomes increasingly relevant.

2. Literature review and problem statement

Decreasing the influence of multicomponent interference on the results of reception of information signals has attracted undiminished attention of specialists. Paper [1] reports results of synthesizing a device for the optimal signal reception against a two-component interference. The proposed processing method is based on the assumption about a noisy nature of the interference's both components. Therefore, a given method is not optimal in situations when one or several components of an interference are structurally deterministic. Study [2] presents a method for the noise-free reception in a communication channel with a multibeam signal propagation. The components of an interference here are the copies of the useful signal that arrive at a receiver, each with a particular delay. Such a type of interference is typical for a narrow class of hydroacoustic systems of communication, which is why the proposed method has a very limited scope of application. Suppression of multi-component interference by using an additional phase information was considered in [3]. The information is acquired from the polynomial approximation of noise phase dependence on time. Since only a single parameter is actually adjusted in a receiving device, the scope of application of this method is also very limited. Investigating a case of the spatial dispersion of interference sources was addressed in paper [4]. The additional information that helps reduce the level of interference is obtained by estimating the spatial arrangement of the sources of these disturbances. The proposed method cannot ensure maximum noise immunity, since the procedure of spatial localization of the sources, which it employs, is artificially introduced to it as an additional processing stage. This procedure is not a consequence of formal synthesis of the optimal receiver. It should be noted that all the proposed methods for optimum noise-immune reception are based on different modifications of the correlation method for processing the signal-interfering mixture. A possibility to improve the optimum receiver that performs classic correlation processing was considered in study [5]. The structure of the correlator was introduced with significant technical improvements. However, the receiver in general did not undergo a set of interrelated improvements. Correlation processing of the input mixture of signal and noise was proposed in paper [6] only as an auxiliary tool to reject unreliable raw data. The use of correlation processing, described in work [7], focuses only on solving a specialized task on evaluating a delay among signals received from the spatially-distributed sensors. The cross-correlational process also underlies a primary signal processing method, discussed in paper [8]. However, it helped resolve a rather specific task on suppressing the interference from local reflectors, similar in type with the signal. In study [9], a model of interference is limited by Gaussian noise only.

The complexity of current electromagnetic environment implies that the types and parameters of noise can vary over short time intervals. The duration of these intervals is practically commensurate to the duration of an information signal. In communication systems that ensure the safety of railroad traffic every such signal has a considerable informational value. Therefore, an optimal receiver must generate a solution for each successive signal. That means that the algorithm for optimized processing must be built based on such computational and logical structures that would enable the rapid formation of the above-specified solution. It was proposed earlier in work [10] to use, for the optimal detection and recognition of signals from automated locomotive signaling system, a method that implied a joint evaluation of signal and noise parameters. In addition, this work substantiated and constructed a mathematical model of the additive mixture of a signal and a three-component interference, describing a typical electromagnetic environment. Paper [11] showed that the use of this model when solving a task on the joint estimation of signal and noise parameters makes it possible to derive a rather compact expression for the mean square of approximation error. Here, an approximation error refers to the difference between the magnitude of sum of the signal and structurally deterministic interference components and the magnitude of total voltage at a receiver's input. The author of article [11] left the above expression in a very general form and confined himself to the proposal to search for the required estimates based on the criterion of a minimum of the mean square of an error. However, there are neglected mathematical and technical means that could be used to compute parameters' estimates and then recognize the information signals. The issue of minimizing the related computational and hardware costs has remained unresolved. Finally, there are no methods that would ensure addressing the situation of an arbitrary number of interferences.

In the target field of subsystems that transmit signals from railroad automatics along rail lines, the research and development of the specified systems were originally conducted, and are still performed, mainly by specialists in circuitry, as well as specialists in operation, who apply specific concepts and categories that have no direct equivalents to the concepts and categories in communication theory.

The research into the field of railroad automation signal reception along rail lines, undertaken in recent years [1, 9, 10], made it possible to estimate the probabilities of correct and incorrect solutions on the type of a received signal for each act of reception. However, it is still difficult to unambiguously compare the results with the characteristics of the systems that operate in railroad transportation.

Thus, the methods and means for suppressing multi-component interference, constructed up to now, contributed to addressing many tasks related to communication and automation. However, there are no identified results that would be applicable beyond the situation when disturbances are similar or when the number of disturbances does not exceed two. In this regard, it is of interest to consider a possibility to solve the problem on the optimal signal reception against the background of at least three different types of interference, which would ensure high noise immunity for the system of automatic locomotive signaling over a wide range of interference parameters.

3. The aim and objectives of the study

The aim of the research that we conducted was to synthesize the structure of a device for the optimal reception of signals, observed against the background of an additive three-component interference. In this case, the two components of an interference were the structurally deterministic oscillations of different type, while the third one was a wideband Gaussian noise.

