A New Algorithmic Approach for Detecting Hidden Periodicity of Noisy Signals in Technically Complicated Systems

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Abstract

Detecting signals with hidden periodicity is a wide and popular task in most complicated technical systems. The fields, where this problem is observed, can be astrophysics, engineering and mechanics, adaptive control, information control system, radio-localization and radio technology, power engineering and telecommunication, ecology and so on. In this paper, process of signal detection under noise background is considered by developing the method based on synchronous detection. Here, it is assumed that the signal is periodic in the background of the noise and part of that signal is partially lost. At the end, comparative empirical results of different algorithms are presented by computer modeling in different platforms and final conclusions are described. At the end comparative results which are received by modeling of various algorithms are presented. The conclusion contains the short review of a problem and a method of its decision.

1. Introduction

As far as signals with hidden periodicity take place among other environments of more serious signals, the latter become the noise in this problem and the whole task concerned raises to the problem of detecting signals in the background of the noise. First of all, in order to cope with this problem, random character of the noise is needed to be taken into account using statistical method of analysis as well as the theory of probability and theory of random process. It is also essential to study the partial loss of actual signal, a priori uncertainty with regard to the frequency and phase of those actual signals, which, as a result, make the problem to be solved in the filed of research work, embarrassing for constructing universal method of solving concerned task.

Problem situation, which make difficulty in the area of matter of research work, is specified as the joint (system-defined) unsolved problem of constructing quantity-based method and algorithm of finding hidden periodicity in the condition of limited length of realization, considerable noise and partial lost of useful signal, a priori uncertainty with regard to frequency and phase of observed signals and means of negotiating those difficulties with the help of parallel processing.

The purpose of the research is to get over the specified problem definition. In this research, we discuss the critical analysis of means and method of finding signals with hidden periodicity, choice and quantity-based analysis of effectiveness of methods and algorithms, which allow us realizing the corresponding information system, oriented toward the requirements of technical application.

To achieve the purpose of the research, we have solved the following scientific tasks which are organized in this paper as follows: In section

2, we analyze the task for finding hidden periodicities of signals and show the problem statement including the review of the filed, where the problems exist, and problems of analysis in finding hidden periodicities of signals. In section 3, we develop the algorithm of detecting hidden periodicities of noisy signals based on synchronous detection or matched filter by analytical approach for solving the problem in the case of sinusoidal signals, for which we firstly determined the major part of regular component, then we analyzed the statistical characteristics of random components, then joint calculation of regular and random components was done. In section 4, we model the proposed method of detecting periodicities of hidden signals. In section 5, we developed the algorithm for organization of detecting hidden periodicities with the help of distributed computing system. In section 6, we research the effectiveness of proposed algorithm in comparison with other existing methods of detecting hidden periodicities. Finally, conclusion comes in section 7.

2. Background theory

As discussed in introduction section, detecting task of hidden periodicities is, on one hand, wide-spread used in technical application, on the other hand, complicated and complex task, in full measure, unsolvable so far. In many technical systems, hidden periodicities can be gradually emergent (therefore, time-dependent) process – for instance, system of technical diagnostic of growing malfunction. On the other hand, there are technical fields, where processes are more stationary – for instance, tasks from astrophysics, where observed objects steadfastly exist for many years, hundred years and even thousand years. It is clear that for solving those problems, researching stationary processes is more preferable because being stationary (time invariance) is an essential condition for ergodicity of random process, and consequently, it is probable to use statistical method in the case of processing single realization.

Problems of finding periodicity of astrophysical signals have been tried to be solved by using analytical approach and methods especially developed around the year 1970. Processes from the astrophysics are positively different from other technical fields because of its being stationary. Therefore, we chose the astrophysics as the more exact object field.

Firstly, in astrophysics, scientists used conventional analysis methods like Fourier analysis, Folding and other [1, 2]. Fourier-analysis method for astrophysical tasks was used by Deeming [3]. Folding methods are Jurkevich's method [4], Taylor expansion, and Buccheri's folding method [5]. Many methods were developed for solving the similar task, among them the well known methods are those which are used in radio technology and astrophysics.

For the problem of influence of random component, in astrophysics, scientists use the conventional statistical methods and characteristics like statistical test of Raler, x2 distribution and others [6].

