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SYNTHESIS OF A DEVICE FOR ANTI-JAMMING RECEPTION OF SIGNALS OF TONAL RAIL CIRCUITS ON THE BACKGROUND OF ADDITIVE FIVE-COMPONENT INTERFERENCE

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An optimal receiving device for information signals of tonal rail circuits has been synthesized. The signals are observed against the background of an additive five-component interference. The first component of the interference is broadband Gaussian noise. The other four components of the interference are structurally determined: single impulse interference, interference from an adjacent tonal rail circuit, and multiharmonic interference from alternating traction current combined with the power line and from the locomotive traction converter. The presence of a complex of interference leads to errors in decision-making regarding the regulation of train traffic. This puts the participants in this movement before the danger of threatening emergencies. Therefore, it is necessary to develop and study means of noise-immune reception of information signals and the formation of dispatch decisions. The decision on the presence or absence of a signal is made by comparing two values of the mean square of the approximation error. This error is understood as the difference between the input voltage of the receiver and the sum of the signal with structurally determined interference. The first value of the error is calculated assuming the presence of a signal in a mixture with structurally determined noise. The second error value is calculated on the assumption that there is no signal in this mixture. The noise component is assumed to be present in both cases. The solution corresponds to a channel with a lower mean squared error. The block diagram of the device is presented. Analytically, it has been shown that the average value of the error in recognizing situations of presence or absence of a signal is two orders of magnitude less than the admissible value according to regulatory requirements. High noise immunity of the developed device will improve the safety of train traffic

Keywords: structurally determined interference, likelihood ratio, optimal signal discrimination, train traffic control

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1. Introduction

Rail chains are the basic element of most railway automation and telemechanics systems. Their work is based on the transmission of information signals via a two-wire communication line, in which a rail pair is used as wires. Such a communication line is extremely weakly protected from the penetration of natural and man-made interference into it. These disturbances are both impulsive and continuous influences. In both cases, they can be either single or periodic. In addition, a rail circuit is usually affected by several different types of interference at the same time. Moreover, the parameters of each of the interference change over time. Therefore, information signals of rail circuits operating at frequencies of hundreds and (or) thousands of hertz (the so-called tonal rail circuits of the TRC) undergo a whole complex of different types of distortions. Since the total number and type of man-made noise sources operating near rails is constantly increasing, the previously introduced methods and signal processing devices become less effective. For the same reasons, the relative number of errors in the reception of TRC information signals is also growing. As a result, train traffic safety is reduced. Therefore, the development of means for noise-immune reception of signals from the TRC is not only in dire need of further scientific research. The results of such development can be used as the basis for new means of ensuring the safety of train traffic. For these reasons, this topic is relevant.

2. Literature review and problem statement

The specialists paid great attention to the issue of ensuring high reliability of reception of useful signals observed against the background of multicomponent interference. Works have been published in which the influence of different amounts of different types of interference on the reception results is considered. The article [1] reports the results of the synthesis of the receiver, which is optimal for the case of two-component interference. The initial assumption of this development was the noise nature of both interference components. Therefore, the issue of device optimization in cases where at least one of the components is structurally determined remains unresolved. The reason for this is the original constraints set in the problem statement. A variant of overcoming this problem can be the introduction of a deterministic signal among the factors to be optimized. In [2], the method of receiving a signal observed against the background of the sum of structurally determined interference is considered. In this case, each component of the interference is a copy of the useful signal arriving at the receiver with a random time delay. However, the issue of optimization of reception for the case of heterogeneous deterministic interference remained unresolved. A possible solution would be optimization with the participation of a parameter that is universal for all types of interference. In this direction, a method for dealing with multicomponent interference is known, based on the use of a polynomial approximation of the interference phase [3]. It is shown that in this way it is possible to significantly increase the noise immunity of reception. In this case, it was not possible to achieve the potentially possible high indicators of noise immunity due to leaving other parameters of noise outside the scope of consideration. It would be necessary to take into account a certain set of interference parameters. Accounting for such a set, generated by different spatial locations of interference sources by preliminary estimation of their coordinates, is described in article [4]. The issue of achieving potentially possible noise immunity is also not solved here, since the procedure for spatial localization of interference is heuristically introduced into the general process of noise-immune reception. Its presence is not a consequence of solving a single problem of synthesizing an optimal receiver. The combination of such a synthesis and taking into account structurally deterministic interference was demonstrated in [5]. It presents the results of the synthesis of a device for optimal signal reception against the background of an additive three-component interference. However, it does not take into account the widespread multiharmonic interference, which greatly reduces the practical noise immunity. In part, this case is covered by the results obtained in the article [6]. It considers the case of an arbitrary number of structurally deterministic noises with random amplitudes and initial phases. These interferences, in principle, can be mutiharmonic. But the class of the considered interference is narrowed down to broadband noise-like interference. There are no such obstacles in the TRC. But there are single impulse noises, noises in the form of a sequence of low-frequency radio pulses and multiharmonic noises with constant parameters over the observation interval. The listed types of interference are not covered by the model adopted in article [6]. In addition, the processing described in this article includes averaging the probability density over unknown amplitudes and initial phases. This reduces the immunity to interference of the device described there. Thus, there is reason to assert that the study of ways to increase the noise immunity must be carried out taking into account a wider set of interference than the one considered earlier.

