В системах управління актуальною проблемою є зменшення впливу шумових завад з метою збільшення співвідношення сигнал/завада (SNR). Ця проблема є також актуальною для інших технічних систем. Дана робота присвячена ортогональній лагерровській фільтрації шумових процесів, які описуються лінійними випадковими процесами. Запропонований метод фільтрації дає можливість зменшити вплив шумових завад, які описуються стаціонарними лінійними випадковими процесами, при роботі кореляційних систем. Ідея цього методу полягає у використанні ортогональних фільтрів Лагерра в якості вхідних ланок кореляційної системи.

На основі ортогональної лагерровської фільтрації стаціонарного білого шуму отримано послідовність шумових процесів, які некорельовані на значному часовому інтервалі їх взаємного зсуву. Такі процеси описуються стаціонарними лінійними випадковими процесами і є моделями широкого кола шумових завад, які досліджуються при роботі різних технічних систем, включаючи системи управління, виявлення, розпізнавання, вимірювання, тощо. При використанні такого методу зменшується вплив шумових завад з різними кореляційно-спектральними характеристиками і збільшується SNR на виході кореляційної системи. Для запропонованого адаптивного методу ортогональної лагерровської фільтрації вирішуються практичні задачі зменшення дії стаціонарних шумових завад, для цього в статті наведена структурно-логічна схема кореляційної системи. За допомогою програмного забезпечення реалізовано алгоритм адаптивної фільтрації на базі складних фільтрів Лагерра. Реалізація була проведена для реальної шумової завади, яка належить до класу RLC шумів, з попереднім навчанням фільтру. Про ефективність зменшення впливу заданої стаціонарної шумової завади свідчить отримані коефіцієнти ефективності у розмірі –6 дБ та –16 дБ для множини точок занулення завади

Ключові слова: шумова стаціонарна завада, лінійний випадковий процес, ортогональний фільтр Лагерра, співвідношення сигнал/завада, кореляційна система

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APPLYING AN ADAPTIVE METHOD OF THE ORTHOGONAL LAGUERRE FILTRATION OF NOISE INTERFERENCE TO INCREASE THE SIGNAL/NOISE RATIO

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1. Introduction

Information signals are widely used in various fields, including their application in control systems. It should be noted that, given the powerful information resource of noise signals, the potential possibilities of their use have not been utilized in full when creating modern information technologies, developing the software and hardware information and control systems. This can be explained by the hypothesis that noise signals in radio-electronic systems are considered as interference, which, accordingly, underlies the methodology of research into reducing their intensity and the level of influence. Such a methodology is still relevant in the analysis and synthesis of technical systems for various purposes. This applies to issues related to the system noise immunity.

The wide range of tasks on processing the information signals under the action of interference is common knowledge. To solve them, classical and modern methods are used. The theoretical foundation of research into noise signals is the boundary theorems of the sum of independent random quantities, which were further advanced within the framework of the theory of linear and harmonized random processes and fields. The practical justification for such studies is the stochastic integrated physical mechanism of noise signals formation and their distribution in different mediums.

It should be noted that known methods for decreasing the signal/noise ratio are based on a limited series of theoretical ideas. An example would be the use of a reference model of the Gaussian random process of white noise as a noise interference [1]. Even though the continuous white noise has not been physically implemented, this model is widely used.

2. Literature review and problem statement

Paper [1] investigates the wireless information transfer systems using an adaptive filter based on the least-squares method (LSM) to reduce the impact of noise interference – the Gaussian white noise. However, the cited paper is generally applied to eliminate the attenuation within the wireless information transfer systems. The results of using an estimate of the signal/noise ratio (SNR) based on Kalman filtration are reported in [2]: the cognitive radio networks were investigated. It should be noted that the Kalman filtration algorithm is described to apply to the Gaussian white noise, for which the SNR estimate is projected, but no results for other types of noise interference were given. The results of changing the dynamics of numerical series and textured objects in image research using a reference model of a random process of the Gaussian white noise, as a random process with uncorrelated (in a broad sense) or independent (in a narrow sense) values, were described in [3]. These results make it possible to evaluate the presence of a Gaussian Markov random field in the tasks on detecting a textured object in a noisy image. It would be expedient to see how these results could be applied to other subject areas. Work [4] examined the low levels of SNR in object detection systems and proposed the use of two new detectors under the action of non-Gaussian noise interference. However, it should be noted that the accuracy of measuring the parameters of a usable signal can be achieved for the case of a correlated non-Gaussian interference. Computer simulation of problems on the recognition of objects under conditions of indirect visibility (Non-Line-of-Sight) employs the methods of inverse correlography with the use of white noise implementations in line with a uniform distribution law [5]. This method is limited due to the use of only correlated non-Gaussian interference. According to the results reported in [6], the use of the phase-rotated spectral correlation detection method for spectral investigations provides for the enhancement of SNR versus the energy and single-cycle cyclo-stationary detector. The detectors, which operate on this principle, surpass energy detectors in terms of analytical results and model experiments but are quite complex in technical implementation. The results of the Xilinx Artix-7 FPGA chip operation in studying the algorithm for orthogonal mutual correlation under a strong exposure to the Gaussian white noise aimed at increasing the SNR are reported in [7]. To implement the algorithm of orthogonal reciprocal correlation of the investigated signals, an additional supporting signal is generated, the phase characteristics of which are shifted by $\pi/2$ relative to the investigated one. This is a known signal orthogonalization method, similar to the method for forming quadratic signals in phase systems. The basic provisions of the theory and practice of noise interference are given in [8]. The linear random processes with infinitely dividing distribution laws, including Gaussian and Poisson, have been used as a mathematical model of noise interference. In practice, noise interference studies that are most used in the study of radio-electronic systems are the white noises, including heat and fractional ones. A given work offers the use of the correlation orthogonal filters for processing the geophysical signals. However, the implementation of such an idea is not clearly formulated; no recommendations for its practical implementation are given. It is proposed, for the technical diagnostics tasks, to use a method for finding the piecewise-homogeneous intervals of noise signals [9]. The method reduces the effect of the interference component due to the use of singular spectral analysis and subsequent sliding processing of the noise sequence. However, when using such a method, it is necessary to clearly define the threshold values used for the sliding processing of the noise sequence, which is not described in practice.