To achieve the set aim, the following tasks have been solved:

– based on the predefined optimality criterion, to substantiate mathematically the objective function that corresponds to it; in this case, the objective function must be represented in the form that would provide for the lowest possible computational cost of its minimization;

– to determine the types and sequence of mathematical operations over the input signal that would match the above-specified criteria and objective function, as well as the composition of technical tools that implement these operations;

– to quantify the noise immunity of the designed device.

4. Synthesis of the structure for an optimum reception device

4. 1. Substantiation of the objective function

To further develop the above-described results reported in [10, 11], the present paper considers a method of the joint estimation of signal and interference parameters based on the criterion of a minimum mean square of approximation error. The objective function, constructed in study [11], takes a rather general form and needs further transformation to make its form computationally efficient.

Given the form of expressions that describe in work [10] the information signals and structurally deterministic interference, it can be assumed that the objective function is multi-extremal. The desired values of assessments in this case correspond to the position of the point of a global minimum in coordinate space. Finding this point is the task of global minimization. The number of unknown parameters in the problem under consideration is seven. It is known that solving a problem with such a dimensionality puts forward an unacceptably large requirements to random-access memory and computational power of a signal processing device [12]. However, resolving a multidimensional minimization problem can be technically implemented if the objective function is subjected to a procedure of the multi-step dimensionality reduction [12]. It is possible if for vector $\vec{X}$ of unknown parameters the objective function $F(\vec{X})$ can be represented in the following form:

$$F(\vec{X})=\sum_{i=1}^{N-1}F_i\left(x(i),x(i+1)\right), \quad (1)$$

where $F_i(...)$ are the two-dimensional functions; $x(i)$ are the components of vector $\vec{X}$.

Note that in this case one imposes a requirement that the numeric values for the components of vector $\vec{X}$ should belong to the singular N-dimensional cube $[0,1]^N$. Such a normalization of parameters is easily feasible in our case. Thus, first of all, we shall focus our efforts on transforming the expression, derived in article [11], which describes the average squared error, to form (1), that is to the sum of two-dimensional functions. By maintaining the terminology and notation adopted in article [11], we note that functions $H_A(...)$, $H_B(...)$, $G_A(...)$ and $G_B(...)$ violate the requirements imposed on the form of the objective function by expression (1). Can we make any assumptions acceptable from a practical point of view, and in so doing make it possible to comply with the specified requirements? To answer this question, we shall clarify the meaning of terms in a given expression within the theory of measurement of signals parameters. According to classic work [13], functions

$$W(U_{mP},\tau_P)=\sum_{k=1}^{K}v_{Pk}^2-2\sum_{k=1}^{K}u_k v_{Pk}, \quad (2)$$

$$Y(U_{mE},\varphi_E)=\sum_{k=1}^{K}v_{Ek}^2-2\sum_{k=1}^{K}u_k v_{Ek}, \quad (3)$$

$$Z(A,B,\tau_s)=Z_A(A,\tau_s)+Z_B(B,\tau_s)=\sum_{k=1}^{K}s_k^2-2\sum_{k=1}^{K}u_k s_k \quad (4)$$

represent the likelihood sampling relationship logarithms of input voltage $\{u_1,u_2,\ldots,u_k\}$, calculated for the relevant groups of parameters and taken with a negative sign. When estimating the parameters of signals, one searches for the maxima of these logarithms. Accordingly, following the sign inversion, the minima should be derived. Therefore, the resulting expression from article [10] can be regarded as the sum of logarithms, taken with a minus sign, of the ratio of the likelihood of sample $\{u_1,u_2,\ldots,u_k\}$ in isolation for each group of parameters (U_{mP}, τ_P), (U_{mE}, φ_E) and (A, B, τ_s) plus four additional terms $G_A(...)$, $G_B(...)$, $H_A(...)$ and $H_B(...)$. These additional terms introduce corrections to the isolated likelihood relations. These corrections are predetermined by the cross-correlational connections between a signal and the interference. Suppose one has found the magnitudes $\hat{U}_{mp}$ and $\hat{\tau}_p$, which minimize the function $W(U_{mP}, \tau_P)$ only. These magnitudes can be considered to be approximate values for the maximum likelihood estimates. How much will affect ignoring the terms $H_A(...)$ and $H_B(...)$ the degree of this approximation when calculating the estimates obtained? If the pulse disturbance has a small energy, the true magnitude of U_{mP} is small. In this case, the pulse of disturbance itself is similar in shape to a low and gentle «bell». Under these circumstances, the correctional mutually-correlated terms $H_A(...)$ and $H_B(...)$ are small and thus do not make a significant contribution to the overall error. However, the substitution of magnitudes $\hat{U}_{mp}$ and $\hat{\tau}_p$ in expressions for $H_A(...)$ and $H_B(...)$ would reduce these expressions to the two-dimensional functions $H_A\left(A,\tau_s|\hat{U}_{mP},\hat{\tau}_P\right)$ and $H_B\left(B,\tau_s|\hat{U}_{mP},\hat{\tau}_P\right)$. These new functions satisfy requirements (9) to the objective function (a vertical line separates the conditions under which new functions acquired a two-dimensional character). If the pulse disturbance has a large energy, then the pair $\hat{U}_{mp}$ and $\hat{\tau}_p$, obtained by minimizing function (2), weakly depends on a relatively low-energy signal s and a second interference v_E. Under these circumstances, the magnitudes $\hat{U}_{mp}$ and $\hat{\tau}$ can be considered to be fairly accurate approximations. This pair can be introduced to expressions for $H_A(...)$ and $H_B(...)$, reducing again to the two-dimensional functions $H_A\left(A,\tau_s|\hat{U}_{mP},\hat{\tau}_P\right)$ and $H_B\left(B,\tau_s|\hat{U}_{mP},\hat{\tau}_P\right)$. In this case, the new functions will have a significant impact on the result of error minimization.