Regardless of the difference between the approaches demonstrated, all of the above devices are based on the correlation method of optimal reception. Considerable efforts have been made to improve this method. In [7], a receiver with an improved base correlator node is described. However, the structure of the receiver as a whole has not undergone improvements in the direction of taking into account the variability of the interference environment. The reason for this was the authors' focus on solving circuitry issues. A possible way to solve the problem is a generalized view of the very concept of correlation. Such an extension of correlation processing is described in [8]. It is shown that it allows solving the highly specialized problem of screening out unreliable primary data. However, the issue of optimal processing of primary data is not touched upon, since it was not the purpose of the work. In [9], this direction was developed, but only one issue was solved – the calculation of the relative delays of signals received from spatially separated sensors. At the same time, to estimate the signal parameters, it is also necessary to obtain at least some information about all components of the signal and noise mixture. This problem was partially solved in [10], where the corresponding cross-correlation procedure is described. However, the purpose of its application is not to evaluate signal parameters, but to suppress signal-like interference from local reflective objects. It is necessary to combine the estimation of the signal and interference parameters. The synthesis of an optimal digital signal receiver carried out in this direction, described in article [11], is limited only to the case of a noise Gaussian interference, while the real composition of the interference also includes structurally determined components. The above indicates the expediency of studying the optimal reception in the conditions of a complex complex of interference.

The modern interference environment is not only multicomponent, but also dynamic: the composition of the set of interference and the parameters of each of them can change in a time close in magnitude to the constant actuation of the TRC executive unit. Therefore, the optimal decision on the presence or absence of a signal should be formed on the basis of the data obtained during the time interval during which the executive unit reacted to the previous interference situation. For this case, in [12], it was proposed to use the method of joint estimation of the parameters of the signal and all the interferences taken into account. It is based on the criterion of the minimum mean square of the difference between the input voltage of the optimal receiver and the sum of the useful signal and structurally determined components of the interference. As a result, a compact mathematical expression is obtained that determines the basic computational structure of the optimal receiver. However, the work [12] does not indicate detailed mathematical transformations over the input mixture of signal and noise. Also, the technical means necessary to form a decision on the presence or absence of a signal from the TRC are not described. In addition, no numerical indicators of noise immunity have been obtained, which could be achieved using the device under development. Accordingly, they have not been compared with similar indicators of the existing TRCs. All these questions require further research.

Thus, the methods and means of suppression of multicomponent noise developed to date provide a solution to a number of important for practice problems of noise-immune reception of information signals. However, it was not possible to find published developments that would cover the situation of simultaneous action of noise interference, as well as structurally deterministic impulse noise and multiharmonic interference typical for TRC. In this regard, it is of interest to consider the possibility of solving the problem of optimal signal reception against the background of a multicomponent interference of this type. This would ensure high noise immunity of the TRC in a difficult jamming environment.

3. The aim and objectives of research

The aim of the study was to synthesize a device for noise-immune reception of the information signal of the TRC under the conditions of the action of a set of five typical for TRC noises. The first interference was broadband Gaussian noise. The other four noises were structurally deterministic: a single impulse noise, noise from a neighboring TRC, and multiharmonic noise from alternating traction current combined with the power line and from the traction converter of the locomotive. Taking into account the effect of a complex of typical interferences will increase the TRC noise immunity and, as a result, the safety of train traffic.

To achieve this aim, the following objectives were solved:

– based on the given general form of the objective function, construct an algorithm of operation and the corresponding structural diagram of the receiver for detecting the TRC signal against the background of a five-component interference typical for the TRC;

– to give a numerical estimate of the noise immunity of the synthesized device.

4. Materials and methods of research

Since the tonal rail circuit (TRC) is essentially a communication channel in which the sum of signal and interference operates, it was considered expedient to use the conceptual and mathematical apparatus of statistical radio engineering for research. The theoretical methods of testing hypotheses about the presence and absence of a signal are used. The term "five-component interference" is used as a generalization to describe the sum of noise interference and four structurally determined interference. The noise immunity of the resulting device is investigated by methods of the theory of signal discrimination. The final analytical expression for calculating the noise immunity index made it possible to directly calculate this indicator. In this case, the numerical characteristics of the correlations between the signal and the components of the interference, as well as the cross-correlations between the components of the interference, were calculated by computer modeling of the signal-interference environment.

5. Research results of the process and means of noise-immune signal reception

5. 1. Construction of an operation algorithm and the corresponding structural diagram of a receiver for detecting signals from a TRC against the background of a five-component interference typical for TRC

An additive mixture of signal and interference acts at the output of the TRC signal transducer

$$u(t)=s(t)+v_C(t)+v_Q(t)+v_T(t)+v_P(t)+n(t),$$

where $s(t)$ – information signal; $v_C(t)$ – interference from an adjacent TRC; $v_Q(t)$ – total interference from the traction current in the rails and from the power line; $v_T(t)$ – interference from the traction converter of the locomotive; $v_P(t)$ – impulse noise; $n(t)$ – stationary Gaussian noise with a uniform spectrum. A detailed description of the components of the input signal is given in [13].

By processing the output voltage of the sensor, observed during the interval T and further uniformly sampled in time, it is necessary to establish the presence or absence of the information signal. The size of the observation interval is specified by the operational requirements. It is necessary to find the structure of a receiver that makes a decision on the presence or absence of an information signal so that the average decision error at each observation interval is minimal.

