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METHOD OF FORECASTING THE CONDITION OF RADIO-ELECTRONIC SITUATION OF MULTIPLE SYSTEMS IN THE CONDITIONS OF UNCERTAINTY

Abstract. The task of forecasting future values of the time series based on its previous values is the basis for planning in the economy, trade, energy and technical fields. Forecasting of a radio-electronic situation in the conditions of shortage of radio-frequency resource is a very important component of modern high-tech military conflicts, the transport basis of which are multi-antenna radio-emitting means. For this purpose, an analysis of the known methods of forecasting the radio-electronic situation is carried out in that article. It is established that nowadays there are many models of time series prediction, namely: regression and autoregressive models, neural network models, exponential smoothing models, Markov-based models, classification models, etc. Based on the above analysis, it is found that the most appropriate for use in the prediction problems of the electronic environment of multi-antenna communication systems are time series prediction methods, which are based on autoregressive models. The article proposes a technique for predicting the condition of the radio-electronic environment, which allows to increase the noise immunity of communication systems in the conditions of deliberate interference and the unsteady nature of the predicted process, in order to ensure electromagnetic compatibility and increase the efficiency of use of radio frequency resource by complexes. To solve the scientific problem, we use the general scientific methods of analysis and synthesis of complex technical systems, the theory of noise immunity of radio engineering systems and methods of mathematical modeling. It is advisable to use this technique while assessing the electronic environment and identifying measures to enhance the security of communications systems. The calculations show that the use of this method allows to reduce the error of the forecast by an average of 20%. It is advisable to practically implement the proposed methodology while developing software for programmable radio stations.

Keywords: multi-antenna systems; noise immunity; radio-electronic environment; intentional interference; unsteadiness; forecasting.

Introduction

The task of predicting future values of the time series, which are based on its previous values is the basis for planning in the economy, trade, energy and technical sectors [1-5]. At the same time, the development of hardware and software provides more and more powerful computing platforms that can implement complex forecasting algorithms. In addition, current approaches to economic and technical management are increasingly demanding accuracy of forecasting.

For today, there are many models of time series prediction: regression and autoregressive models, neural network models, exponential smoothing models, Markov-based models, classification models, etc. The most popular and widely used classes are autoregressive and neural network models [6]. A significant disadvantage of the autoregressive class is a large number of free parameters whose identification is ambiguous and has a considerable resource consumption [7]. A significant disadvantage of the neural network model class is the inaccessibility of intermediate calculations and, as a consequence, the complexity of interpreting the simulation results. In addition, another disadvantage of this class of models is the complexity of choosing a neural network learning algorithm [8].

That is why time series prediction methods, which are based on autoregressive models were chosen as the basic prediction method in this research.

There are known prediction methods, which are based on the methods of Viner and Jaglom [6]. The general theory of predicting random processes, which can be attributed to the radio-electronic environment (REE) is described in details in the works [7-9]. From the analysis of the performed works [7-9], it can be concluded that the effectiveness of the made decisions depends on the volume of a priori data, the processes, which are investigated, and the methods of their presentation. The disadvantage of the existing scientific and scientifically-methodological apparatus (SMA) is the use of the stationarity hypothesis of forecasting procedures, including the analysis of broadband signals.

The purpose of this article є a development of a technique for predicting the state of radio-electronic environment of multi-antenna radio systems operating in a complex electromagnetic environment and shortage of radio frequency resource, in order to ensure electromagnetic compatibility and increase the efficiency of use of radio frequency resource by communication complexes.

Presentation of main material research

In the theory of prediction of the known methods of forecasting processes with discrete-time using rational spectra, as well as one-dimensional stationary processes with a constant step in time. At the same time, the analysis shows [6-13] that the multidimensional case in the general theory of forecasting is much more complicated than the one-dimensional. As a rule, the basis of forecasting in a known SMA is to analyze the time series [5-10]. The most common methods are the least-squares method [8] and its modifications, exponential smoothing method, probabilistic modeling method and adaptive smoothing method. In any case, it is necessary to select the most appropriate model to describe the projected process.

While performing process forecasting, discrete samples of two types are formed:

1. The model of functional dependence of the process is unknown. In this case, the problem of

estimating the functional dependence model from the whole class of available models is solved.

2. The process functional dependency model is known and one only needs to estimate the output model parameters (regression coefficients $b_0, b_1, b_2, \ldots$). As a rule, the following mathematical models are used: linear is $y = b_0 + b_1 x$, hyperbolic is $y = b_0 + b_1 / x$, ostentatious is $y = b_0 + b_1 x$, stepwise is $y = b_0 x^{b_1}$, parabolic is $y = b_0 + b_1 x + b_2 x^2$, logarithmic is $y = b_0 + b_1 \lg x$ and others.