3. Analytical approach for solving the signal detection problem

In the example of observation of binary-stars' radiation, radiation receiver from the earth fetches the incoming rays of periodically covering star, which is rounding the gamma source. Due to the spontaneous process of gamma radiation, those signals themselves even have random process. But in the cosmic, along observed pair of stars, there are other objects. Their radiations bring much noise to the signal, which we want to detect. In this way, important task is to select the useful signals from the noise.

For the example of binary stars, the signals $x_1(t)$ come from cosmic to the earth. Useful signal have the character of random fluctuation due to different spontaneous process and huge amount of noise $n(t)$. Therefore, suppose that receiver got the signals $x_{incom}(t) = x_1(t) + n(t)$, where X_{incom} is the incoming signal.

For further research, it is perspective to use the method of synchronous detector (matched filter). Schema of the process of signals in synchronous detector is presented in the figure 1.

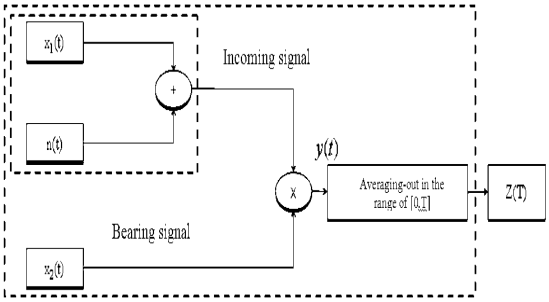

Figure 1. Schema of the process of signal in a synchronous detector

After multiplying incoming signal with bearing signal $x_2(t)$, obtained signal $y(t)$ is averaged over the range of [0, T], forming the output signal $Z(T)$.

$$y(t)=[x_1(t)+n(t)]\times x_2(t)=x_1(t)\times x_2(t)+n(t)\times x_2(t)$$

Values of the signal in output of integrator *Z(T)* at the end of the interval [0, T] can be defined as,

$$Z(T)=\frac{1}{T}\int_0^T y(t)=\frac{1}{T}\int_0^T x_1(t)\times x_2(t)dt+\frac{1}{T}\int_0^T n(t)\times x_2(t)dt$$

$$Z(T)=I_1(t)+I_2(t) \qquad (1)$$

Note that in the above expression, there are two compositions of I_1 and I_2:

$I_1(t)=\frac{1}{T}\int_0^T x_1(t)\times x_2(t)dt$, (regular component)

$I_2(t)=\frac{1}{T}\int_0^T n(t)\times x_2(t)dt$ (random component).

3.1 Determining the boundary of regular component

It is obvious to analyze the case of sinusoidal signals from known (zero) phase and the noise in the form of "white noise". Therefore, useful signals and bearing signals are defined as: $x_1(t)=\sin(\omega_1 t)$ and $x_2(t)=\sin(\omega_2 t)$. For the noise $n(t)$, in computer modeling, we use the sensor of random number, evenly distributed in the interval from 0 to 1.

Therefore, by calculating integral we can present regular component as:

$$I_1(T)=\frac{1}{T}\int_0^T \sin(\omega_1 t)\times\sin(\omega_2 t)dt$$

By solving the above equations, we obtained maximum and minimum of the function $I_1(T)$,

$$I_{per}\Big|_{\omega_1\neq\omega_2}=\frac{1}{2}\left(\frac{1}{(\omega_1+\omega_2)T}+\frac{1}{|\omega_1+\omega_2|T}\right), \qquad (2)$$

$$I_{per}\Big|_{\omega_1=\omega_2}=\frac{1}{2}+\frac{1}{2\omega_1 T} \qquad (3)$$

In this way, for regular component, we can prove that:

- in the lack of convergence of frequency of studied and bearing signals, regular component falls down (in the limit of 0) in the increment of interval of observation;
- in the case of convergence of those frequencies, regular component aims to 0.5 and divergence of that value doesn't exceed $\frac{1}{2\omega_1 T}$.

Especially those results give the statement for searching frequency of signal studied. But there is another case of random component, and we need to follow another approach to cope with it.

3.2 Analysis of statistical properties of random component

The value of random component is defined by the ratio of

$$I_2(t)=\frac{1}{T}\int_0^T n(t)\times\sin(\omega_2 t)dt$$

By the stochastic noise $n(t)$, $I_2(T)$ is random value, which also depends upon the time *T*. Here it needs to do analysis with the help of the theory of random processes. So, for that purpose, we use the approach and methodology stated in [7]. Let the noise be stationary random process with zero mathematical expectation and finite dispersion, then

$M\{n(t)\} = 0$ and $M\{n^2(t)\} = \sigma_n^2$.