Evaluation can be done to formulate similar reasoning and conclusions in relation to the estimates $\hat{U}_{mE}$ and $\hat{\varphi}_E$, obtained by minimizing the function $Y(U_{mE}, \varphi_E)$. Thus, it is possible to minimize the four-dimensional functions $G_A(...)$ and $G_B(...)$ to the two-dimensional functions $G_A\left(A,\tau_s|\hat{U}_{mE},\hat{\varphi}_E\right)$ and $G_B\left(B,\tau_s|\hat{U}_{mE},\hat{\varphi}_E\right)$.

Similar reasoning could be made to the situation of an arbitrary number of disturbances. That would make it possible to represent a multidimensional objective function as a sum of two-dimensional component, which is rational in terms of subsequent minimization [12].

Consequently, the resulting expression from paper [11] can be rewritten as follows:

$$\begin{aligned}\varepsilon_0^2 \approx\; & W(U_{mP},\tau_P)+Y(U_{mE},\varphi_E)+\\ & +Z_A(A,\tau_s)+H_A\left(A,\tau_s|\hat{U}_{mP},\hat{\tau}_P\right)+G_A\left(A,\tau_s|\hat{U}_{mE},\hat{\varphi}_E\right)+\\ & +Z_B(B,\tau_s)+H_B\left(B,\tau_s|\hat{U}_{mP},\hat{\tau}_P\right)+G_B\left(B,\tau_s|\hat{U}_{mE},\hat{\varphi}_E\right); \quad (5)\end{aligned}$$

$$\varepsilon_0^2 = W\left(U_{mP},\tau_P\right)+Y\left(U_{mE}\ ,\varphi_E\right)+$$
$$+R_A\left(A,\tau_s|\hat{U}_{mP},\hat{U}_{mE},\hat{\tau}_P,\varphi_E\right)+$$
$$+R_B\left(B,\tau_s|\hat{U}_{mP},\hat{U}_{mE},\hat{\tau}_P,\varphi_E\right), \tag{6}$$

where $R_A(...)$ equals the sum of all the components that are included in expression (5) with index A, and R_B equals the sum of all the components that are included in expression (5) with index B.

Expression (6) describes the objective function as a sum of two-dimensional functions. Such a form of the function, according to paper [12], ensures a substantial reduction in computational costs during its minimization.

4. 2. Procedure and technical implementation of signal processing

Since the sets of parameters $\{U_{mP},\ \tau_P\}$, $\{U_{mP},\ \tau_E\}$ and $\{A,\ B,\ \tau_s\}$ do not intersect, then

$$\min \varepsilon_0 = \min_{U_{mp},\tau_P} W\left(U_{mP},\tau_P\right)+$$
$$+\min_{U_{mE},\varphi_E} Y\left(U_{mE}\ ,\varphi_E\right)+\min_{A,B,\tau_s}\left[R_A\left(\ldots\right)+R_B\left(\ldots\right)\right]. \tag{7}$$

In this case, the first two terms of a given expression yield the estimates $\hat{U}_{mP}$, $\hat{\tau}_P$, $\hat{U}_{mE}$, $\hat{\varphi}_E$, necessary to minimize its last term. To find these estimates, we shall apply, according to paper [12],

$$\min_{x,y} F\left(x,y\right)=\min_x\left\{\min_y F\left(x,y\right)\right\}. \tag{8}$$

Following this rule, applied to $W(U_{mP},\ \tau_P)$, we obtain $x=\tau_P$, $y=U_{mP}$. Then, taking into account the model for a pulse interference component, introduced in work [10], we obtain

$$\min_{U_{mP}} W\left(U_{mP},\tau_P\right)=\min_{U_{mP}}\left\{\sum_{k=1}^{K} v_{Pk}^2-2\sum_{k=1}^{K} u_k v_{Pk}\right\}=$$
$$=\min_{U_{mP}}\left\{U_{mP}^2\cdot\sum_{k=1}^{K} e^{-2\alpha\left(t_k-\tau_P\right)^2}\cdot\sin^2\left[\beta\left(t_k-\tau_P\right)+\gamma\pi\right]-\right.$$
$$\left.-2U_{mP}\sum_{k=1}^{K} u_k e^{-\alpha\left(t_k-\tau_P\right)^2}\cdot\sin\left[\beta\left(t_k-\tau_P\right)+\gamma\pi\right]\right\}.$$

