The Method of Spectral Analysis of the Determination of Random Digital Signals

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Abstract: The article considers the improved method of spectral analysis. The task of spectral analysis is to find the parameters of random signals, the parameters of the model used, which is selected on the basis of available a priori information about the process under study. An improved method of spectral analysis is proposed, which uses a partially classical Proni method. This method has been improved by replacing the damping sine wave with the use of a non-damping sine wave. Replacing the attenuating sine wave with a non-damping sine wave allows you to very accurately isolate the signal and determine its characteristics against the background of very rich interference in the airspace, against the background of radios that operate legally. For the first time, a fast conversion algorithm was used to solve normal equations to find variables for sequentially determining the parameters of random short-term signals, such as amplitude, frequency, and phase. It is proposed to determine not only static parameters but also the rate of change of these parameters. The rate of change of parameters allows defining more accurately a signal of means of silent reception of information.
The simulation of the processes of determining random short-term pulses that simulate digital signals of silent information reception, based on the proposed method of spectral analysis, the simulation results are presented in the form of three-dimensional graphs.
The main difference is the use of not only the analysis of the amplitude, frequency, phase, and spectrum of the signal but also the basic analysis of the spectral density of the signal.
Analysis of the simulation results fully confirms the advantages of the proposed method for determining random short-term pulses.

Keywords*:* spectral density, model, spectrum, approximation, digital signals.

1. Introduction

Recently, there has been an increasing interest in parametric spectral analysis methods, especially when classical methods based on the use of the Fourier transform do not provide the necessary accuracy. This situation occurs either in the small signal-to-noise ratio or in the small interval of observation of the process under study. In the latter case, in order to improve the accuracy of the spectral density determination, it is necessary to use a priori information about the behavior of the investigated process outside the observation interval.
One of the parametric methods of spectral analysis is the Prony algorithm [1], which uses the representation of the observed process in the form of a complex exponential series. The method allows to find the parameters of these complex exponentials by reading the signal, which in turn makes it possible to record the expression for the spectral density of the investigated signal. The widespread use of the Prony method has become possible only recently, since it is substantially nonlinear and requires a large amount of computational cost. In this regard, there was a need for a detailed study of this method in terms of the optimality of its mathematical implementation, as well as the potential resistance to fluctuations in the readings of the signal and noise sampling.

2. Literature Analysis and Problem Statement

The most powerful apparatus for comprehensive signal analysis in digital processing is spectral analysis [1].
The methods of spectral analysis of random signals are divided into two large classes - nonparametric and parametric. In nonparametric methods, only the information contained in the analyzed signal data is used. Parametric methods imply the presence of some statistical model of a random signal, and the process of spectral analysis in this case contain the determination of the parameters of this model [2].
A significant role in signal analysis belongs to the complex Fourier transform. The Fourier transform (FT) and its discrete analogues (DFT) are well known and widely used in spectral analysis techniques in standard radio signal processing. It is effective in computing and easy to implement.
As a rule, such procedures give good results in the analysis of the frequency composition of long-term radio signals. However, there are known reasons limiting the use of Fourier transforms in the analysis of short signals, such as digital radio pulses, for example, the use of DFT for time-truncated signals leads us to the Gibbs effect, which distorts information on the signal spectrum and does not allow for high accuracy in spectral region in the analysis of harmonic components [1-3].
In [4-6] describes the Fourier transform, more attention is paid to the description of window transformations. This improves the use of these transformations, namely the use of window Fourier transforms improves the estimation of spectra but does not completely solve the problem of detecting pulse signals, which may be signals of illegal means of obtaining information.
Over the last several decades, comprehensive research on digital spectral evaluation has led to a significant development of current technologies in this field. The desire to find transformations that better correspond to the short duration of signals having an arbitrary time-space position, led to the appearance of wavelet analysis [7, 8]. It is based on short functions with temporal (spatial) and frequency localization, which gives a better approximation for short signals and allows to determine more precisely their harmonic components. However, the use of wavelet analysis in the processing of radio signals may have some limitations

in terms of interpretation, which is associated with the formal choice of some orthogonal functions as the basis for the corresponding transformation. From the above we can conclude that the issue of conversion of radio signals with its subsequent analysis is not finally resolved and requires constant improvement. Therefore, the use of advanced Proni decomposition methods, whose refinement is based on the use of complex exponentials or non-damping sine waves, which are better suited to the nature of radio signals, in order to determine short-term random signals is very relevant.