It should be noted right now that by averaging-out, huge number of random values got mixed up. Therefore, from the view of central limit theorem and law of the distribution of value - $I_2(T)$ aims to be normal, therefore we can sufficiently define two parameters (m – mathematical expectation and σ^2 - dispersion), in order to build the interval, into which values of $I_2(T)$ are brought up. In particular, with the probability of 95%, that interval is defined as

$$m \pm 2\sigma$$

And so, mathematical expectation for $I_2(T)$ will be defined as

$$m = M\{I_2(t)\} = M\left\{\frac{1}{T}\int_0^T n(t)\times\sin(\omega_2 t)dt\right\}$$

$$m = \frac{1}{T}\int_0^T M\{n(t)\}\times\sin(\omega_2 t)dt = \frac{1}{T}\int_0^T 0\times\sin(\omega_2 t)dt = 0$$

In this way, $I_2(T)$ becomes central value. Here, its dispersion is defined as

$$\sigma^2 = M\{[I_2(T)\times I_2(T)]\}$$

In the finite values of T, dispersion σ^2 contains falling-down harmonic component, which depends on ωT and own maximum in the case, when $\sin 2\omega t = -1$, i.e., while $2\omega t = \pi, 3\pi, ...(2p+1)\pi$. In this way $\sigma^2_{\max} = \frac{\sigma_n^2}{2T}\left(1+\frac{1}{2\omega T}\right)$ and consequently, interval, into which, with 95% of probability, values of $I_2(T)$ are fell down, can be defined as:

$$I_2(T)\Big|_{95\%} \le \pm\frac{2\sigma_n}{\sqrt{2T}}\sqrt{1+\frac{1}{2\omega T}} \quad (4)$$

3.3 Joint calculation of regular and random component

According to equation (1), value of signal at the output of integrator is defined by total value of regular and random component.

According to the joint calculation of the equation 2, 3 and 4, interval, into which, with 95% of the probability, values of $Z(T)$ are fell into, can be defined as follows.

While $\omega_1 \ne \omega_2$,

$$Z_1(T) = \frac{1}{(\omega_1+\omega_2)T} + \frac{1}{|\omega_1+\omega_2|T} \pm \frac{2\sigma_n}{\sqrt{2T}}\sqrt{1+\frac{1}{2\omega T}}.$$

While $\omega_1 = \omega_2$,

$$Z_2(T) = \frac{1}{2} + \frac{1}{2\omega_1 T} \pm \frac{2\sigma_n}{\sqrt{2T}}\sqrt{1+\frac{1}{2\omega T}}.$$

With the calculation of the symmetry of harmonic signal, fully 95% interval of the case of $\omega_1 = \omega_2$, is defined as

$$Z_2(T) = \frac{1}{2} \pm \left(\frac{1}{2\omega_1 T} \pm \frac{2\sigma_n}{\sqrt{2T}}\sqrt{1+\frac{1}{2\omega T}}\right).$$

4. Modeling on Proposed Method

The purpose of modeling is to analyze the effect of proposed method of finding noisy signals with hidden periodicity. Main part of modeling is performed in Excel + VBA. Moreover, modeling is performed in Mat lab v. 7.3, as well as in VB.net environments.

External interface of the modeling program is presented in figure 3.

By means of modeling in MATLAB, we obtained obvious presentation of joint distinctive impact of relational frequency of signal and the number of averaging-out upon total effect of the performance of synchronous detector (See Figure 4).

When the efficiency of proposed method is proved with confidence in the case of sinusoidal signals, we can freely use developed formula for modeling on proposed method in the case of impulse signals.

By using Excel + VBA for modeling, we generate 8 experimental results for the case of convergence and 8 experimental results for the case of the lack of convergence of frequency of signal with different noises, and they are copied to new work sheet, where obvious presentation is made by means of line graphs. Modeling results for useful signal are obtained obviously as shown in figure 5.