It follows from our analysis that increasing the SNR has not fully used the possibility of decreasing the denominator values of this correlation. In a general statement, this is the issue related to increasing the noise immunity of technical systems.

3. The aim and objectives of the study

The aim of this study is to ensure an increase in SNR at the correlation system output by using the adaptive method of the orthogonal Laguerre filtration of noise interference. Such an approach would make it possible to reduce the value of the SNR denominator.

To accomplish the aim, the following tasks have been set:

– to analyze the operation of a correlation system with the input orthogonal Laguerre filters under the action of white noise with the infinitely dividing distribution laws as a process with the uncorrelated values for analog and digital variants;

– to design a functional structural-logical circuit of the correlation system with the complex orthogonal Laguerre filters, which would give an opportunity to use them in practice;

– to conduct a computer simulation experiment to substantiate the reduction of the influence of the interference at the output of the correlation system when using complex orthogonal Laguerre filters.

4. Analysis of the operation of the correlation system with the input orthogonal Laguerre filters

The responses from the n-channel linear system of the Laguerre filters $\xi_n(\omega, t)$ under the action of stationary white noise $\zeta(\omega, t)$ (Fig. 1) are uncorrelated along the semi-axis of their lateral time-dependent shift as a sequence of the uncorrelated linear random processes.

The theoretical justification of the proposed assertion is based on the following results obtained using [9, 10].

For a continuous case, the reciprocal correlation function of the Laguerre filter response at $n>m$ is determined as follows:

$$R_{mn}(\tau)=\mathrm{M}\left\{\xi_m(\omega,\, t)\cdot\xi_n(\omega,\, t+\tau)\right\}=$$
$$=\begin{cases}(-1)^{m+n-2}\,\alpha^2\sigma_c^2\displaystyle\int_{-\infty}^{\infty}\begin{array}{l}L_{m-1}(2\alpha t)L_{n-1}(2\alpha(t+\tau))\times\\ \times\exp(-2\alpha(t-\tau))dt,\end{array} & \tau\in(0,\infty),\\ 0,\quad \tau\in(-\infty,0].\end{cases}\qquad(1)$$

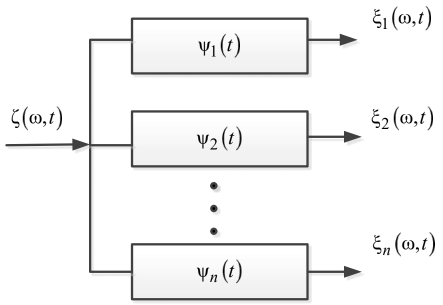

Fig. 1. Schematic of the Laguerre filter system's formation of the sequence of n time-uncorrelated responses along the semi-axis of mutual shift

In this expression: σ_c^2 – variance of the centered continuous input random process of white noise;

$$\{L_j(2\alpha t), j=0,1,2,...,n\}$$

is the sequence of orthogonal continuous Laguerre polynomials, parameter α is the parameter of implementation of the Laguerre filters (for LC filters, $\alpha=\frac{1}{\sqrt{LC}}$, for RC filters, $\alpha=\frac{1}{RC}$).