The means illegal obtaining informations typically emit a random signal. To detect and recognize this random signal against the background of legal radio signals, it is necessary to present this signal in a convenient form for digital analysis. Therefore, the purpose of the study is to represent the signal in the form of a model based on mathticical transformations, which most accurately reflects the signal, and will allow to determine the statistical characteristics of the signal.

3. The Proposed Method

The Prony method [1,4] is a method of analyzing short segments of a signal based on the approximation of a signal to a finite sum of complex exponents, which approximates the sequence of complex data of a model consisting of *p* damped complex exponents:

$$x(n)=\sum_{k=1}^{p} A_k \exp\left[(\alpha_k + j2\pi f_k)(n-1)T + j\theta_k\right], \quad (1)$$

where $1 \le n \le N$, *T* is the interval of reference in c, A_k i α_k amplitude and attenuation coefficient (dimension of attenuation coefficient c^{-1}) k complex exhibitor, f_k frequency, θ_k the initial phase k sinusoids. The values of these parameters are completely arbitrary.

Write the expression (1) in the form:

$$\hat{x}(n)=\sum_{k=1}^{p} h_k z_k^{n-1}, \quad (2)$$

where the complex constants are calculated by the expressions:

$$h_k = A_k \exp(j\theta_k), \quad (3)$$

$$z_k = \exp[(\alpha_k + j2\pi f_k)T]. \quad (4)$$

It should be noted that expression (3) is an expression for a complex amplitude representing a time-independent parameter, and expression (4) is an expression for a complex exponent describing the parameter dependent on time.

Ideally, with *N* segments of data, the sum of squares of errors can be represented as:

$$\rho=\sum_{n=1}^{N}|\varepsilon(n)|^2, \quad (5)$$

where $\varepsilon(n)=x(n)-\hat{x}(n)=x(n)-\sum_{k=1}^{p} h_k z_k^{n-1}$. (6)

The problem is that you need to minimize it by three parameters h_k, z_k and the number of exponents *p*. This is a non-linear problem and requires a lot of cost to solve.

The Pony procedure for adjusting *p* exponents to *2p* segments of data can be presented in three steps, in the first stage the equation for the coefficients of the polynomial is solved $a_1, a_2 \ldots\ldots a_p$, on in the second stage, the roots of the polynomial are calculated $z_1, z_2, \ldots z_p$. Using the obtained root equations, we determine the attenuation factor and the frequency of the sine wave, using the ratios:

$$\alpha_k = \ln\frac{|z_k|}{T}, \quad (7)$$

$$f_k = arctg[\frac{\operatorname{Im} z_k}{\operatorname{Re} z_k}]/2\pi T. \quad (8)$$

The third final step, the roots of the polynomial calculated in the second stage are used to form the elements of the matrix, which is then solved with respect to *p* complex parameters $h_1, h_2, \ldots h_p$. Each parameter is then used to determine the amplitude and initial phase, which are calculated by the expressions:

$$A_k = |h_k|, \quad (9)$$

$$\theta_k = arctg[\frac{\operatorname{Im} h_k}{\operatorname{Re} h_k}]. \quad (10)$$

The described algorithm decomposes *N* complex signal samples into *N/2* complex damping exponential components.

The disadvantages are:

large error of calculation at *N* exceeds 200 samples, because it is necessary to solve equations of the 100th and above order, as well as systems with 100 or more linear equations;

As shown above, it is possible to obtain a suboptimal solution that will provide more or less satisfactory results. Using the first and second steps of the Prony method, the corresponding least-squares linear procedures, we obtain an exponential modeling procedure called the generalized Prony method. In this suboptimal approach, the problem of nonlinear exponential fit is essentially a polynomial factorization problem.

In the predetermined case (we have excess data) the linear difference equation can be reduced to the form

$$\sum_{m=1}^{p} a_m x_{n-m} = e_n, \quad (11)$$

where $p+1 \le n \le N$.

The term of expression (23) e_n characterizes the error of approximation on the basis of linear prediction as opposed to the $\varepsilon(n)$ -error of exponential approximation.

Equation (11) is identical to the equation for linear prediction error, if each term a_m is considered as a parameter of linear prediction. Instead of expression (5), the parameters a_m can now be chosen as parameters that minimize the sum of squares of errors of linear prediction $\sum_{n=h+1}^{N}|e_n|^2$ rather than the sum of squares of errors of exponential approximation ρ defined by expression (5), or else it can be called the covariance method of linear prediction.