The solution of mathematical REE equations involves the calculation of the initial data of the model parameters (free term b_0 and regression coefficients $b_1, b_2, \ldots$). The most widely known of these models is the model, which is described by the regression equation in the form of polynomials of a polynomial:

$$y = f(x) = b_0 + b_1 x + b_2 x^2 + \ldots + b_m x^m ,$$

where $b_0, b_1, b_2, \ldots, b_m$ is the coefficients, which should be determined. To determine regression equation coefficients b_m different methods are used (graphical, average method), but the least-squares method (LSM) is most often used. Determination of coefficients b_0 and b_1 according to the LSM is carried out according to the following equation:

$$b_0 = \frac{\sum_{i=1}^{N-1} x_i^2 \sum_{i=1}^{N-1} y_i - \sum_{i=1}^{N-1} x_i \sum_{i=1}^{N-1} x_i y_i}{N \sum_{i=1}^{N-1} x_i^2 - \left(\sum_{i=1}^{N-1} x_i \right)^2},$$

$$b_1 = \left(N \sum_{i=1}^{N-1} x_i y_i - \sum_{i=1}^{N-1} x_i \sum_{i=1}^{N-1} y_i \right) \Bigg/ \left(N \sum_{i=1}^{N-1} x_i^2 - \left(\sum_{i=1}^{N-1} x_i \right)^2 \right).$$

An LSM-based assessment requires the fulfillment of a number of preconditions, which can lead to errors. LSM is widely used to obtain specific forecasts, which is explained by its simplicity and ease of implementation on the personal computer. The disadvantage of this method is that the trend model is firmly fixed, so a reliable forecast can be obtained only for a short period of time. LSMs are used mainly for short-term forecasting. The method significantly complicates the correct choice of model type, as well as the rationale and choice of weights in the weighted LSM.

There are known techniques for predicting time series, which are based on the use of an autoregressive model of a variable mean with a minimum root mean square error [6]. The basis of the prediction is a random time series, which is an ordered random sequence of quantities that are the values of the received signal. One of the most important tasks while working with time series is to predict the future values of the time series.

Three forms of model representation are presented by the following relationships:

1) using the difference equation:

$$z_{n+1} = \phi_1 z_{n+1-1} + \ldots + \phi_{p+d} z_{n+1-p-d} -$$
$$-\theta_1 a_{n+1-1} - \ldots - \theta_q a_{n+1-q} + a_{n+1};$$

2) as an infinite weighted sum of current and previous impulses a_j:

$$z_{n+1} = \sum_{j=-\infty}^{n+1} \psi_{n+1-l} a_j = \sum_{l=0}^{\infty} \psi_j a_{n+1-j} ;$$

3) as an infinite weighed sum of previous observations plus a random boost:

$$z_{n+1} = \sum_{j=1}^{\infty} \pi_j z_{n+1-j} + a_{n+1} ,$$

where π_j is the weight coefficients.

Existing forecasting methods have the best properties while assuming a linear steady-state process hypothesis. Real processes are often influenced by factors that make up the nonstationary component.

The proposed methodology considers the possibility of extending the use of known forecasting methods to such processes. For stationary (additive) processes, discretization is used with a constant step. For non-stationary processes, they typically use a variable-step signal sampling, with the mandatory zeroing of process formation. An example of a non-stationary signal is a hyperbolic frequency manipulation (HFM) signal, which is widely used in communication systems [10]. While recording a signal

$$S(t) = \sin(\Omega / k) \cdot \ln kt ,$$

where Ω is the initial frequency, k – scale factor characterizing the slope of the modulating function shows that the instantaneous frequency

$$f(t) = \frac{1}{2\pi} \frac{d\psi}{dt},$$

where ψ is the phase of the signal that goes to infinity at t→0. Because the reduction (expansion) operation is not invariant with respect to the time shift operation, information about the start of the implementation to be processed is required to form the process of extrapolation.

While working with this signal, you need to find the location of zero, which determines the beginning of the counts. The proposed method is reduced to the following actions:

1. The input of the output data.
2. There is a temporary compression of the predicted process that is required to provide real-time signal processing [10]. In this case, at each step, the implementation is updated by one count. Thus, a class of implementations is formed that differs from each other by one count offsets. To generate a class of discrete samples, each implementation is subjected to logarithm and sampling operations..

