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WEKTOROWY MODEL SYGNAŁU SZUMU ORAZ JEGO GŁÓWNE SKŁADOWE

Streszczeniey: Autorzy artykułu omawiają uogólniony model sygnału szumu. Opracowany model zaprojektowano i opracowano, aby prowadzić na nim dalsze badania. Dokonano tego na podstawie ogólnie znanych publikacji dotyczących sygnałów szumu oraz wiedzy o fizycznej naturze sygnałów szumu, które powstają (są wzbudzane) w różnych obiektach technicznych – w tym elektrowniach, obiektach produkujących maszyny, w środkach transportu, samolotach i innych. Zaproponowano, aby sygnał szumu reprezentować jako trój-składowy wektorowy proces stochastyczny. Pierwsza składowa opisuje mechanizm of formowania się sygnału szumu, wywoływanego aktywnością wielu elementarnych sygnałów impulsowych o różnej sile (mocy). Druga składowa jest wywoływana aktywnością wielu elementarnych drgań harmonicznych. Trzecia składowa jest determinowana przez tzw. trend, opisujące zmiany oddziaływujące na badany obiekt podczas napraw, modernizacji itp. W artykule opisano także eksperymenty przeprowadzone w celu pomiarów, rejestracji oraz identyfikacji charakterystyk statystycznych drgań występujących w określonych częściach (miejscach) elektrowni wiatrowych. Rozważając specyficzną naturę sygnałów powstających w elektrowniach wiatrowych, autorzy opracowali model sygnału szumu jako addytywne złożenie składowych sygnałów losowych, który może być przydatny w modelowaniu matematycznym oraz komputerowym. Opracowany model oparto na użyciu składowych będących sekwencjami liniowych stacjonarnych procesów stochastycznych; sekwencji zharmonizowanych procesów; aproksymujących funkcje dla wybranych pomiarów. Autorzy analizowali także specyficzne aspekty, związane z wyborem generatora liczb pseudo-losowych do modelowania komputerowego sygnału szumów w elektrowniach wiatrowych.

Słowa kluczowe: sygnał szumu, wektorowy proces stochastyczny, modelowanie komputerowe, elektrownie wiatrowe, liniowy proces stochastyczny, proces zharmonizowany

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VECTOR MODEL OF NOISE SIGNAL AND ITS MAIN COMPONENTS

Summary: The authors present in this work a generalized model of noise signal, developed and grounded for further research, basing on well-known publications concerning noise signals and on physical nature of noise signal formation in various technical objects and systems in power generation, machine building, transportation, aviation, and other areas. It is proposed to represent noise signal as a three-component vector random process. Its first component describes the mechanism of noise signal formation, driven by the action of a substantial number of elementary impulse signals with various strengths. The second component is formed by the action of a substantial number of elementary harmonic vibrations. The third component is a determined trend component, describing changes made to the research object during repairing, upgrading etc. The present work includes experiments, performed to measure, register and identify statistical characteristics of vibrations in certain parts of wind power units. Considering the specific nature of signals formation in wind power units, authors have developed a constructive model of noise signal as an additive mixture of noise signal components, which can be used for mathematical and computer modeling. The model is based on the use of such components as sequences of stationary linear random processes; sequences of harmonized processes; approximating functions of the given measuring at the realization of random value. Authors have also explored specific aspects, related to the choice of a pseudorandom number generator for computer modeling of wind power units' noise signal.

Keywords: Noise Signal, Vector Random Process, Computer Modeling, Wind Power Units, Linear Random Process, Harmonized Process.

1. Introduction

In order to improve the reliability of technical systems and power facilities, it is important to use functional diagnostics systems, that receive data from noise signals, such as vibrations, acoustic noises etc. [1-6]. This approach requires choosing adequate mathematical models for such signals. The models must not only represent the physics of signals originating, but also ensure a possibility of searching for new diagnostic parameters basing on various probabilistic properties of noise signals. However, the problem of determining signals' mathematical models, that could be applied to diagnostic noise signal modeling, has never been fully worked out by now. That makes mathematical and computer modeling of wind power units' noise signal an important problem, which can help increase the accuracy and reliability of data, required for wind power units diagnostics.