In the course of synthesis described below, the results presented in [12] are developed. It proposes to perform the detection of an information signal based on a joint assessment of the parameters of this signal and structurally determined interference by the criterion of the minimum mean square of the approximation error Let's concretize the objective function formed in [12] in relation to situations of signal presence and absence. If to hypothesize the presence of a useful signal, then in terms and notations of [12], the objective function for a time-discretized input process will take the form

$$\begin{aligned}\xi_S \approx {} & \sum_{k=1}^{K} v_{Pk}^2 - 2\sum_{k=1}^{K} u_k v_{Pk} + \sum_{k=1}^{K} v_{Qk}^2 - 2\sum_{k=1}^{K} u_k v_{Qk} + \\ & + \sum_{k=1}^{K} v_{Ck}^2 - 2\sum_{k=1}^{K} u_k v_{Ck} + \sum_{k=1}^{K} s_k^2 - 2\sum_{k=1}^{K} u_k s_k + \\ & + \sum_{k=1}^{K} v_{Tk}^2 - 2\sum_{k=1}^{K} u_k v_{Tk} + 2\sum_{k=1}^{K} v_{Pk} v_{Tk} + 2\sum_{k=1}^{K} v_{Pk} v_{Qk} + \\ & + 2\sum_{k=1}^{K} v_{Tk} v_{Qk} + 2\sum_{k=1}^{K} v_{Tk} v_{Ck} + 2\sum_{k=1}^{K} s_k v_{Tk}. \end{aligned} \quad (1)$$

Here k – the number of the sample; K – the number of samples in the processed sample; ν_{Pk} – impulse noise count; u_k – sample of the input mixture of signal and noise; ν_{Qk} – sample of the total interference from the traction current in the rails and the pickup from the power line; ν_{Ck} – sample of the interference from the adjacent TRC; s_k – sample of the information signal; ν_{Tk} – sample of the interference from the traction converter of the locomotive. In this case, the symbol ν denotes the structurally determined components of the interference. The input mixture u of signal and interference is the sum of structurally determined interference and interference in the form of stationary Gaussian noise. The objective function is formed in accordance with the criterion of the minimum of the mean square of the error, taking into account the relationship between the components of the interference and the signal, as well as the component of the interference with each other [12].

If to put forward a hypothesis about the absence of a useful signal, then the objective function will take the form

$$\begin{aligned}\xi_F \approx {} & \sum_{k=1}^{K} v_{Pk}^2 - 2\sum_{k=1}^{K} u_k v_{Pk} + \sum_{k=1}^{K} v_{Qk}^2 - 2\sum_{k=1}^{K} u_k v_{Qk} + \\ & + \sum_{k=1}^{K} v_{Ck}^2 - 2\sum_{k=1}^{K} u_k v_{Ck} + \sum_{k=1}^{K} v_T^2 - 2\sum_{k=1}^{K} u_k v_{Tk} + \\ & + 2\sum_{k=1}^{K} v_{Pk} v_{Tk} + 2\sum_{k=1}^{K} v_{Pk} v_{Qk} + 2\sum_{k=1}^{K} v_{Tk} v_{Qk} + 2\sum_{k=1}^{K} v_{Tk} v_{Ck}. \end{aligned} \quad (2)$$

The detection of a useful signal consists in comparing the values of ξ_F and ξ_S: which of them is less, that hypothesis is correct. That is, the task of detecting a useful signal is reduced to the task of distinguishing pseudo-signals described by the following relations:

$$z_{Fk} = v_{Pk} + v_{Qk} + v_{Ck} + v_{Tk}, \quad (3)$$

$$z_{Sk} = s_k + v_{Pk} + v_{Qk} + v_{Ck} + v_{Tk}, \quad (4)$$

where k=1, 2, ..., K.

Before starting this comparison, an assessment of all signal parameters and structurally determined interference should be performed. This interference is an integral part of the described pseudo-signals. Pseudo-signals are distinguished by the presence or absence of a useful term s_k. Thus, the problem of signal detection against the background of a TRC five-component noise characteristic is reduced to the problem of distinguishing two pseudo-signals with a completely known structure, but unknown parameters. Their parameters are assessed at each observation interval, which provides a response to changes in interference parameters in real time.

Estimates of signal and noise parameters are based on the concept of "isolated logarithm of the likelihood ratio taken with a negative sign" introduced in [5]. Then, in formula (1), the first pair of terms is the ILLRN $W_P\left(\vec{\lambda}_P\right)$ of impulse noise (($\vec{\lambda}_P$ is the vector of unknown parameters of this noise). The second pair of terms represents the ILLRN $W_Q\left(\vec{\lambda}_Q\right)$ interference from the traction current in the rails and from the pickup from the power line ($\vec{\lambda}_Q$ is the vector of unknown parameters of this interference). The third pair of terms is the ILLRN $W_C\left(\vec{\lambda}_C\right)$ of interference from a complex TRC ($\vec{\lambda}_C$ is the vector of unknown parameters of this interference). The fourth pair of terms is the ILLRN $W_S\left(\vec{\lambda}_S\right)$ of the signal ($\vec{\lambda}_S$ is the vector of unknown signal parameters). The fifth pair is the ILLRN $W_T\left(\vec{\lambda}_T\right)$ of interference from the traction converter of the locomotive ($\vec{\lambda}_T$ is the vector of unknown parameters of this interference).

The rest of the terms make corrections to the values of the objective functions. According to the considerations set forth in [5], when minimizing the objective function, one can be satisfied with the parameter estimates obtained by minimizing each of the ILLRN separately. Since the sets of parameters of different ILLRN do not overlap, the minimization of the objective function as a whole consists in minimization of each ILLRN separately.