The signal implementation is resampled on a logarithmic time scale $t \to \ln t$. Since the original process comes with a steady step, it is first restored to a discrete process that is solved by the interpolation procedure. In the case of non-stationary resampling, it is assumed that the implementation zero is known.

Suppose a given process in discrete views over a single sampling interval over an interval of length *M*-1, which corresponds to the *M*-countdown. Suppose also that *m* has a value $m \in (0 \ldots M-1)$. While logarithmic scaling of the signal with step *q* we have:

$$\ln\left(q^{m}\right)-\ln\left(q^{m-1}\right)=\ln(q), \sum_{n=0}^{\infty} q^{n}=M-1=1/1-q.$$

From here we have $q=(M-2)/(M-1)$. The interpolation procedure should begin with the last reference of the signal implementation, considering its value as the last reference of the interpolated process. The specified approach to interpolation completely stores the information, which is contained in the signal.

It can be seen that an infinite number of samples is required for the logarithmic sampling of the N-1 interval. Therefore, we restrict ourselves to the sampling of only a portion of the interval, which is formed by the finite sum of geometric progression $\left(q^{K-1}-1\right)/(q-1)$. Start for nodes interpolation $k \in (0 \ldots K-1)$ is determined by the value:

$$t_0=N-1-\left(q^{K-1}-1\right)/(q-1).$$

For verification it is seen that when $K \to \infty$ $t_0 \to 0$. While using the standard interpolation procedure, you must set the values of the interpolation nodes from left to right. If you invert the reference numbers by law $k \in (0 \ldots K-1): k_1=K-1-k$, then the interpolation nodes are set by values:

$$UI_k=(N-1)-\left(q^{K-1-k}-1\right)/(1-q).$$

After resampling the processes for each implementation of the $s_n(t)$ formes a spectral function $S_n(f,T)$:

$$S_n(f,T)=\int_0^T s_n(t)\exp(-2\pi f t)\,dt.$$

The energy spectrum is then formed:

$$X_n(f)=\frac{1}{T}\left|S_n(f,T)\right|^2.$$

The following procedure is proposed to determine the start of implementation. It is proposed to use entropy as a criterion for the choice of implementation (Kulbak information) [13]:

$$H(f)=-\int_{-1/2}^{1/2}\ln\left(X(f)\Big/\int_{-1/2}^{1/2}(X(f))\,df\right)df, \quad (1)$$

where $X_n(f)=X(f)\Big/\int_{-1/2}^{1/2}(X(f))\,df$

is the normalized energy spectrum of the sample,

$$X(f)=\sum_{n=-\infty}^{\infty} r_{ss}(n)\exp(-2\pi f n),$$

$r_{ss}(n)$ is the process correlation function.

A heuristic explanation for choosing this criterion consists in the fact that it minimizes fortuity.

Then, the maximum entropy value is determined in accordance with relation (1). This action leads to compare the responses with the threshold voltage. When the threshold is exceeded, it is decided that the maximum is found.

To realize maximum entropy, we use the operation of resampling the prediction result at the exponential time scale t→expt.

The specified conversion is the reverse of the conversion, which was discussed earlier. It should be noted that the previously scaled hyperbolic process (non-stationary) on a logarithmic scale actually made it close to the tone. Such a signal is a stationary and well-predicted known method. Expotential transformation made it possible to return to the original hyperbolic process.

The use of the proposed method allows to obtain a more accurate prediction than using known procedures.

To test the proposed methodology, a statistical experiment was conducted in which the effectiveness of the proposed forecasting technique was evaluated:

$$\sigma_m=\frac{1}{N1+1}\cdot\sum_{n=0}^{N1+1-1}\left(\frac{\breve{s}_{n,m-AA_m}}{\operatorname{var}(\breve{s}_m)}-\frac{\widehat{s}_{n,m}-BB_m}{\operatorname{var}(\widehat{s}_m)}\right)^2,$$

where $\breve{s}_m$ is the output process, $\hat{s}_m$ is the result of the forecast, AA, BB are the arithmetic average mean of the processes defined by expressions:

$$AA_m=\frac{1}{N1+1}\sum_{n=0}^{N1+1-1}\breve{s}_{n,m}, \quad BB_m=\frac{1}{N1+1}\sum_{n=0}^{N1+1-1}\text{€}_{n,m},$$

$\operatorname{var}(\breve{s}_m), \operatorname{var}(\hat{s}_m)$ is the variation of processes $\breve{s}_m$ and $\hat{s}_m$ is determined by the formula

$$\operatorname{var}(\breve{s}_m)=\frac{1}{N1+L}\sum_{n=0}^{N1+L-1}\left(\breve{s}_{n,m}-AA_m\right)^2,$$

1. The classical forecasting procedure, the model of which is implemented in the mathematical forecasting environment MathCad 14, which is based on the hypothesis of stationarity of the input data (counts distributed evenly over time) and is estimated as an autoregressive component of the forecast (Fig. 1).