For a discrete case, the digital Laguerre filters under the condition of $n>m$, the mutual correlation function of their responses under the action of the centered discrete stationary white noise is determined as follows:

$$r_{mn}(s_j)=\begin{cases}\frac{(-1)^{n-m}\sigma_v^2}{\sqrt{1-\exp(-\lambda)}}\exp\left(\frac{-\lambda s_j}{2}\right)\times \\ \times\begin{bmatrix} l_{n-m}(s_j)- \\ -\exp\left(-\frac{\lambda}{2}\right)l_{n-m-1}(s_j)\end{bmatrix}, j\in\left[\overline{1,\infty}\right), \\ 0,\ j\in\left(\overline{-\infty,0}\right].\end{cases} \quad (2)$$

In this expression: σ_v^2 – variance of the centered discrete stationary white noise; $\{l_i(s_j), i=0,1,2,...\}$ – the orthogonal Laguerre polynomials of the discrete argument; $\{s_j=j\cdot\Delta t, j\in Z\}$ – the discrete uniform grid whose pitch Δt is determined from the time sampling conditions, and Z – the set of integers; λ – the digital Laguerre filter parameter.

The main provisions from the theory of statistical decisions and the theory of linear random processes (LRP) make it possible to use theoretical results for solving practical tasks.

A mathematical model of the input actual noise interference, which is described by the stationary LRP, is recorded for a discrete case as follows

$$\xi(\omega,t_j)=\sum_{i=-\infty}^{\infty}\phi_0(t_j-\tau_i)\zeta(\omega,\tau_i), \quad (3)$$

accordingly, the autocorrelation function of an actual noise interference model takes the form:

$$r_\partial(s_j)=\sigma_i^2\sum_{i=-\infty}^{\infty}\phi_0(t_i)\phi_0(t_i+s_j), \quad (4)$$

where $\phi_0(t_i)$ is the pulse transition function of the linear forming filter.

Typical continuous actual noise interference can be divided into two types:

a) the low-frequency broadband with a forming filter

$$\phi_0(t)=\alpha\exp(-\alpha t)U(t),$$

where $U(t_i)$ is the Heaviside function; α is the parameter of the pulse transition function of a filter (for example, RC filter);

b) the high-frequency narrowband with a forming filter

$$\phi_0(t)=e^{-\alpha t}\sin 2\pi f t,$$

where α and f are the parameters of the filter's pulse transition function (for example, RLC filter). A series of publications [4, 8] use the following titles of actual noise interference, respectively:

a) RC noise;

b) RLC noise.

Given the known statistics on the implementations of model (3), the use of methods for statistical processing of time series and the LRP theory, the statistical estimates of the process characteristics $\zeta(\omega,\tau_i)$ and functions $\xi(\omega, t_j)$ are determined unequivocally. A statistical estimation of the autocorrelation function is also determined (4). To solve practical problems, it is necessary to additionally introduce the following limitations, which are often when studying the operation of correlation systems. A statistical estimate $r_0(s_j)$ is obtained under the condition that two ergodic hypotheses hold for model (3), namely, the mathematical expectation and correlation function. The need for the implementation of ergodic hypotheses for a stationary LRP is connected to that the algorithm for computing a statistical estimation $r_0(s_j)$ is implemented not by the operator of the mathematical expectation of model (3) but the correlation operator of the time-averaged stationary LRP implementations.

The adaptive method of the orthogonal Laguerre filtration is proposed to ensure that the correlation system with the input Laguerre filters produces a decrease in the interference effect at the output.

The main provisions of a given method are based on the following:

– using the orthogonal Laguerre filtration of actual noise interference based on the complex digital Laguerre filters (complex Laguerre filters) with corresponding weight coefficients;

– determining the autocorrelation function of an input noise interference to form, over the predefined sequence, a reduction of the values of this function over the corresponding time shift sequence;

– determining the weight coefficients of the components of a complex Laguerre filter depending on the predefined sequence of reduction of the value of the mutual correlation function of noise interference at the output of the system;

– deriving the reduced values of the mutual correlation function of actual noise interference at the output of the correlation system;

– evaluating the effectiveness of the proposed method.

To implement this method, we have developed a structural-logic scheme.

5. Development of the scheme of the correlation system with complex orthogonal Laguerre filters

The functional structural-logical scheme of the correlation system with complex Laguerre filters is shown in Fig. 2.

The filter itself is composed of a sequence of the Laguerre filters, interconnected in parallel (Fig. 1); and in each of them, the responses are independently formed under the interference influence.

Using an adaptive method in practice implies the stage of training.

At the training stage, the autocorrelation function of the input noise component $r_0(s_j)$ is determined, which is described by a stationary LRP. At this stage, the complex Laguerre filters are formed with the pulse transient functions in the following form

$$\psi_1(t_j)=\sum_{k=1}^{m}\alpha_k\phi_k^{(1)}(t_j),$$

$$\psi_2(t_j)=\sum_{r=1}^{n}\beta_r\phi_r^{(2)}(t_j), \tag{5}$$

where

$$\left\{\phi_k^{(1)}(t_j),\phi_r^{(2)}(t_j),k\in[\overline{1,m}],r\in[\overline{1,n}]\right\}$$

is the system of orthonormal Laguerre functions of the discrete argument, $\left\{\alpha_k,\beta_r,k\in[\overline{1,m}],r\in[\overline{1,n}]\right\}$ – the valid numerical weight coefficients, in this case,

$$\phi_k^{(1)}(t_j)\neq\phi_r^{(2)}(t_j);\quad \alpha_k\phi_k^{(1)}(t_j)\neq 0;\quad \beta_r\phi_r^{(2)}(t_j)\neq 0.$$

