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DIAGNOSTICS OF GEAR PAIR DAMAGE USING THE METHODS OF BIPERIODICALLY CORRELATED RANDOM PROCESSES. PART 2. INVESTIGATION OF VIBRATION SIGNALS OF THE WIND POWER GENERATOR GEARBOX

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ABSTRACT

The results of processing the vibration signals of the wind power generator gearbox are given. The model of vibration in the form of biperiodically correlated random processes (BPCRP), which describes its stochastic repeatability with two different periods, is considered. Least squares (LS) estimates of the periods of the deterministic part of the vibration signal and the temporal changes of power of its stochastic part were obtained. The amplitude spectra of deterministic oscillations and dispersion of stochastic oscillations for different degrees of gearbox damage were analyzed. The most effective indicators of defect development, which are formed on the basis of amplitude spectra, are proposed for practical use. The correlation structure of the stochastic vibration component of the wind power generator gearbox was analyzed.

KEYWORDS: wind power generator gearbox, vibration, periodical nonstationarity, deterministic oscillations, correlation function, defect development indicator

INTRODUCTION

Solution of the problems of technical diagnostics is effective using the methods of statistical analysis of vibration signals based on a theory and methods of periodically correlated random processes (PCRP) [1] and their mutual analysis [2]. One of such problems is evaluation and control of operation of elements of complex mechanical systems, detection of defects nucleated in mechanisms, search of indicators reacting on insignificant deviation of parameters of technical condition from standard. Work [3] proposes a model in form of biperiodically correlated random processes (BPCRP) for analysis of vibration of a damaged gear pair of wind power generator (WPG) gearbox where modulation interaction of deterministic oscillations of two wheels is characterized by BPCRP mathematical expectation and interaction of stochastic vibrations by BPCRP correlation function. Fourier series of the mathematical expectation and correlation function consist of harmonics of frequencies of wheels rotation, their multiples and combinations. Harmonics of coupling frequencies are the separate BPCRP harmonics of signal representation. Specific content of harmonics of deterministic and stochastic oscillations depends on a level of defect development and place of its location.

An approach proposed in [3] was used for analysis of signals of WPG gearbox vibration using PCRP for defect diagnostics. In process of analysis of vibration signals there were determined the amplitude spectra of oscillations deterministic constituent and power of time changes of stochastic constituent was used as typical characteristics for evaluation of level of defect development. Based on the results of vibration signal processing there was proposed the most sensitive indicator for detection of WPG gearbox defects.

ANALYSIS OF REAL DATA

The results of analysis of a half-year monitoring of signals of WPG gearbox vibrations are provided with the following characteristics: number of gear teeth — 25, number of wheel teeth — 94. Duration of obtained vibration signals — 3.35 s (8192 points). Figure 1 shows the fragments of vibration signals corresponding to different stages of development of gear tooth defect. Rotation speeds of a high-speed shaft were measured using a tachometer and made respectively 1451.55, 1442.85 and 1404.75 rpm for each of failure

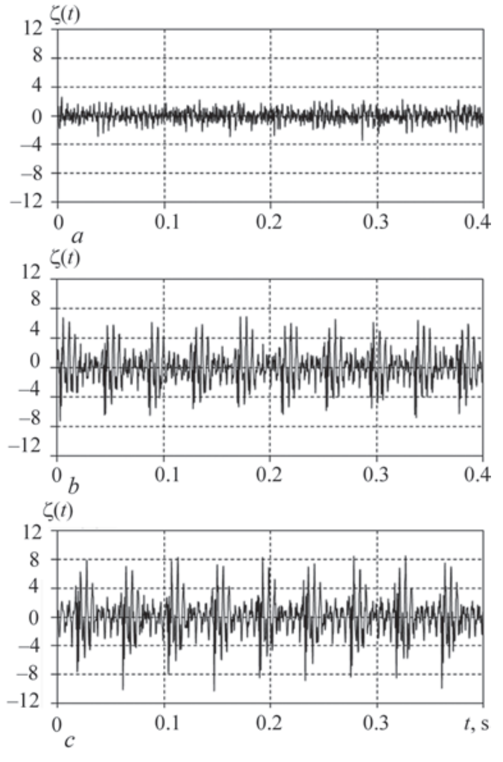

Figure 1. Fragments of realization of vibration signals for three stages of defect development of gear tooth

stages. Figure 1 shows that vibration signals for second (Figure 1, *b*) and third (Figure 1, *c*) failure stages contain clear strokes provoked by presence of developing defect and time intervals between the strokes are close to a period of shaft rotation.