2. Publications analysis. Problem statement

The noise signals integrally represent fluctuating processes of various physical effects, such as thermodynamic, electromagnetic, hydrodynamic, mechanical, optical ones etc. In electronic and radio-electronic devices and systems, fractional, thermal and flicker noise signals are well known. We also know vibrational and vibroacoustic noises of technical systems and mechanisms, tribomechanical noises, acoustic emission signals, aerodynamic and hydrodynamic noises in gas and liquid flows etc. [1]. Such noise signals are the main subjects of researches, dedicated to noise diagnostics.

Any mathematical model of noise signals must meet two key requirements — it must represent the most important aspects of processes under research; and for the purpose of practical application of mathematical models of noise signals, it is necessary to have a developed mathematical tool for their research.

The simplest model of a noise signal, representing its broadbandness, is a white noise [2-3], which is a particular case of constructive models of noise signals. Development of constructive mathematical models of noise signals is based on a number of assumptions, representing the physics of these signals formation. We know, for today, two basic methods of noise signal models generalization, depending on the physics of signals formation: models of harmonized processes [4] and models of linear random processes [5-6].

In the course of wind power units operation analysis [7-10], the developed noise signal models cannot fully reflect physical processes, that are running, for example, during shaft rotation with direct relation to stochastic nature of wind's impact on the machine's wind wheel. Additionally, noise signal models should be based on the periodicity of probabilistic properties of shaft rotation, caused by the wind's occasional impact, while also enabling statistical estimations of various physical processes, which arise in a running wind power unit and result from shaft rotation. This leads to a problem of creating new constructive models for noise signals in wind power units.

3. Research goal and objectives

To develop a generalized model for noise signals, basing on well-known publications about noise signals and on physical nature of noise signal formation in various technical objects and systems in power generation, machine building, transportation, aviation, and other areas. For the purpose of describing all possible variants of noise signal formation — to develop a constructive model of a noise signal in wind power units, which could be used for mathematical and computer modeling as a three-component vector random process.

4. General mathematical model of vector noise process

The authors propose the following general mathematical model of noise signal, represented as a three-component vector random process:

$$\begin{aligned}
&\Xi_3(\boldsymbol{\omega},t)=\left({}_1\xi(\omega_1,t),\ {}_2\xi(\omega_2,t),\ A(t)/\xi(\omega_0,t_0)\right),\\
&\boldsymbol{\omega}=(\omega_0,\ \omega_1,\ \omega_2),\ \ \omega_0\in\Omega_0,\ \ \omega_1\in\Omega_1,\ \ \omega_2\in\Omega_2,\\
&\boldsymbol{\Omega}=(\Omega_0,\ \Omega_1,\ \Omega_2),\ \ t\in T
\end{aligned} \tag{1}$$

Range of definition $\Xi_3(\boldsymbol{\omega},t) \Rightarrow \boldsymbol{\Omega} \times T$, and range of value is a set of real numbers $\Xi_3(\boldsymbol{\omega},t) \in R(-\infty,\infty)$. Generally, characteristics of the model $\Xi_3(\boldsymbol{\omega},t)$ are defined with consideration of both correlation (energy) theory and higher moments.
The components of such model are as follows:

1 component ${}_1\xi(\omega_1,t)$ is a non-stationary random process, describing the mechanism of noise signal formation, driven by the action of substantial number of elementary impulse signals with various strengths;

2 component ${}_2\xi(\omega_2,t)$ is a non-stationary random process, formed by the action of substantial number of elementary harmonic vibrations (waves);

3 component $A(t)/\xi(\omega_0,t_0)$ is a determined trend component $A(t)$ with initial random conditions $\xi(\omega_0,t_0)$, which describes changes made to the research object during repairing, upgrading etc.

5. Development of a constructive model for wind power units' noise signals

5.1. Experimental analysis of wind power units' noise signals

In order to define a constructive model for wind power unit's noise signals, it is necessary to conduct a study with real data, obtained during wind power units operation. For this purpose, we made some testing on the wind turbine USW 56-100, set up on a stand in PA Pivdenmash. During wind turbine operation in motor mode with rotation by a generator, a number of experiments were made for measuring, registering and determining statistical characteristics of vibrations in certain parts of the wind power unit.
During wind power unit rotation by a generator in motor mode, the average angular velocity of high-speed shaft rotation was 1449 rpm, and for the wind turbine hub-shaft (low-speed shaft) the average angular velocity was 72 rpm.
The monitored object within the experiments was the gear (transmission) casing at the position of the bearing of the low-speed shaft, equipped with an acceleration sensor ДН-4 (DN-4), which converted a vibrating wave, actuated by operation of wind power unit parts, to an electrical signal. The sensor's output signals were transmitted to a microcontroller, which matched these signal parameters with conversion board inputs and also converted analog vibration signals to a digital code. The sampling period for analog signals, at their conversion to a digital code, was 64 µs (with sampling frequency at 15625 Hz). The registered sample included 5000 readings. There were measured 10 realizations during the experiment. The averaged diagnostics results for the monitored object are shown below.
The obtained noise signals have had a trending component, which can be well observed in Fig. 1.