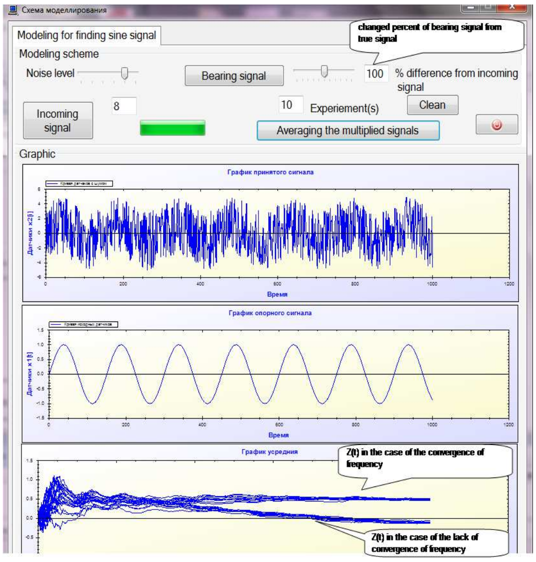

Figure 3. Modeling for sinusoidal signals

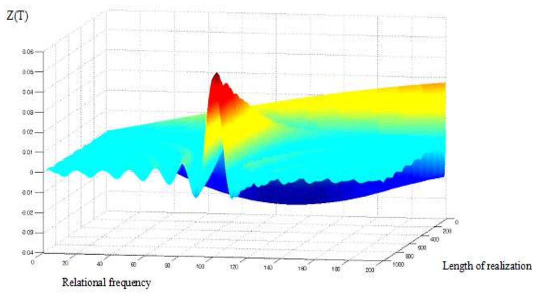

Figure 4. 3-D views of joint influence of relational frequency of bearing signal and length of realization upon the signal $Z(t)$

In this way, the program obviously models the experimental results for both variant of convergence and lack of convergence of frequency of source and bearing signals.

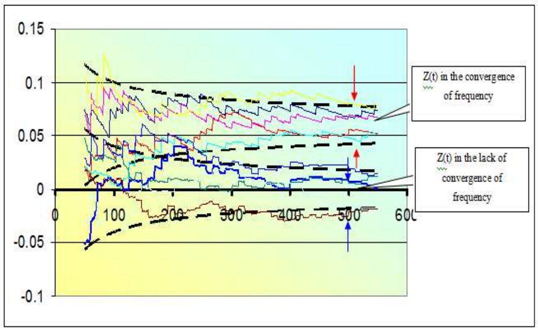

Figure 5. Graph for obvious presentation of selecting interval in impulse signals

5. Proposed method for distributed computing system

As described in the section 2 and 3, for practically solving the task of finding hidden periodicities in the condition of high noise level, and also in the case of a priori uncertainty of relational frequency and phase of useful signals, it is required to gather huge amount of data and to provide high performance of computing. Therefore, procedure of the proposed algorithm in a distributed computing system can be organized in the following way.

Step 1: To organize physical and virtual computing network based on computers of one or several observatories.

Step 2: To map the plan of computing process starting from first computers in computing network, starting from assigning frequency of bearing signal (in the range under study) for the research on discrete node of network.

Step 3: To send achieved true signal to all nodes of network.

Step 4: In each node, to calculate for the group of phase and for given frequency (given group of frequency) is performed.

Step 5: To collect all calculated results and choose the best for narrowing the range of frequency and further specified calculation.

Step 6: To repeat previous steps for narrowing the range of frequency.

6. Proposed method versus existing methods

In order to compare proposed method with the existing ones, we firstly generate source data and then model the existing methods and proposed one using the same generated source data and compared obtained results.

As the results of Fourier-analysis [8], in the noise level 3, only 20 % of periodicity could be guessed in sight from the impulse of spectral of useful signal. From the noise level 4, impulses of spectral of useful signals are sunk in the noise.

As for autocorrelation function, although it could detect periodicity of noisy sequence in the noise level 1, in the noise level 3, it could not detect the periodicity.

When used phase analysis, although periodic peaks of useful signal are well detected till noise level =3, from the noise level 4, the method stops to work to cope with periodicities.

Results of developed method prove that, when period of bearing signal is congruent with period of useful signal, the method confidently detects the useful signal till noise level 8 and lost level = 50%.

7. Conclusion

We provided joint solution of the problem of constructing quantity-based method of noise-immunity and algorithm of finding hidden periodicity in the condition of limited length of realization, considerable noise and partial lost of useful signal, a priori uncertainty about frequency and phase of signal under study.

In order to achieve the solution, we did analysis and developed the algorithm for finding hidden periodicities of noisy signal with the method of synchronous detection and defined confidential interval and did modeling for it. And we proposed algorithm for distributed computing system to solve the mentioned problem. At last, we compared proposed method with other methods of finding hidden periodicities.

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