This is a quadratic (and thus a single-extremal) function of the magnitude U_{mP}. Therefore, the estimate of $\hat{U}_{mP}$ is to be found from the condition that the first derivative from the contents of braces equals zero. It is easy to see that this estimate, as a function of parameter τ_P, takes the following form:

$$\hat{U}_{mP}\left(\tau_P\right)=\frac{\sum_{k=1}^{K} u_k e^{-\alpha\left(t_k-\tau_P\right)^2}\cdot\sin\left[\beta\left(t_k-\tau_P\right)+\gamma\pi\right]}{\sum_{k=1}^{K} e^{-2\alpha\left(t_k-\tau_P\right)^2}\cdot\sin^2\left[\beta\left(t_k-\tau_P\right)+\gamma\pi\right]}. \tag{9}$$

According to (8), the estimate of $\hat{\tau}_P$ is to be found as a point at which

$$W\left(\hat{U}_{mP},\hat{\tau}_P\right)=\min_{\tau_P}\left\{W\left(\hat{U}_{mP},\tau_P\right)\right\}. \tag{10}$$

This requires a one-dimensional global minimization of the contents of a brace in the right-hand side of expression (10) for parameter τ_P. Such an operation can be performed, for example, based on a simple tabulation within the observation interval $[T_1,\ T_2]$ or by other known methods [12].

The function $Y(U_{mE},\ \varphi_E)$ has a structure similar to the structure of function $W(U_{mP},\ \tau_P)$, which is why the course of its minimization is similar. It is easy to show that

$$\hat{U}_{mE}\left(\varphi_E\right)=\frac{\sum_{k=1}^{K} u_k \sin\left(\omega_E t_k+\varphi_E\right)}{\sum_{k=1}^{K} u_k \sin^2\left(\omega_E t_k+\varphi_E\right)} \tag{11}$$

and that the estimate of $\hat{\varphi}_E$ is derived as a point where the following ratio holds

$$Y\left(\hat{U}_{mE}\ ,\hat{\varphi}_E\right)=\min_{\varphi_E}\left\{Y\left(\hat{U}_{mE}\ ,\varphi_E\right)\right\}, \tag{12}$$

in this case, global minimization should be performed within an interval $\left[0,2\pi\right)$.

Next, to fully minimize the objective function, we have to find the last term from expressions (7). Given that functions $R_A(A,\ \tau_s)$ and $R_B(B,\ \tau_s)$ «overlap» for argument τ_s, dimensionality reduction can be performed according to the following algorithm [12]

$$\min F\left(\vec{X}\right)=\min_{0\le x(N)\le 1}\psi_N\left[x\left(N\right)\right], \tag{13}$$

where

$$\psi_2\left[x\left(2\right)\right]=\min_{x(1)} F_1\left[x\left(1\right),x\left(2\right)\right], \tag{14}$$

$$\psi_i\left[x\left(i\right)\right]=\min_{x(i-1)}\left\{\psi_{i-1}\left[x\left(i-1\right)\right]+F_{i-1}\left[x\left(i-1\right),x\left(i\right)\right]\right\}, \tag{15}$$

$$i=3,\ldots,N.$$

In this case, the components $x(i)$ of vector $\vec{X}$ must belong to a single cube $[0,\ 1]^N$. To satisfy this condition, one must perform the appropriate normalization of parameters of an actual problem prior to starting the construction of a minimization procedure. The A and B parameters will be normalized relying on the definition given in paper [10]. We shall consider that in practice of operation the U_{ms} amplitude ranges from 0 to a certain a priori known boundary magnitude U_M, while sine and cosine lie within [–1, 1]. It is easy to verify that the normalized parameters that match the A and B magnitudes are the following variables:

$$x\left(1\right)=\frac{A}{2U_M}+0.5, \tag{16}$$

$$x\left(3\right)=\frac{B}{2U_M}+0.5. \tag{17}$$

The magnitude of signal delay τ_s ranges from 0 until the moment T_2 of observation end, therefore, the corresponding normalized parameter:

$$x\left(2\right)=\frac{\tau_s}{T_2}. \tag{18}$$

The relations between the actual and normalized parameters that follow from ratios (16) to (18) are:

$$A=U_M\left[2x\left(1\right)-1\right], \tag{19}$$

$$B=U_M\left[2x\left(3\right)-1\right], \tag{20}$$

$$\tau_s=T_2 x\left(2\right). \tag{21}$$

Next, one can build a function that is included in the right-hand side of equality (14) in the following form:

$$F_1\left[x(1),x(2)\right]=$$
$$=R_A\left(U_M\left[2x(1)-1\right],T_2x(2)|\hat{U}_{mP},\hat{U}_{mE},\hat{\tau}_P,\hat{\varphi}_E\right)=$$
$$=0.5C_c\left(2U_Mx(1)-U_M\right)^2-$$
$$-2\left(2U_Mx(1)-U_M\right)\sum_{k=1}^{K}u_kf\left(t_k-T_2x(2)\right)\sin\omega_st_k+$$
$$+2\hat{U}_{mP}\left(2U_Mx(1)-U_M\right)\sum_{k=1}^{K}f\left(t_k-T_2x(2)\right)e^{-\alpha\left(t_k-\hat{\tau}_P\right)^2}\times$$
$$\times\sin\left[\beta\left(t_k-\hat{\tau}_P\right)+\gamma\pi\right]\sin\omega_st_k+$$
$$+2\hat{U}_{mE}\left(2U_Mx(1)-U_M\right)\times$$
$$\times\sum_{k=1}^{K}f\left(t_k-T_2x(2)\right)\sin\omega_st_k\cdot\sin\left(\omega_Et_k+\hat{\varphi}_E\right). \quad (22)$$

This is a quadratic function relative to variable $x(1)$. Because a coefficient at the square of this variable is positive, then the only extremum of this function is a minimum. We shall equate a derivative from expression (22) for $x(1)$ to zero and solve the resulting equation. By denoting the solution result as $\chi_1(x(2))$, we obtain

$$\chi_1\left(x(2)\right)=\frac{1}{2}+\frac{1}{C_cU_M}\sum_{k=1}^{K}u_kf\left(t_k-T_2x(2)\right)\sin\omega_st_k-$$
$$-\frac{\hat{U}_{mP}}{C_cU_M}\sum_{k=1}^{K}f\left(t_k-T_2x(2)\right)e^{-\alpha\left(t_k-\hat{\tau}_P\right)^2}\times$$
$$\times\sin\left[\beta\left(t_k-\hat{\tau}_P\right)+\gamma\pi\right]\sin\omega_st_k-$$
$$-\frac{\hat{U}_{mE}}{C_cU_M}\sum_{k=1}^{K}f\left(t_k-T_2x(2)\right)\sin\left(\omega_Et_k+\hat{\varphi}_E\right)\sin\omega_st_k. \quad (23)$$

Given this result, expression (14) can be written in the form:

$$\psi_2\left[x(2)\right]=F_1\left[\chi_1\left(x(2)\right),x(2)\right]=$$
$$=R_A\left(U_M\left[2\chi_1\left(x(2)\right)-1\right],T_2\cdot x(2)|\hat{U}_{mP},\hat{U}_{mE},\hat{\tau}_P,\hat{\varphi}_E\right). \quad (24)$$

Following algorithm (13) to (15), we then search for function:

$$\psi_3\left[x(3)\right]=\min_{x(2)}\left\{\psi_2\left[x(2)\right]+F_2\left[x(2),x(3)\right]\right\}. \quad (25)$$

In line with (1) and (6), we obtain

$$F_2\left[x(2),x(3)\right]=R_B\left(\tau_s,B|\hat{U}_{mP},\hat{U}_{mE},\hat{\tau}_P,\hat{\varphi}_E\right)=$$
$$=R_B\left(T_2\cdot x(2),U_M\left[2x(3)-1\right]|\hat{U}_{mP},\hat{U}_{mE},\hat{\tau}_P,\hat{\varphi}_E\right).$$

Then, considering (24), one can record:

$$\psi_3\left[x(3)\right]=$$
$$=\min_{x(2)}\left\{R_A\left(U_M\left[2\chi_1\left(x(2)\right)-1\right],T_2\cdot x(2)|\hat{U}_{mP},\hat{U}_{mE},\hat{\tau}_P,\hat{\varphi}_E\right)+\right.$$
$$\left.+R_B\left(T_2\cdot x(2),U_M\left[2x(3)-1\right]|\hat{U}_{mP},\hat{U}_{mE},\hat{\tau}_P,\hat{\varphi}_E\right)\right\}. \quad (26)$$

In accordance with work [12], in order to compute each value for the function $\psi_3\left[x(3)\right]$, one should assign the magnitude $x(3)$ and then perform a one-dimensional global minimization for $x(2)$ of the right-hand side of expression (26). The magnitudes for parameter $x(2)$ that ensure a minimum of this content at the assigned $x(3)$ are denoted as $\chi_2\left(x(3)\right)$. Thus, we tabulate the function $\psi_3\left[x(3)\right]$ over range [0, 1]. The result would be the accumulated totalities of triples of numbers $\left\{x(3),\psi_3\left[x(3)\right],\ \chi_2\left(x(3)\right)\right\}$. Note that specific algorithms for the rapid one-dimensional global minimization can be built based on known methods [12].