As shown in [13], all structurally deterministic components of the input signal and noise mixture are periodic or directly multiharmonic functions of time, with the exception of a single impulse noise. This has determined different approaches to minimizing the corresponding ILLRN. It is more convenient to estimate the parameters of the impulse noise by directly using its counts in time. Applying the model and designations introduced in article [13], let's obtain the following ILLRN of a single impulse noise:

$$\begin{aligned} &W_P\left(U_{OP}, U_{mP}, f_P, \varphi_P\right) = \\ &= \sum_{k=k_1}^{k_1+\Delta k-1} U_{OP}^2 - 2U_{OP} \sum_{k=k_1}^{k_1+\Delta k-1} u_k + \\ &+ U_{mP}^2 \sum_{k=k_1}^{k_1+\Delta k-1} sin^2\left(2\pi f_P k\Delta t + \varphi_P\right) - \\ &-2U_{mP} \sum_{k=k_1}^{k_1+\Delta k-1} u_k \cdot sin\left(2\pi f_P k\Delta t + \varphi_P\right), \end{aligned} \quad (5)$$

where k_1 – the number of the time reference corresponding to the beginning of the pulse; Δk – pulse duration; Δt – time sampling step; U_{0P} – constant component of impulse noise; U_{mP} – amplitude of the alternating component of the impulse noise; f_P and ϕ_P are the frequency and the initial phase of the alternating component of the impulse noise, respectively.

The first two terms represent the ILLRN of the constant term of the impulse noise:

$$W_{P1}\left(U_{OP},\ k_1,\ \Delta k\right) = U_{OP}^2 \cdot \Delta k - 2U_{OP} \cdot \sum_{k=k_1}^{k_1+\Delta k-1} u_k. \quad (6)$$

It is easy to see that the minimum of this function with respect to the parameter is attained at

$$\hat{U}_{OP} = \frac{\sum_{k=k_1}^{k_1+\Delta k-1} u_k}{\Delta k}. \quad (7)$$

Substitution of this relation into formula (6) gives

$$W_{P1}\left(U_{OP},\ k_1,\ \Delta k\right) = -\frac{\left(\sum_{k=k_1}^{k_1+\Delta k-1} u_k\right)^2}{\Delta k}. \quad (8)$$

This is the simplest case of a separable function of two variables k_1 and Δk [14]. Its minimization requires relatively low computational costs. As a result, let's find an estimate $\hat{k}_1$ of the number of the initial sample of the impulse noise and an estimate $\Delta\hat{k}$ of the duration of the impulse noise. Substituting them into relation (7), let's find an estimate of the value.

To estimate the parameters of the second pair of terms in expression (5), let's use the fact that they represent the ILLRN of the sinusoidal term of the impulse noise:

$$\begin{aligned} &W_{P2}\left(U_{mP}, f_P, \varphi_P\right) = \\ &= U_{mP}^2 \sum_{k=k_1}^{k_1+\Delta k-1} \sin^2\left(2\pi f_P k\Delta t + \varphi_P\right) - \\ &-2U_{mP} \cdot \sum_{k=k_1}^{k_1+\Delta k-1} u_k \cdot \sin\left(2\pi f_P k\Delta t + \varphi_P\right). \end{aligned} \quad (9)$$

This function is quadratic in the parameter U_{mP}; therefore, the estimate of this parameter is the quantity

$$\hat{U}_{mP} = \frac{\sum_{k=k_1}^{k_1+\Delta k-1} u_k \cdot \sin\left(2\pi f_P k\Delta t + \varphi_P\right)}{\sum_{k=k_1}^{k_1+\Delta k-1} \sin^2\left(2\pi f_P k\Delta t + \varphi_P\right)}, \quad (10)$$

where the values k_1 and Δk are taken to be equal to their estimates, respectively, $\hat{k}_1$ and $\Delta\hat{k}$ obtained by minimizing $W_{P1}(U_{OP}, k_1, \Delta k)$.

As a result, the estimate of the amplitude turned out to be expressed through the known values of the input voltage readings and through the unknown values of f_P and ϕ_P with the previously obtained estimates $\hat{k}_1$ and $\Delta\hat{k}$, because $\hat{U}_{mP} = f_U\left(f_P, \varphi_P | \hat{k}_1, \Delta\hat{k}\right)$ Substitution of estimate (10) into formula (9) leads to the fact $W_{P1}(U_{mP}, f_P, \phi_P)$ turns out to be a function of not three parameters, but only two:

$$W_{P2}\left(f_P, \varphi_P | \hat{k}_1, \Delta\hat{k}\right) = f_W\left(f_P, \varphi_P\right). \quad (11)$$

This is also the simplest case of a separable function of two variables [14], the minimization of which is accompanied by relatively low computational costs.

Thus, estimates of the set of six parameters of a single impulse noise can be obtained as a result of simple two-dimensional (rather than six-dimensional according to the number of unknown parameters) minimization procedures.

The parameters of the useful signal s (t), interference from the adjacent TRC $v_C(t)$, interference from traction current and power lines $v_Q(t)$, and interference from the traction converter of the locomotive $v_T(t)$ are conveniently estimated by analyzing the input signal-interference mixture in the frequency domain ...All of them are periodic functions of time on the observation interval. Therefore, it is convenient (and the function $v_T(t)$ is the only one possible from a priori information) to represent them in the form of Fourier series. The harmonic frequencies of the $s(t)$ and $v_C(t)$components are known from the technical characteristics of the TRC, and the frequencies of the $v_Q(t)$component are also known and are multiples of 50 Hz. These circumstances make it possible to apply spectral analysis while minimizing the ILLRN. The statistical justification for this approach is as follows. The logarithm of the likelihood ratio of a structurally deterministic oscillation received against a background of Gaussian noise is equivalent to the problem of approximating the observed process $u(t)$ by a function $x(t)$ using the least squares method [14, 15]. Minimization of the ILLRN value is performed, which is the same. It is known that the representation of the process $u(t)$ by the Fourier series is precisely the result of its approximation by the least squares method using the sum of sinusoids with multiple frequencies [16]. Therefore, estimates of the amplitudes, frequencies and initial phases of the harmonics of oscillations $s(t)$, $v_C(t)$, $v_Q(t)$, and $v_T(t)$ can be obtained by subtracting from $u(t)$ the previously measured single pulse $v_P(t)$ and after that expand the remainder in a Fourier series. For the numerical implementation of this operation, there are fast (and economical in terms of computational costs) methods [17]. Considering that the frequencies of the harmonics of the oscillations $s(t)$, $v_C(t)$and $v_Q(t)$ are known, and the frequencies of the harmonics of the oscillations $v_T(t)$ are unknown [13], it is advisable to modify the above procedure as follows. After expanding the remainder into a Fourier series, only estimates of the amplitudes and initial phases of the oscillation harmonics $s(t)$, $v_C(t)$, and $v_Q(t)$ at their previously known frequencies should be found as numerical values of the readings, respectively, of the amplitude spectrum and the phase spectrum of the indicated remainder. Moreover, the slopes of the spectra of the phases of the signal s (t) and the interference $v_C(t)$ from the adjacent TRC are, respectively, their shifts t_S and t_C relative to the beginning of the observation. In view of the triviality of the mentioned numerical relationships in the spectra, the mathematical description of their application is omitted.