Let's calculate evaluations of spectral densities of stationary approximation of signals for each of the stages using Hamming windows:

$$k(\tau)=\begin{cases}0.54+0.46\cos\dfrac{\pi\tau}{\tau_p}, & |\tau|\le\tau_p,\\ 0, & |\tau|>\tau_p,\end{cases}$$

where τ_p is the point of correlogram truncation. It appears from the obtained results (Figure 2) that a spectrum of oscillation power lies in a range of 0–10 kHz (Figure 2, *a*) and the main constituent of power spectrum lies in a range limited by 3 kHz (Figure 2, *b*).

Diagrams on Figure 2 have a comb-shape with different amplitudes and bandwidths. The evaluation value acquires peak values in the points matching with coupling frequency and frequencies multiple to it, rotation frequency of gear, multiple to it and their mutual combinations. We note the frequency bands which correspond to powerful resonances, i.e. $[f_p; 1.8f_p]$ and $[2.2f_p; 3f_p]$, where f_p is the coupling frequency. Powers of spectral constituents corresponding to wheel rotation frequency (approximately 6.4 Hz) and multiple to it are insignificant. Therefore, it is possible to assume that deterministic and stochastic modulations caused by PCRP oscillations of a shaft rotation period are also insignificant, and formally current data can be analyzed as PCRP realizations.

Let's carry out an analysis of properties of signal on frequencies less than $1.8f_p$. The evaluations of correlation function and spectral density for stationary approximation of filtered signals corresponding to three stages of gear tooth failure are given on Figures 3, 4.

Presence of undamped "tail" is a typical feature of evaluations of PCRP correlation function. It comes from a formula for stationary approximation of PCRP correlation function [3]:

$$R(\tau)=R_0(\tau)+\frac{1}{2}\sum_{k=1}^{L_1}|m_k|^2\cos k\frac{2\pi}{P}\tau \qquad (1)$$

that a undamped "tail" contains the cosine oscillations with amplitudes corresponding to power of each deterministic constituent of harmonic. In point $\tau = 0$ expression (1) determines the sum power of deterministic and stochastic oscillations. In point $\tau_r = \tau P$, where r is the natural number, for which $R_0(rP) \approx 0$, a value of power of deterministic oscillations is obtained. For three considered stages of degradation of a gear tooth the sum power of vibration signal equals $0.95G^2$, $5.84G^2$ and $7.73G^2$ and power of deterministic

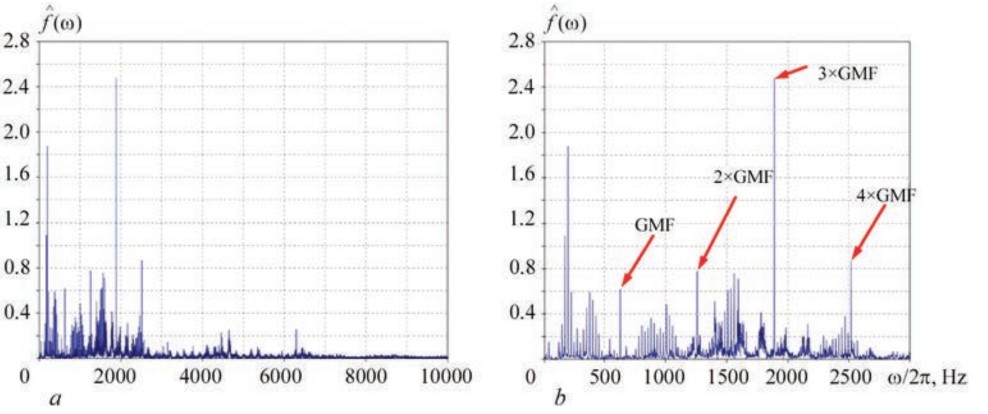

Figure 2. Evaluation of spectral density of power of vibration signal in stationary approximation for first stage: *a* — full spectrum; *b* — LF fragment of spectrum

constituent of oscillations vibration signal is $0.72G^2$, $5.12G^2$ and $6.73G^2$, respectively. Therefore, part of power of stochastic oscillations reduces with defect development. If this part on the initial stage of defect development approximately equals 30% then for the last stage it equals only 14 %.