Next, we shall perform, in accordance with expression (13), a global minimization of function $\psi_3\left(x(3)\right)$. As a result, we shall find among the above-mentioned totalities a set at which variable $x(3)$ takes such a numeric value χ_3, so that $\psi_3\left[\chi_3\right]=\min$. In this case, the magnitude of $\chi_2\left(\chi_3\right)$ will be unambiguously determined. Substituting this magnitude in the right-hand side of expression (23) yields, instead of $x(2)$, a numeric value for the magnitude $\chi_1\left(\chi_2\left(\chi_3\right)\right)$. The knowledge of triples of numeric values for $\left\{\chi_1,\chi_2,\chi_3\right\}$ will, in accordance with expressions (19) to (21), make it possible to obtain estimates for $\hat{A}$, $\hat{B}$ and $\hat{\tau}_s$.

An automated locomotive signaling system employs three information code signals: Green (G), Yellow (Y), Red-yellow (R). To form a decision on the form of a received signal, it is necessary, in accordance with the final expression from article [11], to calculate the magnitudes of mean squared errors ε_0^2 along three processing channels. Each of these channels has its own code envelope *f(t)*. It should be assumed that such a signal is received for which the magnitude of ε_0^2 is the smallest. A structural diagram of the corresponding device for the optimal reception of code signals is shown in Fig. 1.

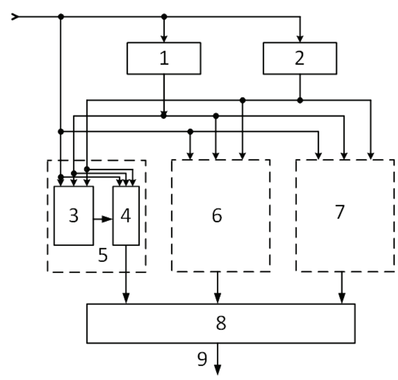

Fig. 1. Structural diagram of a device for the optimal reception of information signals from an automated locomotive signaling system: 1 – shaper U_{mP}, τ_P; 2 – shaper U_{mE}, φ_E; 3 – shaper *A*, *B*, τ_s; 4 – computational unit ε_0^2; 5 – channel *G*; 6 – channel *Y*; 7 – channel *R*; 8 – a minimum selection unit; 9 – decision on *G, Y*, or *R*

The auxiliary units that perform the conversion of an analog signal into digital and store constant magnitudes are not shown in the diagram.

4. 3. Quantification of noise immunity of the designed device

Computer simulation was conducted in order to numerically evaluate the characteristics of the designed optimal receiver. Fig. 2 shows a chart of the code signal Green (Y), distorted by a pulse interference, by an interference from a power line (PL) and by a Gaussian noise. Numerical magnitudes of the signal model parameters are as follows: signal amplitude U_{ms}=0.2 V, signal carrier frequency f_s=25 Hz, initial signal phase φ_s=75°, time offset of the signal relative to the onset of observation τ_s=0.4 s. The model of a pulse interference corresponds to the experimental curve reported in article [14]. A given curve was obtained when a locomotive moved over a track switch at speed 75 km/h. The amplitude of a pulse interference U_{mP}=1.5 V, the pulse interference attenuation $\alpha=10^3$, the angular frequency of a pulse interference β=60 rad/s, the position of a maximum of a pulse interference over time relative to the onset of observation τ_P=1.17 s, the coefficient of the initial phase of a pulse interference γ=0.5, the amplitude of the PL-induced interference U_{mE}=0.05 V, the frequency of the PL-induced interference f_E=50 Hz, the initial phase of the PL-induced interference φ_E=248°, the standard Gaussian noise voltage is 0.005 V, the noise bandwidth is 250 Hz. At such an arrangement of the interference pulse a typical receiver in the system of automated locomotive signaling makes an erroneous decision on the reception of Yellow signal (Y) [15].

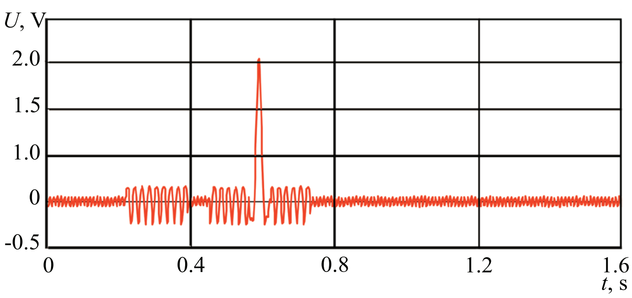

Fig. 2. A Green signal (Y), distorted by a pulse disturbance, a PL-induced interference, and continuous Gaussian noise

When employing the procedure, proposed in the present work, the input signal was correctly identified as Green at $\varepsilon_0^2=0.225$ (along an R channel, the magnitude is $\varepsilon_0^2=1.97$; along an Y channel, the magnitude is $\varepsilon_0^2=1.83$). The signal parameters estimation along a G channel amounted to $\hat{U}_{ms}=0.206$ V, $\hat{\tau}_s=0.4$ s, $\hat{\varphi}_s=76.2°$, that is they are very close to the exact values for the parameters.