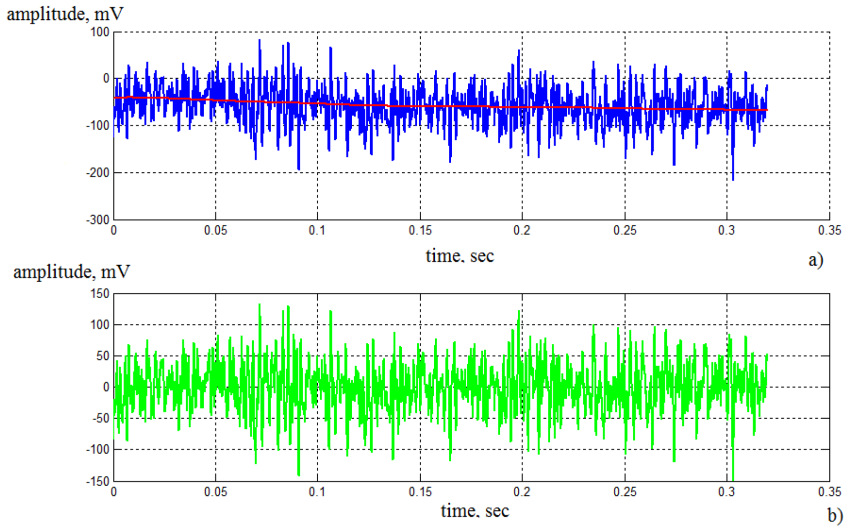

Figure 1. Realization of a timing series and a trend (a); trend-free timing series realization (b)

Fig. 2 and Fig. 3 graphically represent empirical frequency distribution and auto-correlation function of noise signal timing series realization in a wind power unit.

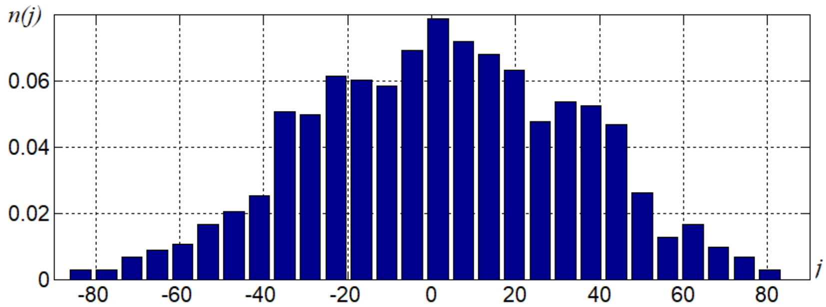

Figure 2. Estimation of empirical frequency distribution of timing series realization

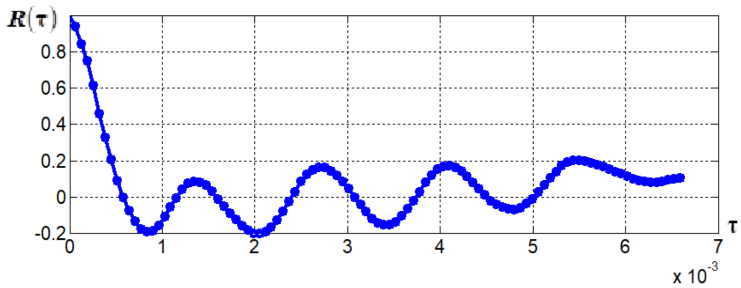

Figure 3. Estimation of auto-correlation function of timing series realization

As seen from the provided graphs of realization, the timing series represents the Gaussian law of distribution, and its vibrations distribution has a cyclical nature.
Basing on this, one may form a constructive model of wind power units' noise signals.