Then, by summing these harmonics, let's restore the time function $s(t)+v_C(t)+v_Q(t)$ and subtract it from the remainder $[u(t)-v_P(t)]$. Now the new remainder contains only the interference $v_T(t)$ and Gaussian noise. The system of harmonics found in this new remainder is the harmonics that interfere with $v_T(t)$. In such a situation, the methods of automatic detection of harmonics described in [18, 19] are effective. As a result of applying any of these methods, it becomes possible to obtain the numerical values of the amplitudes, frequencies and initial phases of these harmonics and to restore the dependence $v_T(t)$ in continuous or discrete time. Having reconstructed the signal and structurally determined interference in the observation interval, it is possible to calculate the values of the objective functions ξ_S and ξ_F, compare them with each other and make a decision on the presence or absence of the TRC signal.

The block diagram of the corresponding device for optimal signal reception of the TRC is shown in Fig. 1. Auxiliary devices for analog-to-digital conversion and synchronization are not shown here.

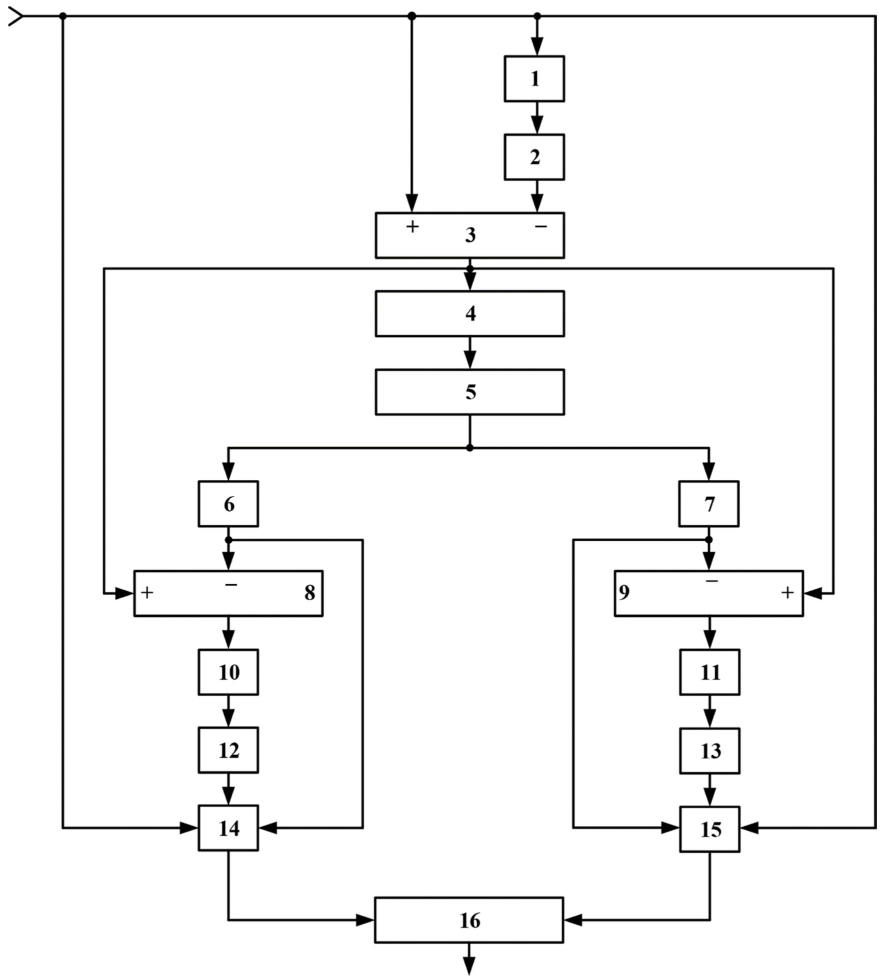

Fig. 1. Block diagram of the device for optimal reception of signals of tone rail circuits: 1 — shaper of estimates of values U_{OP}, U_{mP}, f_P, ϕ_P; 2 — pulse recovery unit v $v_P(t)$; 3 — adder ("+" — summation input, "-" — subtraction input); 4 — block of Fourier transform; 5 — generator of estimates of the parameters of oscillations $s(t)$, $v_C(t)$, $v_Q(t)$ and thevaleus τ_S and τ_C; 6 — vibration recovery unit $v_C(t)+v_Q(t)$; 7 — oscillation recovery unit $s(t)+v_C(t)+v_Q(t)$; 8, 9 — adders ("+" — summation inputs, "-" — subtraction inputs); 10, 11 — blocks for automatic detection of harmonics; 12, 13 — blocks of restoration of the oscillation $v_T(t)$; 14 — block for calculating ξ_F; 15 — block for calculating ξ_S; 16 — device for selecting the lesser of the values

To implement the structure of the circuit of the device shown in Fig. 1, processors widely available at present can be used [20].