We obtain, at the output of the correlation system, taking into consideration the expressions (4) and (5), a response from the system as a mutual correlation function of the input noise interference in the form

$$r_{mn}(s_j)=\sigma_q^2\sum_{i=-\infty}^{\infty}\sum_{k=1}^{m}\sum_{r=1}^{n}\alpha_k\beta_r h_{k,r}^{(1,2)}(\tau_i)r_0(s_j-\tau_i),$$

$$j\in\left(\overline{-\infty,\infty}\right), \tag{6}$$

where a mutual correlation transformation of the complex Laguerre filters is determined as follows:

$$h_{k,r}^{(1,2)}(\tau_i)=\sum_{j=-\infty}^{\infty}\phi_k^{(1)}(t_j)\phi_r^{(2)}(t_j+\tau_i),$$

$$i\in\left(\overline{-\infty,\infty}\right).$$

In general, expression (6) is the algorithm for the functioning of a correlation system with the input complex Laguerre filters under the effect of input noise interference, which is described by a stationary LRP in form (3).

In order to reduce the impact of noise interference, a sequence of values for the mutual correlation function $r_{mn}(s_j)$ is taken to be 0 over the predefined set of time-shift points $s_j\in[-K,K]$.

Next, it is necessary to determine the weight coefficients α_k and β_r in expression (5), based on the condition $K\leq m(n-1)$. To this end, it is necessary to solve the system of equations (6) relative to unknown α_k and β_r, by selecting m and p so that the number of equations equals the number of unknowns. Such a correlation system with the orthogonal filters makes it possible to ensure, for the input noise interference over the set of shifts $s_j\in[-K,K]$, the reduced values $r_{mn}(s_j)$.

To estimate the efficiency of the adaptive method for reducing the effect of noise interference, we shall use the expressions to compute the following numerical efficiency coefficients with the use of values for the mutual correlation function $r_{mn}(s_j)$. over the interval of time shifts $s_j\in\left[\overline{-P,P}\right]$:

$$A_1=10\cdot\lg\frac{\frac{1}{2P}\sum_{j=-P}^{P}\left|\tilde{r}_{mn}(s_j)\right|}{\frac{1}{2P}\sum_{j=-P}^{P}\left|\tilde{r}_0(s_j)\right|}, \tag{7}$$

$$A_2=10\cdot\lg\frac{\sqrt{\frac{1}{2P}\sum_{j=-P}^{P}\tilde{r}_{mn}^2(s_j)}}{\sqrt{\frac{1}{2P}\sum_{j=-P}^{P}\tilde{r}_0^2(s_j)}}. \tag{8}$$

The use of expression (8) has been theoretically substantiated to a greater degree.

The correlation system with the input complex Laguerre filters is adaptive to:

– the type and value of the intensity of the input noise stationary interference, which is taken into consideration by its autocorrelation function;

– the frequency range of the examined interference, which is determined by the choice of the λ parameter for the complex Laguerre filters;

– the number of channels for two complex Laguerre filters, which enables obtaining $2m(n-1)$ values of a sequence of reducing the correlation function at the output of the system.

The implementation of such a functional structural-logical scheme makes it possible to practically use the complex orthogonal Laguerre filters in order to reduce the signal/noise ratio.

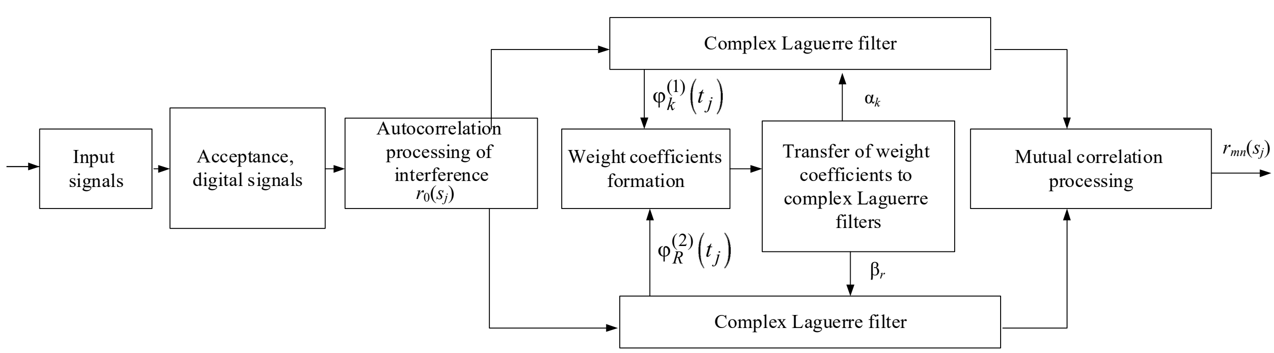

Fig. 2. The structural-logical scheme of a correlation system to implement an adaptive method

6. Results of computer simulation of the adaptive method of orthogonal Laguerre filtration of noise interference

The algorithm of the adaptive filtration has been implemented based on the complex Laguerre filters. The computer simulation experiment was conducted employing the Visual C++ programming environment.