5.2. Constructive model for mathematical modeling of noise signals

Experimental analysis shows that the wind power unit's noise signal has a trending component and represents a Gaussian linear random process. Moreover, its vibrations have a cyclical nature, which means that harmonized processes are also present. Therefore, basing on the specific nature of signal formation in wind power units, there was developed a constructive model of a noise signal, which can be applied for mathematical and computer modeling. This model has the form of an additive mixture of noise signal components:

$$\begin{aligned}&\Xi_3(\boldsymbol{\omega},t) = {}_1\xi(\omega_1,t) + {}_2\xi(\omega_2,t) + A(t),\\ &\boldsymbol{\omega} = (\omega_0,\ \omega_1,\ \omega_2),\ t\in T\end{aligned} \quad . \tag{2}$$

The components of a random process of type (2) are as follows:

1) component ${}_1\xi(\omega_1,t) = \sum_{i=1}^{n} {}_1\xi_i(\omega_1,t)\, I(t,\Delta T_i)$ where $\left\{{}_1\xi(\omega_1,t), i=\overline{1,n}\right\}$ is a sequence of stationary linear random processes;
2) component ${}_2\xi(\omega_2,t) = \sum_{j=1}^{n} {}_2\xi_j(\omega_2,t)\, I(t,\Delta T_j)$ where $\left\{{}_2\xi(\omega_2,t), j=\overline{1,m}\right\}$ is a sequence of harmonized processes;
3) component $A(t) = \sum_{l=1}^{k} A_l(t) I(t,\Delta T)$ where $\left\{A_l(t),\ l=\overline{1,k}\right\}$ are the approximating functions at realization of a random value $\xi(\omega_0,t_0)$;
4) indicator function is set by the following expression:

$$I(t,\Delta T_j) = \begin{cases} 1, & t\in\Delta T_j \\ 0, & t\notin\Delta T_j \end{cases} \tag{3}$$

and practically is formed by time moments of disruption of studied components' harmonization (stationary state).
We shall study the noise signal components in more detail.

Linear random process. A Gaussian linear random process in modeling problems can be presented as the following constructive model [5]:

$$\eta(\omega,t) = \int_0^t \phi(t,\tau)\, x(\omega,\tau)\, d\tau\ , \tag{4}$$

where $\phi(t,\tau)$ is an impulsive admittance function of linear generating filter, $x(\omega,\tau)$ is a Gaussian white noise in form of a generalized derivative of Gaussian process with independent increments. For a stationary random process, the expression (4) takes the following form:

$$\eta(\omega,t)=\int_{0}^{\infty}\phi(t-\tau)x(\omega,\tau)d\tau \quad (5)$$

Classes of linear processes are to be chosen depending on the research problem. One may, for example, consider stochastic periodicity in technical diagnostics of objects, systems, and mechanisms.

Harmonized random process. Another name for a random process is "harmonized Loyev process" if it can be presented as follows [4]:

$$\xi(\omega,t)=\int_{-\infty}^{\infty}e^{i2\pi ft}dZ(\omega,f),\ \omega\in\Omega,\ t\in R \quad (6)$$

From all harmonized random processes, stationary random processes are studied most frequently. An actual stationary harmonized random process, as a particular case, is presented as follows:

$$\begin{aligned}\xi(\omega,t)=&\int_{0}^{\infty}\cos(2\pi ft)d\eta_c(\omega,f)+\\&+\int_{0}^{\infty}\sin(2\pi ft)d\eta_s(\omega,f),\ t\in R\end{aligned}, \quad (7)$$

where, respectively, random functions $\eta_c(\omega,f)$ and $\eta_s(\omega,f)$ are the functions with orthogonal increments.

Thus, the general mathematical model of noise signals with harmonic components is a non-stationary harmonized random process of type (6).

6. Special considerations for computer modeling of white noise realization

The engineers, dealing with computer modeling of noise signals, face the problem of choosing a pseudorandom number generator for white noise modeling that would be the closest to real data. After analyzing publications [11-15], there were established some recommendations on how to choose a generator of pseudorandom numbers, distributed under the uniform law, so that its realizations would follow the uniform law at statistically more significant level basing on quality characteristics. It is recommended to choose a pseudorandom number generator according to the scheme shown in Fig. 4.