To more broadly assess the noise immunity of the designed device, computer simulation was performed. The result is the magnitudes for the mean squares of errors ε_0^2 along each of the three processing channels. A Green (G) signal was chosen as the signal to be recognized. The following source data were accepted for simulation:

1) amplitude U_{mS} of the code signal (identical for signals R, G, Y);

2) frequency f_s and initial phase φ_s of the code signal (identical for all signals);

3) time-delay τ_s of the coded signal relative to the onset of observation (same for all signals);

4) the pulse interference parameters, the PL-induced interference parameters, and the Gaussian noise parameters (their definitions are given in explanations to Fig. 2).

All oscillations were sampled over time with an interval of $\Delta t=0.004$ s. Numerical magnitudes of the code signal parameters are the same as in annotations to Fig. 2. When computing Table 1, the numerical magnitudes of all other model parameters coincided with those given in annotations to Fig. 2, except for a pulse interference amplitude U_{mP}. The magnitude of this amplitude varied in the range 0...1.5 V, typical for practical situations.

Table 1

Values for the mean square of approximation error ε_0^2 along the R, G, Y channels based on amplitude U_{mP} of the pulse interference

U_{mP}, V	0.0	0.2	0.5	0.8	1.0	1.2	1.5
ε_{0R}^2, V^2	1.743	1.745	1.862	2.082	2.286	1.757	1.970
ε_{0G}^2, V^2	0.054	0.038	0.279	0.380	0.584	0.141	0.225
ε_{0Y}^2, V^2	1.703	1.713	1.781	1.939	2.104	1.734	1.830

When computing Table 2, the magnitude of pulse interference amplitude U_{mP} was taken to be equal to 1 V. The numerical magnitudes of all other model parameters coincided with those given in annotations to Fig. 2, except for the amplitude of the PL-induced interference U_{mE}. Its magnitude varied in a range of 0...0.5 V, which is also typical for practical situations.

Table 2

Values for the mean square of approximation error ε_0^2 along the R, G, Y channels based on the PL-induced interference amplitude U_{mE}

U_{mE}, V	0.00	0.05	0.10	0.20	0.30	0.40	0.50
ε_{0R}^2, V^2	2.291	2.286	2.291	2.291	2.290	2.267	2.222
ε_{0G}^2, V^2	0.598	0.584	0.598	0.598	0.584	0.562	0.482
ε_{0Y}^2, V^2	2.104	2.111	2.111	2.106	2.105	2.088	2.026

Based on the results of simulation, we have built the curves for dependences of the mean-squared error ε_0^2 along each of the three processing channels on magnitude U_{mP} (Fig. 3) and magnitude U_{mE} (Fig. 4), respectively.

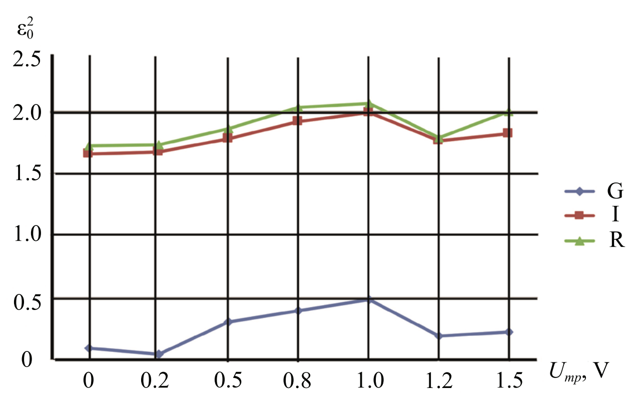

Fig. 3. Dependence of the mean square of approximation error ε_0^2 along the R, G, Y channels on amplitude U_{mP} of the pulse interference

Based on the results of computer simulation, we can conclude that the synthesized device makes it possible to reliably distinguish the transmitted code signal (in this case, G) from other code signals that can arise in an automated system of locomotive signaling. Such a high ability to discriminate is maintained over a wide range of amplitudes of a pulse interference and a PL-induced interference, characteristic of actual operating conditions. The magnitude of RMS voltage of the Gaussian noise, accepted during simulation, is relatively small, which is also characteristic of such conditions.