To conduct the experiment, the following actions were performed:

1. One of the random process implementations has been received. A function for the normal distribution of pseudo-random values was used for this purpose.

Initial data:

Sample volume: N=10,000.

Mathematical expectation $M\zeta = 0$.

Variance $D\zeta = 1$.

The chart of the obtained implementation $r(i)$ is shown in Fig. 3.

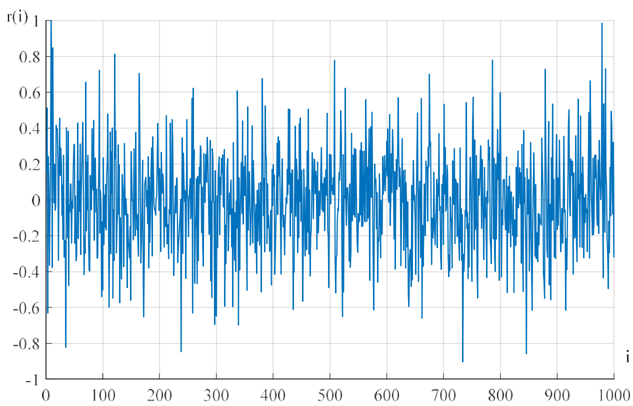

Fig. 3. The implementation of a discrete random process (first 1,000 values)

The estimates of mathematical expectation and variances have been computed, $M\zeta = 0{,}0004$ and $D\zeta = 0{,}9726$, respectively.

The estimation chart of the correlation function of one of the implementations of white noise $R(s)$, where $s \in (0{,}10)$, is shown in Fig. 4.

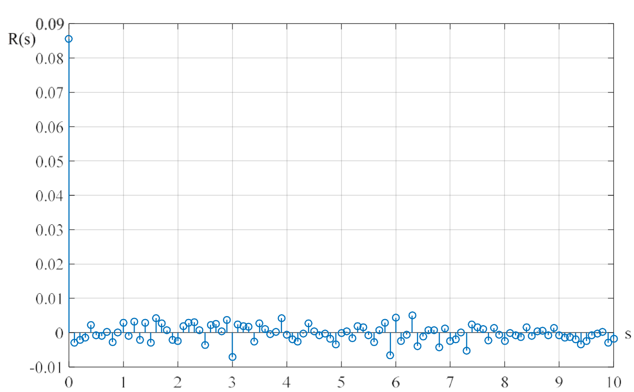

Fig. 4. The estimation chart of the correlation function of one of the implementations of white noise $R(s)$

The derived statistical characteristics of the white noise implementation confirm the expediency of using such a generator to obtain a sampling of the values with the Gaussian distribution. Further research is based on the received implementation.

2. Based on a sampling of the values with the Gaussian distribution law, the implementation of RLC-noise (Fig. 5) was formed to train the filter.

Initial data:

Implementation of the basic white noise.

Sample volume: N=10,000.

Pulse transition function of the RLC filter:

$$\phi_0(t_i) = e^{-\alpha t_i} \sin 2\pi f t_i, \quad i \in \left[\overline{0,N}\right].$$

A forming filter parameter: $\alpha = 0{,}1$.

Frequency: $f = 0{,}17$.

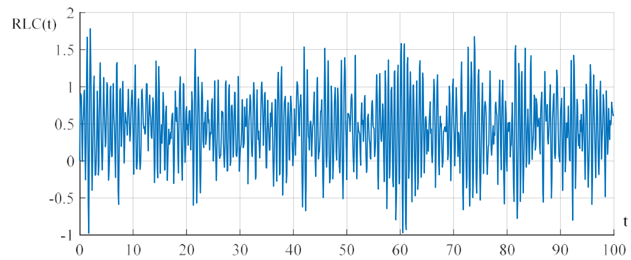

Fig. 5. The implementation of RLC noise (first 100 values)

The estimation chart of the autocorrelation function of the implementation of RLC noise R0(s), where $s_j \in (0{,}50)$, is shown in Fig. 6.

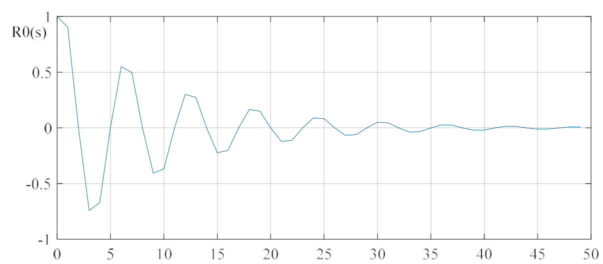

Fig. 6. The chart of the statistical estimation of the normalized autocorrelation function of the input noise interference at the stage of training

The resulting chart shows that the autocorrelation function of the noise interference accepts rather large values, which affects the signal/noise ratio at the output of the system. In order to reduce the impact of interference, the experiment involved the following actions.