We determine the values of the parameters $z_1, z_2, \ldots z_p$ by linear least squares prediction and polynomial factorization, then the exponential approximation described by equation (2) becomes linear with respect to the remaining unknown parameters $h_1, h_2, \ldots h_p$, minimizing the sum of squares of errors for each parameter, we obtain the following complex normal equation with the matrix $p \times p$

$$(z^H z)h = (z^H x), \quad (12)$$

where $(N \times p)$ - matrix *Z*, $(p \times 1)$ - vector *h*, $(N \times 1)$ - the vector of data responses *x* is defined by the expressions:

$$Z=\begin{vmatrix}1\ 1\ \ldots\ldots\ldots1\\ z_1z_2\ldots\ldots\ldots z_p\\ \ldots\ldots\ldots\ldots\ldots\\ z_1^{N-1}z_2^{N-1}\ldots z_p^{N-1}\end{vmatrix},h=\begin{vmatrix}h_1\\ h_2\\ \ldots\\ h_p\end{vmatrix},x=\begin{vmatrix}x_1\\ x_2\\ \ldots\\ x_N\end{vmatrix}. \quad (13)$$

The emitting $(p\times p)$ - matrix Z^HZ has the form

$$z^Hz=\begin{vmatrix}\gamma_{11}\gamma_{12}\ldots\gamma_{1p}\\ \ldots\ldots\ldots\ldots\\ \gamma_{p1}\gamma_{p2}\ldots\gamma_{pp}\end{vmatrix}, \quad (14)$$

де $\gamma_{jk}=\sum_{n=0}^{N-1}(z_j^*z_k)^n=\gamma_{kj}^*$. (15)

If the $x(n)-\varepsilon(n)$ difference is used in the model of the main Prony method instead of $x(n)$ then the linear difference equation that describes this process, consisting of the sum of the exponents and the additive white noise, will look like:

$$x(n)=-\sum_{k=1}^{p}a_mx(n-m)+\sum_{k=1}^{p}a_m\varepsilon(n-m) \ . \quad (16)$$

Equation (30) is a random signal model with noise.
The first step of the Prony method uses the linear prediction equation:

$$x(n)=-\sum_{k=1}^{p}a_mx(n-m)+e_n \,. \quad (17)$$

Comparing expressions (16) and (17), we see that they do not correspond to each other, for this reason, the Prony method in general does not provide good results at a significant level of additive noise, there are errors in determining the noise attenuation coefficient, the values of these coefficients far exceed their true value.
This disadvantage is the basis for the determination of random radio signals. The variant of spectrum selection on the background of interference in which the coefficient exceeds the real one allows to determine with very high probability a random radio signal, which is typical for digital or impulsive means of silent receiving of information.
We modify the Prony least-squares method described above by a model consisting of non-decaying ($\alpha=0$) complex sine waves.
Model, for example, select a model containing an even number of components. Then the model (the model contains a *2p* component) will look like:

$$x(n)=\sum_{k=1}^{2p}A_k\exp\left[j2\pi f_k(n-1)T+j\theta_k\right]=\sum_{k=1}^{2p}h_kz_k^{n-1} \ , \quad (18)$$

where $1\le n\le N, h_k=A_k\exp(j\theta), z_k=\exp(j2\pi f_kT)$, considering that z_k has a unit module $|z_k|=1$. If h_k and z_k are complex conjugated pairs and $f_k\neq 0$ or $f_k\neq\frac{1}{2T}$ then the sequence from the readings of the real data can be approximated by a model consisting of an even and odd number *p* of real non-attenuating sine waves:

$$x(n)=\sum_{k=1}^{p}A_k\cos\left[j2\pi f_k(n-1)T+j\theta_k\right]= \\ =\sum_{k=1}^{p}(h_kz_k^{n-1}+h_k^*(z_k^*)^{n-1}) \ , \quad (19)$$

where $1\le n\le N$.
In the modified Prony method, in the first step, the linear prediction error defined by equation (11) is replaced by the conjugations symmetric linear smoothing error:

$$e_p^s(n)=x_n+\sum_{k=1}^{p}(g_p(k)x_{n+k}+g_p^*(k)x_{n-k}) \,. \quad (20)$$

Defined by $p+1\le n\le N-p$ and minimizes the sum of squares of smoothing errors:

$$\rho_p^s=\sum_{n=p+1}^{N-p}\left[e_p^s(n)\right]^2 , \quad (21)$$

and not the sum of squares of linear prediction errors defined by expression (5).
If we equate to zero complex derivatives from A to C, we obtain normal equations that can be written in the form of matrix equations:

$$R_{2p}g_{2p}=\begin{pmatrix}O_p\\ 2\rho_p^s\\ O_p\end{pmatrix}, \quad (22)$$

where the centrosymmetric matrix R_{2p} and the conjugate symmetric vector of column g_{2p} are defined by the expressions:

$$R_{2p}=\begin{vmatrix}r_{2p}(0,0)\ldots\ldots r_{2p}(0,2p)\\ \ldots\ldots\ldots\ldots\ldots\ldots\\ r_{2p}(2p,0)\ldots r_{2p}(2p,2p)\end{vmatrix}, g_{2p}=\begin{vmatrix}g_p(p)\\ \ldots\ldots\\ g_p(1)\\ 1\\ g_p^*(1)\\ \ldots\ldots\\ g_p^*(p)\end{vmatrix} . \quad (23)$$

The elements of the matrix R_{2p} are defined by the expression:

$$r_{2p}(j,k)=\sum_{n=2p+1}^{N}(x_{n-j}^*\cdot x_{n-k}+x_{n-p+j}\cdot x_{n-p+k}^*) \,. \quad (24)$$

In the process of finding a means of silent receiving of information, signal processing time is very important, so I propose a quick algorithm to solve (24) the equation.
It consists in the fact that in expression (24) we take $O_p-(p\times p)$ zero vector, then we have an expression for the centrosymmetric matrix in the form:

$$R_{2p}=\sum_{n=2p+1}^{N}(x_{2p}^*(n)x_{2p}^T(n)+J\,x_{2p}(n)x_{2p}^H(n)J) \,. \quad (25)$$

If the members of the smoothed error $e_{2p}^s(N-p), e_{2p}^s(p+1)$ are not used, the resulting error square is minimized.

$$p_{2p}^{s''}=\sum_{n=p+2}^{N-p-1}\left|e_{2p}^s(n)\right|^2 . \quad (26)$$

So we get the following normal equation:

$$R_{2p}^{''}g_{2p}^{''}=\begin{pmatrix}O_p\\ 2\rho_p^{s''}\\ O_p\end{pmatrix}, \quad (27)$$

where the double stroke marks the solution for the case of omitted error terms, then expression (25) will be:

$$R_{2p}^{''}=\sum_{n=2p+2}^{N}(x_{2p}^*(n)x_{2p}^T(n)+J\,x_{2p}(n)x_{2p}^H(n)J) \,. \quad (28)$$

The developed fast algorithm requires to solve this equation $Np+18p^2$ of the calculation, in addition we obtain the solution of least squares for all unknown smaller orders. In the case where the number of sine waves is unknown, this

property of the algorithm allows to check all models containing from one to p sine wave.
In the future. After obtaining the solutions of equations (25) and (28), the algorithm of calculating the amplitudes and initial phases of the sine waves by equations (7-10) is repeated.
Therefore, the modified Prony method reduces the computation time of the amplitude and initial phase of the sine wave, which is the main purpose when converting signals into a method of searching for means of silent receiving of information.
But the Prony method and the modified Prony method using the fast algorithm to solve the above equations allows us to determine the signal parameters (amplitude, frequency and phase). This is not sufficient to determine the nature of the signal, especially the digital signal. A full spectrum analysis requires calculation of the signal spectrum. Therefore, it is necessary to continue processing the signal and calculate its spectrum. The signal spectrum is determined in terms of the exponential approximation $\hat{x}(n)$, not in terms of the original time sequence $x(n)$. To calculate the spectrum requires a number of assumptions:
One of them is that the sum of the exponents of the discrete time in equation (2) is defined on the interval $-\infty \le n \le \infty$ as a one-sided function of the form:

$$\hat{x}_1(n+1)=\begin{cases}\sum\limits_{k=1}^{p} h_k z_k^n, & n\ge 0\\ 1 & ,n\le 0\end{cases}. \qquad (29)$$

If signal $x(n)$ is valid, then the exponents will be pairs $e^{\pm j(2\pi f_k+\theta)}$, which will allow the formation of one cosine term $\cos(2\pi f_k+\theta)$, z of the transformation from (29):

$$\hat{X}_1(z)=\sum_{k=1}^{p}\left(\frac{h_k}{1-z_k z^{-1}}\right). \qquad (30)$$

Which converges at $|z_k|<|z|$. The second assumption is that $|z_k|<1$, so all the damping parameters are negative, indicating that the exponents are damped.
If the assumptions are correct then the substitution of form $z=e^{j2\pi fT}$ into expression (50) will give a discrete-time transformation, the deterministic sequence $\hat{x}_1(n)$, then the spectral energy density of our model will be:

$$\hat{S}_1(f)=\left[T\hat{X}_1 e^{j2\pi fT}\right]^2. \qquad (31)$$

This equation is defined on segment $\frac{-T}{2}\le f\le\frac{T}{2}$. The peculiarity of this method of determining the energy density of the spectrum is that it is very convenient for the analysis of short-term signals. That's what it takes to analyze pulse digital signals.