5. 2. Numerical assessment of the noise immunity of the developed device

For a numerical assessment of the noise immunity of the developed device, a computer simulation of the signal and interference was carried out and the subsequent calculation of their energy characteristics. Fig. 2 shows a graph of the dependence of the input signal of the device on time over an interval of 1 s. The useful signal has a carrier frequency of 420 Hz and a modulation frequency of 8 Hz, the interference from an adjacent TRC has a carrier frequency of 480 Hz and a modulation frequency of 12 Hz. The amplitude U_{mS} of the useful signal is equal to 0.042 V, which is a typical value of the input voltage of the transformer at the receiving end of the TRC [21]. The amplitude of the interference from the adjacent TRC is 0.01 V. The parameters of other interference required for the subsequent energy calculation are as follows: the amplitude of the non-sinusoidal interference υ_T from the traction converter of the locomotive is 0.8 V; the amplitude of the non-sinusoidal interference υ_Q from the traction current and interference from the power line 0.09 V; amplitude of impulse noise 1.5 V with impulse duration τ_P=0.05 s; root-mean-square deviation σ_r of stationary Gaussian noise 0.19 V with a uniform spectrum ΔF 2500 Hz.

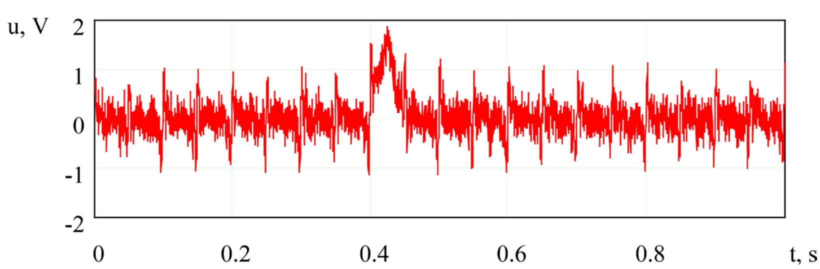

Fig. 2. Useful signal distorted by impulse noise, traction current and power line noise, locomotive traction converter noise, and continuous Gaussian noise

For the direct calculation of the noise immunity of the developed device, the well-known expression (12) was used to calculate the average probability of an error in distinguishing two equally probable structurally determined P_{EM} signals using the maximum likelihood method. This expression is given, for example, in [22]. In this work, let's apply the differentiation of signals by the criterion of least mean squares. Under the condition of observing signals against a background of Gaussian interference, such a distinction, as is known, is mathematically equivalent to a distinction based on the criterion of maximum likelihood. Therefore, the indicated expression gives the value of the potential noise immunity of a synthesized device using an isolated logarithm of the likelihood ratio of the ILLRN:

$$P_{EM} = 1 - \Phi\left\{\sqrt{q_S \cdot (1+\delta-2\rho_{S1}) \cdot 0.25}\right\}, \quad (12)$$

where $\Phi(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{y^2}{2}} \mathrm{d}y$ – normal distribution function;

$q_S = \frac{2E_1}{N_0}$ – ratio of the energy E_1 of the oscillation Z_{Sk} to the spectral power density of the Gaussian noise N_0;

$$N_0 = \sigma_r^2 / \Delta F;$$

δ – ratio of the energy E_2 of the vibration Z_{Fk} to the energy of the vibration Z_{Sk};

$$E_1 = \sum_{k=1}^{K} z_{Sk}^2 \cdot \Delta t;$$

$$E_1 = \sum_{k=1}^{K} z_{Fk}^2 \cdot \Delta t;$$

$\Delta t = 1/(2\Delta F)$ – sampling interval of the input oscillation u_k in time;

$\rho_{S1} = B_S / E_1$ – normalized cross-correlation function of oscillations Z_{Sk} and Z_{Fk};

$B_S = \sum_{k=1}^{K} Z_{Sk} \cdot Z_{Fk} \cdot \Delta t$ – the cross-correlation function of the above fluctuations.

Table 1 shows the results of calculating the value P_{EM} as a function of the amplitude of the useful signal U_{mS} at three different values of the rms voltage of the Gaussian noise: σ_r=0.1 V; σ_r=0.19 V and σ_r=0.5 V. The symbol "0" means a numerical value, the smallness of which lies outside the accuracy of calculations.

On the basis of the calculation results, the curves of the dependence of the P_{EM} value on the U_{mS} amplitude were plotted for each of the three numerical values of the σ_r value (Fig. 3).

The results of the calculation of the noise immunity of the developed device were compared with the requirements of the DSTU 4178-2003 standard "Complexes of technical means of control systems and regulation of train traffic. Functional safety and reliability. Requirements and test methods" (its European counterpart is CENELEC EN50126: Railway Application - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety). This standard establishes the permissible probability of failures leading to dangerous failures equal to $1.6 \cdot 10^{-10}$ per one hour of operation. The developed device makes a decision on the presence or absence of a signal every second (but the value of the interval can be changed in any direction, that is, it is not fundamental). Thus, the probability of having at least one erroneous solution is P_{E3600}=1 $(1-P_{EM})$ 3600≈1–1+3600P_{EM}=3600P_{EM}. Therefore, to meet the requirements of the standard, the value of the P_{EM} per second error should be no more than $1.6 \cdot 10^{-10}/3600 \approx 4.45 \cdot 10^{-14}$. Comparing this value with the results of calculating the noise immunity illustrated in Fig. 3, it can be concluded that the developed device exceeds the DSTU requirements in a wide range of useful signal amplitudes and noise interference powers.