3. The estimates of the weight coefficients β_r were calculated based on formula (6).

Initial data:

Estimation of the values of the correlation function of RLC-noise $\tilde{r}_0(s_j)$.

The number of zeroing points – 15.

The complex Laguerre filter parameter $\lambda = 0.1$;

$m = 1$;

$n = 16$;

$\alpha_k = \alpha_1 = 1$;

$r \in \left[\overline{2,16}\right]$.

The value of the mutual correlation function at the stage training must be equated to $r_{mn}(s_j) = 0$ over the range $s_j \in (0{,}15)$.

We determined the matrix of coefficients at unknown β_r in the system of 15 linear equations (Fig. 7).

By using the obtained coefficients, the values of the coefficients β_r were determined (Fig. 8).

A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12
-1,96E-05	-3,18E-05	-3,35E-05	-2,03E-05	1,71E-05	8,38E-05	0,000155	0,000132	-0,00018	-0,00075	-5,11E-05	0,006263	0,008673
-3,47E-05	-6,18E-05	-8,26E-05	-9,70E-05	-9,26E-05	-4,38E-05	7,75E-05	0,000243	0,000216	-0,00055	-0,00189	0,002324	0,029279
-5,13E-05	-9,77E-05	-0,00015	-0,00023	-0,00034	-0,00049	-0,00067	-0,0009	-0,00149	-0,0038	-0,01169	-0,03085	-0,05884
0,000456	0,00083	0,001182	0,00162	0,002241	0,003215	0,004892	0,00803	0,014135	0,025766	0,046194	0,079176	0,141461
-0,00221	-0,004	-0,00565	-0,00767	-0,01043	-0,01448	-0,0206	-0,02994	-0,04395	-0,06409	-0,09156	-0,12698	-0,15623
0,007035	0,0126	0,017381	0,022679	0,029198	0,037577	0,048449	0,06233	0,079349	0,098729	0,117403	0,125086	0,097061
-0,01439	-0,02545	-0,03421	-0,04289	-0,05226	-0,06267	-0,07409	-0,08596	-0,0969	-0,10403	-0,10231	-0,08696	-0,07301
0,020219	0,035312	0,046298	0,055896	0,064726	0,072731	0,079342	0,083454	0,083415	0,077411	0,065245	0,052013	0,041025
-0,02026	-0,03496	-0,04472	-0,05201	-0,05724	-0,06023	-0,06053	-0,0576	-0,05125	-0,04227	-0,0326	-0,02198	7,28E-05
0,014394	0,024521	0,030576	0,034197	0,035679	0,035071	0,032462	0,02818	0,022899	0,017353	0,011351	0,004139	0,006868
-0,00699	-0,01175	-0,01426	-0,01532	-0,01517	-0,01401	-0,01214	-0,00987	-0,00741	-0,00476	-0,00233	-0,00309	-0,00726
0,002253	0,003741	0,004437	0,004617	0,004403	0,003902	0,003203	0,002353	0,001427	0,000787	0,001105	0,000956	-0,00872
-0,00046	-0,00075	-0,00088	-0,0009	-0,00081	-0,00064	-0,0004	-0,00019	-0,00017	-0,00036	-4,10E-05	0,001863	-0,00262
2,17E-06	-2,02E-06	-1,73E-05	-4,42E-05	-7,55E-05	-8,93E-05	-4,98E-05	5,71E-05	0,000131	-8,49E-05	-0,00046	0,001135	0,004857
-1,71E-05	-2,78E-05	-3,42E-05	-4,48E-05	-6,83E-05	-0,0001	-0,00012	-7,09E-05	8,09E-05	0,000119	-0,00043	-0,00052	0,006533

Fig. 7. Equation coefficients values at unknown β_r

β
1,42360618
-1,239471282
0,808731126
-0,411236058
0,164521666
-0,05167857
0,012627266
-0,002362099
0,000330347
-3,34E-05
2,31E-06
-1,01E-07
2,42E-09
-2,23E-11
0,5

Fig. 8. Values of the β_r coefficients

It is necessary to check that the calculation is correct by the values of coefficients β_r. To test the filter performance, it is sufficient to determine the values for a mutually correlated function Rmn(s) using the derived coefficients (Fig. 9).

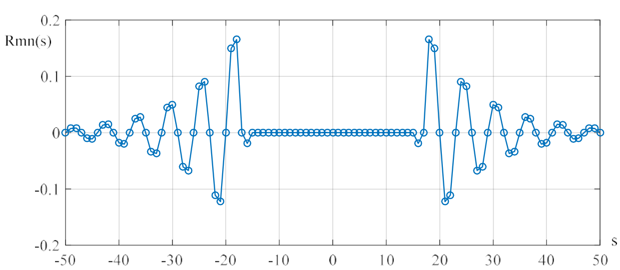

Fig. 9. The chart of statistical estimation of the response from the normalized correlation system with complex Laguerre filters under the action of noise interference at the stage of training

The built chart (Fig. 9) shows that, when using these coefficients, the complex orthogonal filter fully eliminates the interference as $r_{mn}(s_j)=0$ at points $s_j \in (-15,15)$.