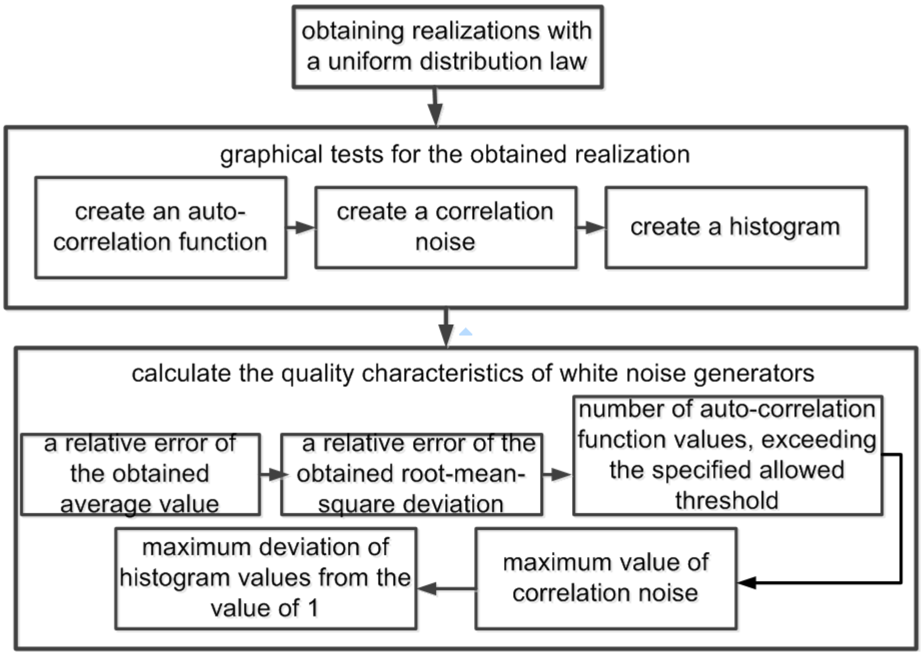

Figure 4. Flowchart of white noise realizations evaluation

The Kolmogorov-Smirnov criterion and the χ^2 -criterion have been used to test hypotheses about uniformity of the studied realization.

As shown in Fig. 4, calculation of the generator's quality characteristics was preceded by some graphical tests, which let create an auto-correlation function and a histogram for the obtained realization. The so-called correlation noise [16] is obtained by extracting value of 1 from a normalized auto-correlation function at a noise state. Fig. 5 shows an example of how correlation noise is obtained for pseudorandom number generator with the uniform distribution law applied.

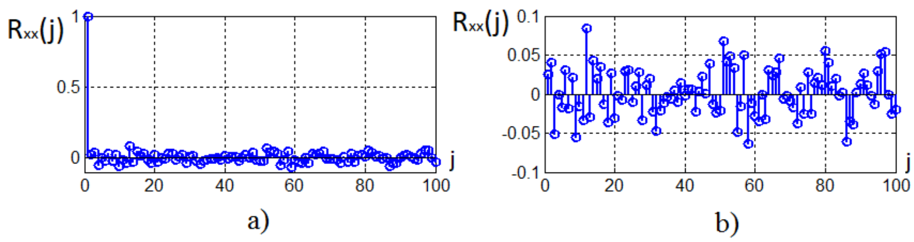

Figure 5. Statistic estimation of auto-correlation function (a) of white noise and corresponding correlation noise (b).

Since theoretical values of mathematical expectation and dispersion for the uniform distribution law are well known, it is quite simple to find a relative error of the obtained average value and a root-mean-square deviation of white noise realization.

To calculate the quality characteristics of white noise generators according to graphical tests, it was necessary to find the following:

- number of auto-correlation function values, exceeding the specified allowed threshold (the threshold is defined depending on the results of repeated statistical modeling);
- maximum value of correlation noise;
- maximum deviation of histogram values from the value of 1.

Basing on the characteristics above, we may choose a generator of pseudorandom number sequence. For this purpose, the Pareto method for multi-objective problems resolving is used, which lets discard knowingly unnatural or disadvantageous solutions and keep only solutions, for which there are no dominating ones in a multi-objective problem [17].

More detailed results of white noise modeling can be found here: [11-12].

7. Conclusions

In this work, we have developed and grounded a vector model of wind power units' noise signal. In practice, noise signals may consist of multiple components, since they are formed by the action of a substantial number of elementary harmonic vibrations (waves) and impulse signals with various strengths. Therefore, we propose to represent the general noise signal model as a three-component vector process, where each component has its own physical meaning.

The authors have conducted a study on a wind turbine with the wind-electric set rotated by a generator in motor mode. Basing on the specificity of the obtained results, a constructive model of noise signals has been developed, in form of an additive mixture of noise signal components, which can be used for mathematical and computer modeling.

We also presented here some features, related to computer modeling of white noise realizations and used for computer modeling of wind power units' noise signal.

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