4. Discussion of experimental results

To test the proposed method, we will simulate short-term random signals. We will choose pulse signals with different duration. These signals are fully consistent with digital means of obtaining information. Depending on the duration of these pulses, we determine the spectrum and energy density of the corresponding signals, and perform a comparative analysis. The results are presented as graphs.
The obtained results are presented in Fig. 1 - 6.

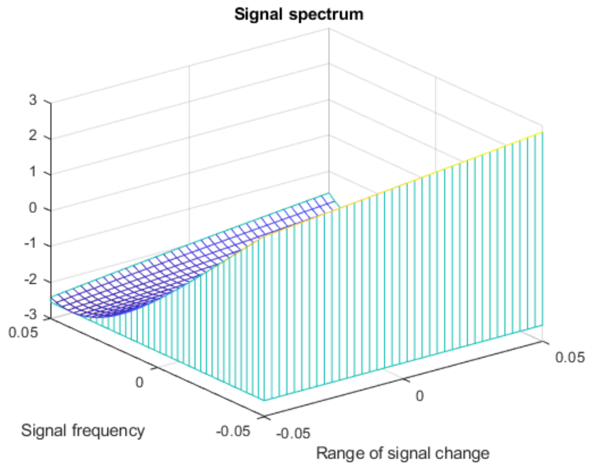

Figure 1. Graph of the spectrum at the frequency of the exponent of relative units.

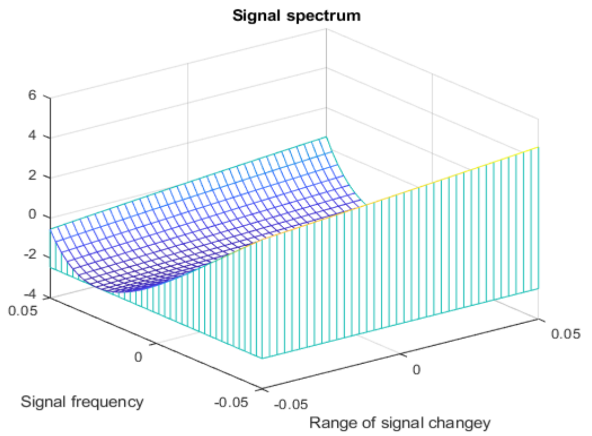

Figure 2. Graph of the spectrum at the frequency of the exponent of relative units.

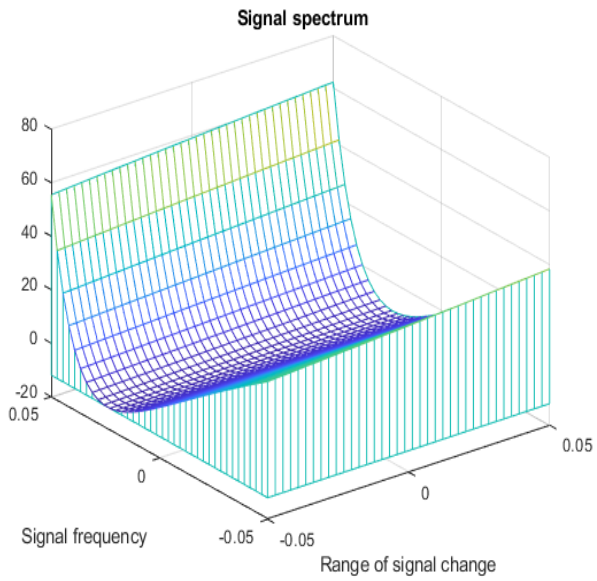

Figure 3. Graph of the spectrum at the frequency of the exponent of relative units.

The analysis of the graphs Fig.1-3 shows that the dependence of the spectrum of a short-term random signal on the frequency of the exponent (transformation of signals by exponents), which is practically of the same character, is slightly different in amplitude, which makes it difficult to determine the signal, especially against the background of legally operating devices.

The graphs of the spectral energy density of the signal are shown in the Fig.4-6, clearly different from each other, which makes it possible to determine these signals with a very high probability.