Thus, the stage of training was performed for a given experiment. In the future, for the noise interference of the same type, one can use the calculated coefficients of the complex orthogonal Laguerre filter to compute the values for the mutual correlation function. To experimentally find a mutual correlation function, the following was performed.

4. We re-generated the RLC noise with similar parameters.

5. By using the calculated coefficients β_r of the complex orthogonal Laguerre filter, the value of the mutually correlated function Rmn(s) was calculated (Fig. 10).

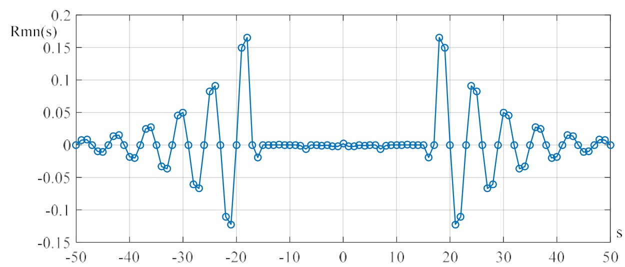

Fig. 10. The chart of statistical estimation of the response from the normalized correlation system with complex Laguerre filters under the action of noise interference at the stage of using

Fig. 10 shows the operation of the complex orthogonal Laguerre filter over the set of points $s_j \in (-15,15)$. Over this range, the values $r_{mn}(s_j)$ are not equal to 0 because it is impossible to accurately generate the identical interference. The practical use of the adaptive method implies the same. However, it should be noted that the following values of the system performance coefficients were obtained. For the set of points $s_j \in (-50,50)$

$$A_1 = -5{,}89984 \text{ dB},$$

$$A_2 = -5{,}90125 \text{ dB},$$

and for the set $s_j \in (-15,15)$

$$A_1 = -16{,}47063 \text{ dB},$$

$$A_2 = -16{,}48631 \text{ dB}.$$

The obtained numerical data confirm the fact of reducing the impact of noise interference, by –6 dB and –16 dB, respectively.

The implementation of computer simulation using the adaptive method was carried out for an actual noise interference, which belongs to the class of RLC noise. A given class of noise interference is formed in the typical links of radio-electronic systems.

7. Discussion of results of using the adaptive method of orthogonal Laguerre filtration

The justification of the correlation system using the complex Laguerre filters has been given. To this end, the theoretical information on the analog and digital Laguerre filtration was provided. It should be noted that up to now the complex Laguerre filters have not been used in practice. Because of this, we have proposed an adaptive method of the orthogonal Laguerre filtration and outlined its main provisions. The use of the adaptive method of the orthogonal Laguerre filtration makes it possible to form the uncorrelated linear stationary random processes along the semi-axis of their mutual time shift, which describe a wide range of actual noise interference. In this, a given method differs significantly from previously known methods.

The special feature of applying the method of the adaptive orthogonal Laguerre filtration when using the digital variant of processing the investigated signals is that it makes it possible to avoid solving a series of hardware tasks related to the creation of the appropriate analog modules of the correlation system.

The advantages of the method are as follows:

1. The theoretical justification, based on the results, of the theory of orthogonal functions and random processes, including LRPs.

2. The solution of the applied tasks using:

– known results of the theory and practice of processing stationary noise interference because the signals and interference create the non-stationary combinations and this largely restricts the range of research methods while the stationary noise interference is typical of the most applied problems;

– the digital variant of the method as an algorithm for operating a correlation system and the implementation of the concept model–algorithm–software in a computer simulation;

– the reduction of impact exerted by noise interference described by a stationary LRP for SNR assessment;

– the uniqueness of the orthogonal Laguerre filtration of a stationary white noise process – to form a sequence of uncorrelated noise processes over a significant time interval of their mutual shift;

– the potential capabilities to undertake, based on an LRP model, noise interference research not only within the framework of the correlation theory but with the use of higher moments;

– the pulse transition functions of linear forming filters.

Restrictions on the use of the adaptive method include:

1. The Laguerre filters are filters of lower frequencies, which narrows the frequency range of the examined noise interference.

2. In order to define SNR, additional research should be performed taking into consideration the transformation of signals in the links of a correlation system with the input Laguerre filters.

3. For the practical use of the method, it is necessary to conduct a training phase to the input noise interference.

4. In each case, it is necessary to assess the effectiveness of the method and decide on its application taking into consideration:

– an infinite interval of the orthogonality of Laguerre polynomials replaced with a finite one;

– changes in the values of the Laguerre discrete argument polynomials at their quantization;

– unbiasedness and effectiveness of the obtained statistical estimates of the mutual correlation function $r_{mn}\left(s_j\right)$.