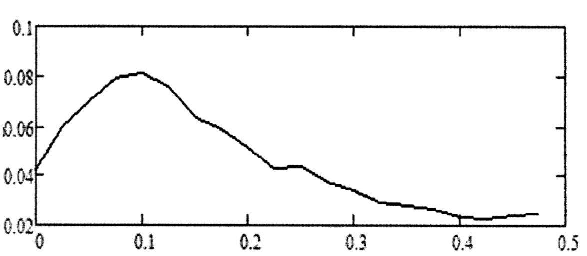

Fig. 1 The prediction error distribution depending on the change in the upper frequency of the signal

2. Procedures that use hyperbolic symmetry to implement the prediction procedure.

In the conducted experiment the method of efficiency estimation of procedures forecasting was allocated. With this approach, knowing the signal and noise characteristics, they were given a full description of the effectiveness of these procedures. The estimation of the prediction error is determined according to the ratio:

$$\sigma_m = \frac{1}{N1+1} \sum_{n=0}^{N1+1-1} \left(\frac{\breve{s}_{n,m} - AA_m}{\operatorname{var}(\breve{s}_m)} - \frac{\hat{s}_{n,m} - BB_m}{\operatorname{var}(\hat{s}_m)} \right)^2 ,$$

where $\breve{s}_m$ is the output process, $\hat{s}_{n,m}$ is the result of forecasting, AA, BB is the arithmetic average mean of the processes whose mathematical description is given in the work [8]. To form it, the input process was split into two parts, where the first part of the process is considered as an input sample and the second part is unknown, but is formed by the future part of the process. By partitioning with a section overlap by half the size of the section and the operation of averaging the difference of estimations, we obtain an overall average estimation of the prediction error:

$$\wp^2 = \left(1/(M/2)\right) \cdot \sum_m \left(s_m - \wp_m\right)^2 , \qquad (2)$$

where $M/2$ means that there is an overlap half the length of the sections.

Score (2) was calculated for the forecasting procedures according to the first and second methods while changing the upper frequency. From Fig. 1. we can draw the following conclusion:

1. As the frequency band increases, the prediction error decreases.

2. Frequencies ranging from zero to 0.1 show a sharp increase in prediction error.

3. Starting at a frequency of 0.1 or more, there is a slow decrease in the prediction error.

The result of the estimation of the average correlation of prediction depending on the frequency band is shown in Fig. 2.

From Fig. 2 we can draw the following conclusion:

1. With an increasing frequency band, the correlation coefficient of the prediction increases.

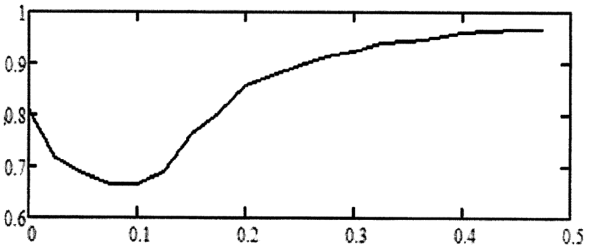

Fig. 2. Distribution of the prediction correlation depending on the change in the upper frequency of the signal

2. At frequencies up to 0.1, there is a fall in the value of the correlation coefficient of prediction to frequencies within 0.1.

3. Starting at a frequency of 0.1 or more, a slow increase in the prediction correlation coefficient is observed.

Conclusions

The technique of forecasting the state of the radio-electronic situation in multi-antenna systems in conditions of uncertainty is developed in the article. This approach allowed us to increase the volume of a priori data by forming a sample for forecasting data, that is, on the time plane $(\Delta, t), 0 \le \Delta \le \infty, -\infty < t < \infty$.

The developed method is characterized in that the technique additionally has operations of recirculation of the input data on one count, resampling of the output process on a logarithmic time scale, finding the energy spectrum of the received signal, determining the response, entropy of the energy spectrum of the corresponding sample, which is subject to the maximum of the recurrent finding a prediction for realizing the maximum value of entropy, resampling the prediction result in exponential timescale.