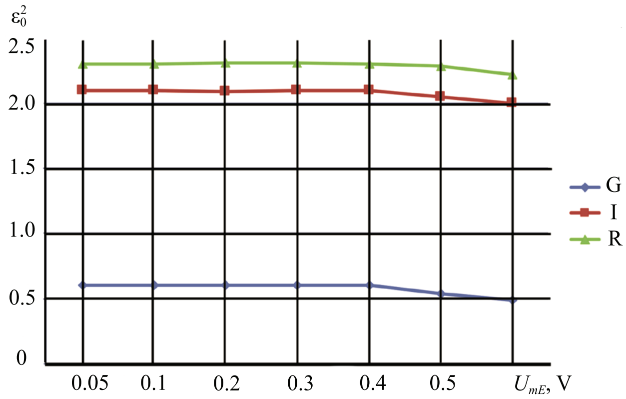

Fig. 4. Dependence of the mean square of approximation error ε_0^2 along the R, G, Y channels on the PL-induced interference amplitude U_{mE}

5. Discussion of results of synthesizing a device for the optimal reception of code signals from an automated locomotive signaling system

The processing of input oscillations in the synthesized device for optimal signal reception is based on the previously known maximization of the input sample likelihood ratio in first approximation only. The improvement of noise immunity is achieved in it due to accounting for the corrections to the isolated likelihood ratios (this feature was not considered in previous works). The specified corrections take into account the cross-correlational connections of a signal and each interference component. The research underlying the present work were aimed primarily at easing the impact of structurally deterministic interference. As a result, the designed device is capable to respond quickly to changes in the parameters of such an interference. A noise interference was assumed to be stationary. This limits the applicability of the device. Accounting for the non-stationarity of random noise is regarded as one of the avenues for further research.

In the cases, characteristic of actual operation, of a negligible magnitude of the intra-interference correlation, the formula that describes the magnitude of a squared error is represented as the sum of computational segments. Each of these segments describes the contribution of only one type of noise. For example, in expression (6), the computational segment $[W(...)+H_A(...)+H_B(...)]$ describes the individual contribution of a pulse interference to the total magnitude of error ε_0^2. This segment becomes zero and hence can be excluded from the procedure if there are any a priori reasons to believe that there are no pulse interferences. A similar conclusion can be easily extended to the case of an arbitrary number of mutually uncorrelated interferences. The proposed method of segmentation provides for the fundamental possibility to build an optimal receiver in a modular fashion. In this case, the modules can be connected and disconnected in accordance with the a priori predicted composition of the interference set, while the «library» of modules can be replenished when the new types of interference emerge. The main difficulties are expected when looking for ways to represent an arbitrary set of interferences in the form that allows the application of a multi-step procedure of dimensionality reduction.

We consider the estimation of noise immunity, based on the results of software simulation, to be preliminary. Strictly speaking, it is necessary to calculate the magnitudes of the first- and second-kind error when making decisions. The standard DSTU 4178-2003 «Complexes of technical means for systems of control and regulation of train motion. Functional safety and reliability. Requirements and test methods» (its European analog is CENELEC EN 50126: Railway Application – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety) requires that the likelihood of failures that lead to dangerous malfunctions should be at the level 10^{-10} per one hour of operation. However, we do not have enough computing power to identify such a small error. Therefore, the possibility is being investigated at present to analytically estimate the noise immunity of the designed device.

We did not consider the related energy costs because when designing and investigating communication devices and, in particular, their processing units, it is a commonly accepted practice to evaluate the number of basic mathematical operations required to achieve a set goal, and the corresponding number of arithmetic and logical units (adders, multipliers, comparators, etc.). Determining the magnitude of associated energy costs in the synthesis of receiving devices is assumed by default to be an additional task to be resolved within a framework of specialized research and development.

6. Conclusions

1. The optimality criterion for processing an additive mixture of signal and a three-component interference has been selected. Based on realistic assumptions about the statistical relationships between the signal and interference components, it has been demonstrated that the objective function is the sum, taken with an opposite sign, in which the number of summands is limited by the quantity of isolated logarithms of the likelihood and correction functions ratios. A special feature of the proposed approach is that it makes it possible to build an optimal receiver based on a flexible modular design.

2. We have synthesized a signal processing device that recognizes the received information signal through the multiparameter minimization of the objective function. A decrease in the computational cost has been achieved by a multi-step reduction of dimensionality. Namely, according to paper [12]: while minimizing via direct search, one needs a total number of computations at the order of N^n (where n is the dimensionality of an objective function, N is the number of its computations for each parameter), while at a multi-step dimensionality reduction, the total number of calculations is a much less magnitude of the order Nn.

3. By employing computer simulation, it has been shown that in a channel corresponding to the formation of a correct solution the magnitude of an approximation error is about 6 times less than that in the other two channels. This ratio holds when the amplitude of a pulse interference exceeds the signal amplitude by up to 7.5 times. The above ratio is true in the case when pulse interferences exceed the useful signal by 5 times, and interference from power lines – up to 2.5 times. These indicators characterize high noise immunity when the designed device recognizes code signals over a wide range of interference parameters.

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