The subject areas of method application are statistical hydroacoustics, geophysics, and radiophysics. The method could be used for vibration diagnostics and non-destructive control of technical systems, as well as in noise-reduction, which is a relevant field in the theory and practice of modern information technologies of measurements.

A computerized modeling experiment was implemented to further the expediency of the adaptive method of orthogonal Laguerre filtration. As a result of an example of calculating the parameters of pulse transitional characteristics with the orthogonal Laguerre filters, it is possible to draw the following conclusion. If one uses a predefined interference, it is possible to calculate the system of orthonormal functions of the Laguerre discrete argument. The values of these functions make it possible to build a filter that enables determining the characteristics of the correlation conversion of a usable signal over a certain offset range.

Thus, based on the use of the adaptive method of the orthogonal Laguerre filtration, we can create correlation systems to reduce the influence of stationary noise interference.

7. Conclusions

1. The operation of a correlation system with the input orthogonal Laguerre filters under the action of the white noise process with the infinitely dividing distribution laws as a process with the uncorrelated values for analog and digital variants has been analyzed. At the known statistics of the model implementations, the use of methods for the statistical processing of time series, and the LRP theory, the statistical evaluations of the process characteristics and functions are determined unequivocally; the statistical evaluation of the autocorrelation function is also determined. The adaptive method of the orthogonal Laguerre filtration has been proposed to ensure that the correlation system with the input Laguerre filters produces, at the output, a decrease in the interference impact.

2. Based on the proposed adaptive method, the functional structural-logical scheme of a correlation system with the complex orthogonal Laguerre filters has been developed, in which the filter is composed of a sequence of the Laguerre filters, which are interconnected in parallel, each of them independently forms the feedback under the action of interference. The proposed structural-logical scheme would make it possible to use them in practice to reduce SNR at the output of the system.

3. A computer simulation experiment has been conducted to substantiate the reduction of an interference influence at the output of the correlation system when using complex orthogonal Laguerre filters. As a result of the experiment, for an actual noise interference belonging to the RLC class of noise, the values of performance coefficients were obtained, –5 dB and –16 dB, depending on the range of values. Such results indicate a significant reduction in the impact of interference over the selected ranges.

References

1. Das, S., Sarma, K. K. (2012). Noise cancellation in stochastic wireless channels using coding and adaptive filtering. International Journal of Computer Applications, 46 (14), 21–25.
2. Miao, L. (2018). Research of Snr Estimation and Prediction Method Used in Cognitive Radio. Procedia Computer Science, 131, 1164–1169. doi: https://doi.org/10.1016/j.procs.2018.04.290
3. Arias-Castro, E., Bubeck, S., Lugosi, G., Verzelen, N. (2018). Detecting Markov random fields hidden in white noise. Bernoulli, 24 (4B), 3628–3656. doi: https://doi.org/10.3150/17-bej973
4. Artyushenko, V. M., Volovach, V. I. (2016). Measuring information signal parameters under additive non-Gaussian correlated noise. Optoelectronics, Instrumentation and Data Processing, 52 (6), 546–551. doi: https://doi.org/10.3103/s8756699016060030
5. Metzler, C. A., Heide, F., Rangarajan, P., Balaji, M. M., Viswanath, A., Veeraraghavan, A., Baraniuk, R. G. (2020). Deep-inverse correlography: towards real-time high-resolution non-line-of-sight imaging. Optica, 7 (1), 63–71. doi: https://doi.org/10.1364/optica.374026
6. Sun, C., Lu, P., Cao, K. (2019). Phase-Rotated Spectral Correlation Detection for Spectrum Sensing at Low SNR Regimes. IEEE Signal Processing Letters, 26 (7), 991–995. doi: https://doi.org/10.1109/lsp.2019.2917046
7. Hu, P., Liu, L., Shen, L. (2019). The Application of orthogonality cross correlation algorithm in weak signal detection. Journal of Physics: Conference Series, 1314, 012154. doi: https://doi.org/10.1088/1742-6596/1314/1/012154
8. Zharovskiy, R. O. (2010). Correlation orthogonal systems in problems of processing geophysical signals. Naukovyi visnyk NLTU Ukrainy, 20.7, 283–292.
9. Martyniuk, H. V., Shcherbak, L. M. (2018). Shumovi syhnaly ta yikh kharakterystyky. LAP Lambert Academic Publishing, 112.
10. Martyniuk, G., Onykiienko, Y., Scherbak, L. (2016). Analysis of the pseudorandom number generators by the metrological characteristics. Eastern-European Journal of Enterprise Technologies, 1 (9 (79)), 25–30. doi: https://doi.org/10.15587/1729-4061.2016.60608
11. Kozlovskyi, V., Korzh, R., Petrovska, S., Balaniuk, Y., Boiko, Y., Yakoviv, I. (2019). Low-Frequency Schemes of Substitution of Segments Inhomogeneous Transmission Lines. 2019 3rd International Conference on Advanced Information and Communications Technologies (AICT). doi: https://doi.org/10.1109/aiact.2019.8847844