The calculations show that the use of this method allows to reduce the error of the forecast by an average of 20%. The direction of further research is the development of an advanced technique for the selection of operating frequencies for communication and data transmission systems. The direction of further research should be the development of advanced operating frequency selection techniques for communication and data transmission systems.

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Методика прогнозування стану радіоелектронної обстановки багатоантенних систем в умовах невизначеності

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Завдання прогнозування майбутніх значень часового ряду на основі його попередніх значень є основою для планування в економіці, торгівлі, енергетиці та технічних галузях. Прогнозування радіоелектронної обстановки в умовах дефіциту радіочастного ресурсу є дуже важливою складовою сучасних високотехнологічних воєнних конфліктів, транспортною основою яких виступають багатоантенні радіовипромінюючі засоби. З цією метою в зазначеній статті проведено аналіз відомих методів прогнозування радіоелектронної обстановки. Встановлено, що на сьогоднішній день існує безліч моделей прогнозування часових рядів, а саме: регресивні і авторегресійні моделі, нейромережеві моделі, моделі експоненціального згладжування, моделі на базі ланцюгів Маркова, класифікаційні моделі та інш. На основі зазначеного аналізу встановлено, що найбільш доцільним для використання в задачах прогнозування радіоелектронної обстановки багатоантенних систем радіозв'язку є методи прогнозування часових рядів на основі авторегресійних моделей. У статті запропонована методика прогнозування стану радіоелектронної обстановки, що дозволяє підвищити завадозахищеність систем зв'язку в умовах впливу навмисних завад та нестаціонарному характері процесу, що прогнозується, з метою забезпечення електромагнітної сумісності та підвищення ефективності використанні радіочастотного ресурсу комплексами зв'язку. Для вирішення наукового завдання використані загальнонаукові методи аналізу та синтезу складних технічних систем, теорії завадозахищеності радіотехнічних систем та методи математичного моделювання. Зазначену методику доцільно використовувати при оцінці радіоелектронної обстановки та визначення заходів, що спрямовані на підвищення завадозахищеності систем зв'язку. Розрахунки показують, що використання зазначеної методики дозволяє зменшити похибку прогнозу в середньому на 20%. Практично реалізувати запропоновану методику доцільно при розробці програмного забезпечення програмованих радіостанцій.

Ключові слова: багатоантенні системи; завадозахищеність; радіоелектронна обстановка; навмисні завади; нестаціонарність; прогнозування.

Методика прогнозирования состояния радиоэлектронной обстановки многоантенных систем в условиях неопределенности

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Аннотация. Задача прогнозирования будущих значений временного ряда на основе его предыдущих значений является основой для планирования в экономике, торговле, энергетике и технических областях. Прогнозирование радиоэлектронной обстановки в условиях дефицита радиочастного ресурса является очень важной составляющей современных высокотехнологичных военных конфликтов, транспортной основой которых выступают многоантенные радиоизлучающие средства. С этой целью в указанной статье проведен анализ известных методов прогнозирования радиоэлектронной обстановки. Установлено, что на сегодняшний день существует множество моделей прогнозирования временных рядов, а именно: регрессивные и авторегрессионные модели, нейросетевые модели, модели экспоненциального сглаживания, модели на базе цепей Маркова, классификационные модели и др. На основе указанного анализа установлено, что наиболее целесообразным для использования в задачах прогнозирования радиоэлектронной обстановки многоантенных систем радиосвязи являются методы прогнозирования временных рядов на основе авторегрессионных моделей. В статье предложена методика прогнозирования состояния радиоэлектронной обстановки, которая позволяет повысить помехозащищенность систем связи в условиях воздействия преднамеренных помех и нестационарном характере прогнозируемого процесса с целью обеспечения электромагнитной совместимости и повышения эффективности при использовании радиочастотного ресурса комплексами связи. Для решения научной задачи использованы общенаучные методы анализа и синтеза сложных технических систем, теории помехозащищенности радиотехнических систем и методы математического моделирования. Указанную методику целесообразно использовать при оценке радиоэлектронной обстановки и определения мер, направленных на повышение помех защищенности систем связи. Расчеты показывают, что использование указанной методики позволяет уменьшить погрешность прогноза в среднем на 20%. Практически реализовать предложенную методику целесообразно при разработке программного обеспечения программируемых радиостанций.

Ключевые слова: многоантенные системы; помехозащищенность; радиоэлектронная обстановка; умышленные помехи; нестационарность; прогнозирование.