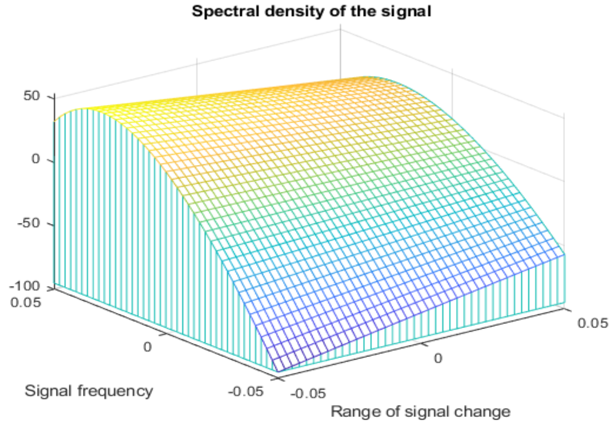

Figure 4. Graph of the spectral density of the signal at the frequency of the exponent of relative units.

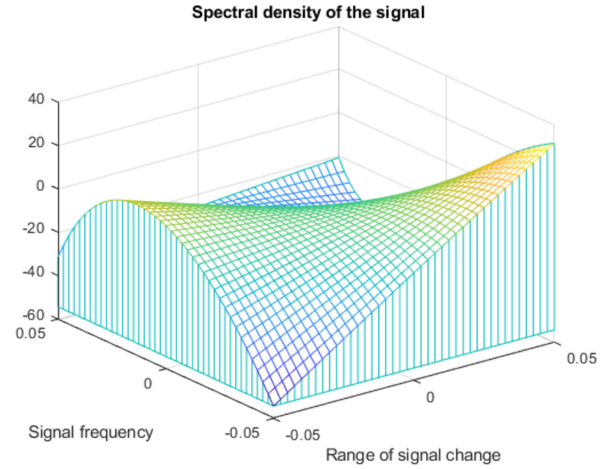

Figure 5. Graph of the spectral density of the signal at the frequency of the exponent of relative units.

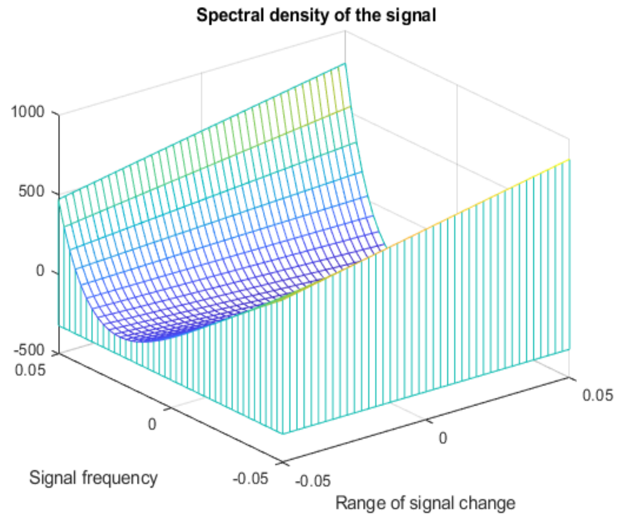

Figure 6. Graph of the spectral density of the signal at the frequency of the exponent of relative units.

The simulation results have practically proved the advantages of the proposed technique for determining short-term random signals that correspond to digital signals of the silent receiving of information and allow to determine the signal of the digital devices of silent receiving of information the background of legally operating devices.

5. Conclusions

An improved spectral analysis method is proposed, based on the classical Prony method. Which has been improved by replacing damping sinusoids with the use of non-damping sinusoids, which allows to distinguish the signal very accurately and to determine its characteristics against the background of many obstacles of the air space. A fast conversion algorithm is applied to solve the normal equations for finding variables to sequentially determine signal parameters such as amplitude, frequency, and phase. The method of analysis of not only parameters static signal but also the rate of change of these parameters is proposed. Which allows measuring the amplitudes and frequencies of the signal with an error of 0.5%.
The simulations and the obtained graphs of the pulse signal spectrograms and the graphs of the spectral energy density are simulated. The obtained graphical data fully confirm the advantages of the proposed method of determining the spectral energy density, for spectral analysis of random short-term pulses. The results of the simulation proved the advantage of the method of determining the spectral energy density over the method of obtaining the signal spectrum. The proposed method of illegal obtaining information detection increases the accuracy of the detection of signals, of the means of illegal obtaining receiving of information by 15%.

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