The results of calculating the P_{EM} value allow to conclude that the developed device reliably recognizes the situation of the presence of a useful signal of the TRC in the input mixture of this signal and typical interference. Variations in the amplitudes of structurally determined noise in the course of calculations showed that the values given in Table 1 dependencies are extremely little sensitive to these changes (no more than in the second decimal place). This means that the device is resistant to structurally determined interference of the considered types.

Table 1

Average probability of P_{EM} discrimination error at different numerical values of rms noise voltage σ_r as a function of the useful signal amplitude U_{mS}

U_{mS}, V	0.001	0.005	0.010	0.020	0.030	0.040	0.060	0.080	0.100
					P_{EM}				
At σ_r=0.1 V	0.430	0.188	$3.86\cdot10^{-2}$	$2.04\cdot10^{-4}$	$5.69\cdot10^{-8}$	$7.69\cdot10^{-13}$	0	0	0
At σ_r=0.19 V	0.463	0.321	0.176	$3.14\cdot10^{-2}$	$2.63\cdot10^{-3}$	$9.90\cdot10^{-5}$	$1.19\cdot10^{-8}$	$4.91\cdot10^{-14}$	0
At σ_r=0.5 V	0.486	0.430	0.362	0.240	0.144	$7.87\cdot10^{-2}$	$1.70\cdot10^{-2}$	$2.34\cdot10^{-3}$	$2.04\cdot10^{-4}$

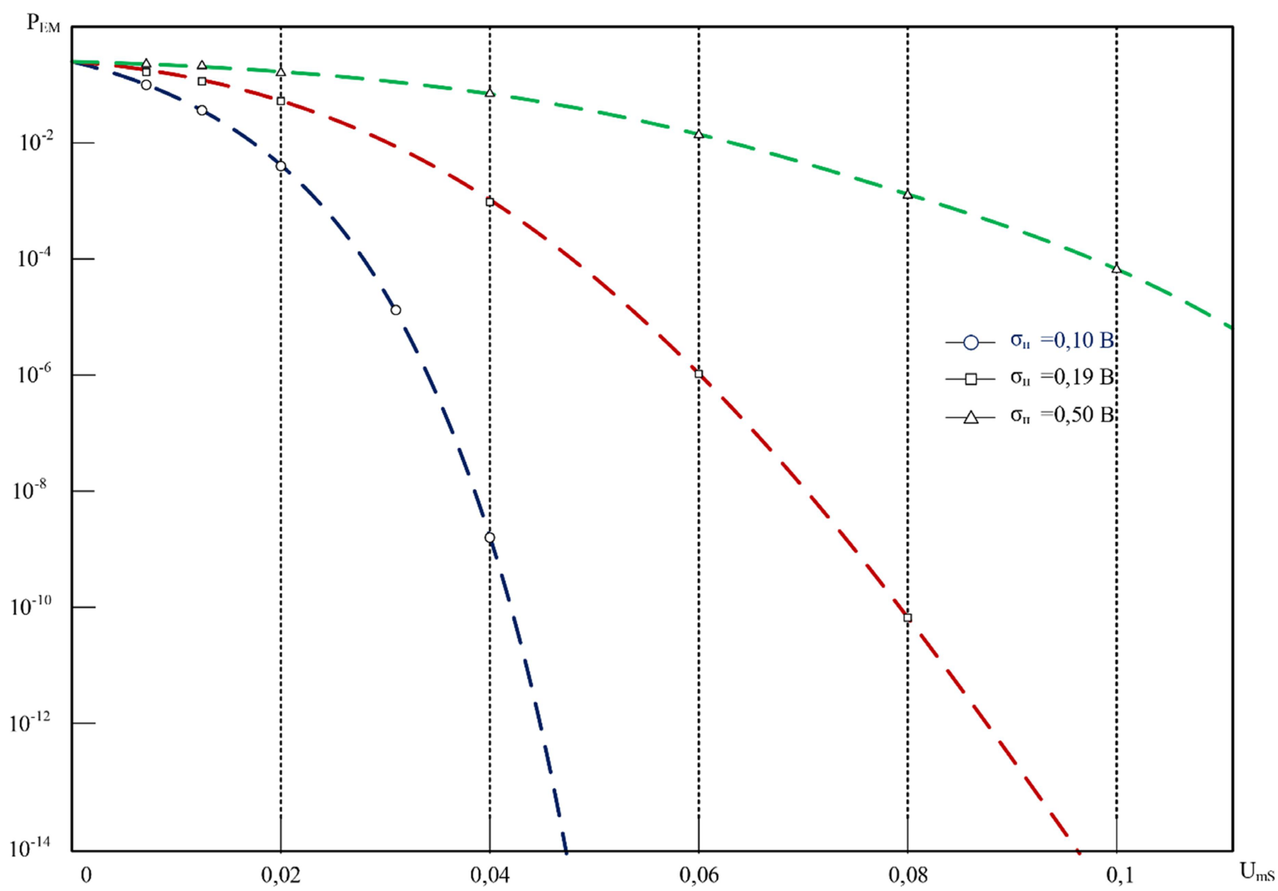

Fig. 3. Dependence of the average probability of the P_{EM} discrimination error on the amplitude UmS of the useful signal of the TRC at different values of the rms noise voltage σ_r

6. Discussion of the results of the synthesis of a device for noise-immune reception of TRC signals

The presentation of the procedure of noise-immune reception in the form of two parallel channels of correlation processing with the introduction of correction terms and subsequent comparison of the voltages at the outputs of the channels is proposed (Fig. 1). This type is explained by the solved classical (despite the five-component interference) problem: there is a signal in the input mixture or not. A feature of the processing method is the use of joint estimation of signal parameters and structurally determined interference components. The use of such an estimation limits the scope of research to situations in which structurally determined disturbances can be described with analytical expressions rather accurately. The expansion of the diversity of the jamming environment indicates that the considered set of jamming types will become insufficient after some time. In the future, this drawback can be eliminated by the flexibly reconfigurable modular organization of the processing procedure (where each module provides information about one specific type of interference). Or, to approximate the structurally determined interference component of the input signal, it is possible to use some generalizing function of time that can give an adequate description of the predictable number of interference components. Both of these options represent possible paths for the development of this study. When moving along the first of them, it is necessary to overcome difficulties in substantiating the mathematically and physically correct modular representation of the processing procedure. When moving along the second path, the same can be said about the construction of the indicated generalizing function of time.

The calculation of statistically substantiated estimates of signal parameters and structurally determined interferences is based on the fact that typical TRC interferences, except for impulse interferences, are periodic functions in the observation interval. TRC signal is also such a function. Periodic functions of real processes have a one-to-one representation in the form of a Fourier series. Therefore, the parameters of noise and signal are estimated in a combined way: the parameters of periodic processes are estimated by their reconstruction from harmonic components, and the parameters of impulse noise – by analytical optimization of the logarithm of the likelihood ratio (5)–(11). Since Fourier analysis of a signal against a background of Gaussian interference is equivalent to maximum likelihood estimation, both approaches provide methodological uniformity of estimates. This method of assessment, as far as can be judged from the covered literary sources, has not yet been used. However, its optimality is limited to the case when the structurally indeterminate interference is stationary Gaussian noise. It seems interesting to find the possibility of extending the generated optimal reception procedure to the case of non-Gaussian and non-stationary interference.

The solution of the problem of numerical estimation of the noise immunity of the synthesized device could be performed in two ways. The first of them is its computer modeling with the simultaneous accumulation of statistics of erroneous decisions. However, the standard for railways value of the probability of an erroneous decision according to the CENELEC EN50126 standard: Railway Application – The Specification and Demonstration of Reliability, Availability, Maintainability and Safety is of the order of 10^{-9}. The accumulation of model statistics for a reliable assessment of such a small error probability presents certain difficulties, which are associated with the need to use supercomputers that are still not widely used. Therefore, the second method was used – an analytical calculation of the average probability of an error in distinguishing two equally probable structurally determined signals using the maximum likelihood method. The limitation of this method is its focus only on the case when the random component of the input signal of the receiver is Gaussian. Simulation would be able to provide an estimate of the noise immunity for any law of distribution of interference. The potential universalism of its results so far runs up against an experimental obstacle – the limited performance of the available computing facilities.

The synthesized optimal receiver of the TRC signal is based on the well-known methods of correlation reception and spectral analysis of signals. However, these methods were applied not to isolate a purely signal component from the general signal-interference mixture, but to fully estimate the parameters of both the useful signal and structurally determined interference. This makes it possible to determine in real time the composition and parameters of the aggregate of such interference. The described method of action was not considered in previous works. Thus, the developed device actually receives a composite pseudo-signal formed by the sum of the useful information signal and structurally determined interference. This practically eliminates the undesirable possibility of false triggering of the SEC equipment at large amplitudes of structurally determined noises, since during processing all the parameters of these noises are measured and their influence on the useful signal is compensated. Only stationary Gaussian noise remains the actual noise. This is a limiting factor in the application of the developed device in the case of non-stationary noise interference. Extending the capabilities of this device to the situation of non-stationary noise is a direction for further research.

Comparison of the mean error of discrimination provided by the synthesized receiver with the requirements of the current standard made it possible to conclude that the developed device exceeds the requirements of this standard in a wide range of useful signal amplitudes and noise interference powers.

The authors did not consider the issue of energy costs associated with the operation of the device due to the fact that when developing noise-immune receivers, it is generally accepted to synthesize a signal processing procedure. The calculation of the electricity costs required for the operation of such devices is traditionally considered a task that lies in a different plane of interest. Its solution is the goal of subsequent research and development.

6. Conclusions

1. On the basis of a given general form of the objective function, its modifications are constructed, corresponding to the presence or absence of a useful signal in the input signal-interference mixture. As a consequence, the algorithm for detecting a useful signal is reduced to the well-known procedure for distinguishing between two structurally determined oscillations. These oscillations are formed as the sum of structurally determined components of the interference and the useful signal, or as the sum of only the indicated components of the interference and are called pseudo-signals. It is shown that the statistically justified estimates of the parameters of the pseudo-signal are the estimates obtained by minimizing the isolated logarithms of the likelihood ratio of the signal and each of the structurally deterministic interference (ILLRN). These ILLRNs were introduced in [5]; they are the summands of both modifications of the objective function. The terms of the objective function not included in the ILLRN are calculated on the basis of the above estimates and make corrections to the values of both modifications of the objective functions.

2. For a numerical assessment of the noise immunity of the developed device, the average error of discrimination of pseudo-signals was calculated. If the value of the root-mean-square deviation of the interference is not more than 0.1 V and the signal amplitude is not less than 0.08 V, the error value does not exceed $4.9 \cdot 10^{-14}$. This is the threshold value of the current standard. Practical interference values are less, and signal amplitudes are greater, therefore, it can be concluded that the developed device exceeds the requirements of the standard in a wide range of useful signal amplitudes and noise interference powers.

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