It is noted that the undamped "tail" of correlation function has a group structure, the time interval between the separate groups is close to a period of shaft rotation. Presence of the undamped "tail" in evaluation of the correlation function results in appearance of discrete constituents in evaluation of spectral density which are presented by peaks on certain frequencies (Figure 4). Detected peaks can also be a result of a narrow band characteristic of stochastic constituents. Therefore, obtained spectra of the vibration signal complicate interpretation of the results of spectral evaluation and their quantitative analysis. For discrete evaluation of spectrum use [3]

$$\hat{f}_d(\omega) = \int_{-\infty}^{\infty} f_d(\omega_1)\lambda(\omega-\omega_1)d\omega_1,$$

where

$$f_d(\omega) = \frac{1}{2}\sum_{k=1}^{L_1}|m_k|^2 f(\omega - k\omega_0)$$

and $\lambda(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} k(\tau)e^{-i\omega\tau}d\tau$.

So

$$\hat{f}_d(\omega) = \frac{1}{2}\sum_{k=1}^{L_1}|m_k|^2 \lambda(\omega - k\omega_0).$$

Since $\lambda(0) \le \tau_p$ then the peak values do not equal the power of separate harmonic and change if τ_p changes. Therefore, it is necessary to divide continuous and discrete constituents of spectrum and their separate analysis using corresponding methods. It is in particular important for monitoring of mechanisms since discrete and continuous constituents can be caused by different types of defects.

Evaluation of a period is the initial stage of selection and analysis of deterministic constituent of vibration oscillations. It is necessary to note that the accuracy of period evaluation should be sufficiently high in order to reach the minimum displacement of initial averaging point. Period evaluation is carried out using the method of least squares because in this case we can consider total power of selected harmonics of the deterministic constituent that increase evaluation effectiveness. It should be noted that a systematic error of evaluations of the least squares method of period

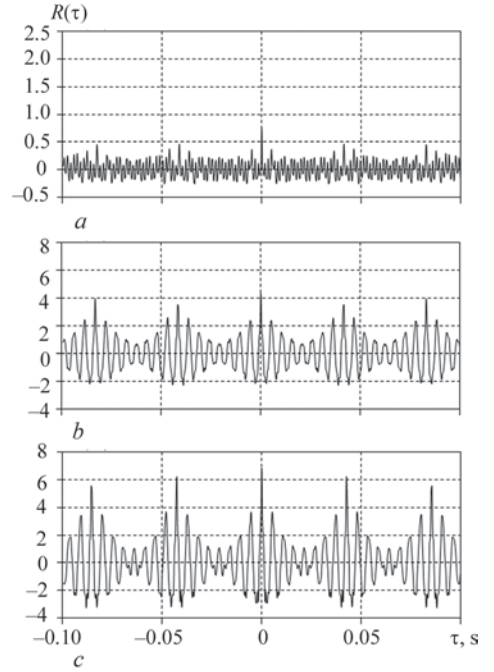

Figure 3. Evaluations of correlation function of filtered signals for three stages of development of defect of gear tooth

has $O(T^{-2})$ order and root-mean-square value of a random error $O\left(T^{-\frac{3}{2}}\right)$ [4].

Dependencies of a quadratic functional, calculated by [3], from a trial frequency for three stages of failure of gear is presented on Figure 5. The points of maximum of functional for each of three stages with accuracy up to three characters after coma correspond to basic evaluation of frequency and equal $\hat{f}_0$ = = 24.206 Hz (Figure 5, *a*), $\hat{f}_0$ = 24.055 Hz (Figure 5, *b*) and $\hat{f}_0$ = 23.423 Hz (Figure 5, *c*) respectively. Cal-

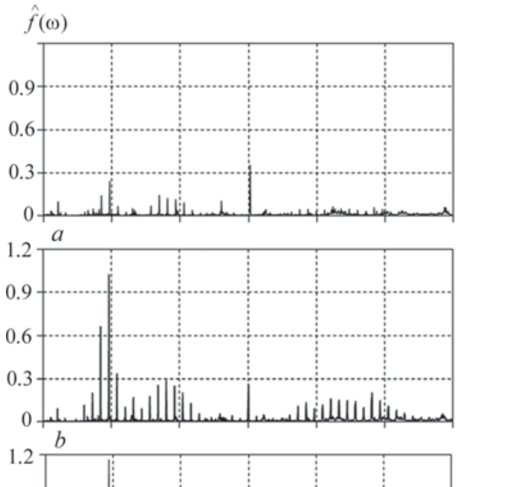

Figure 4. Evaluations of spectral density of power of filtered signals for three stages of development of defect of gear tooth

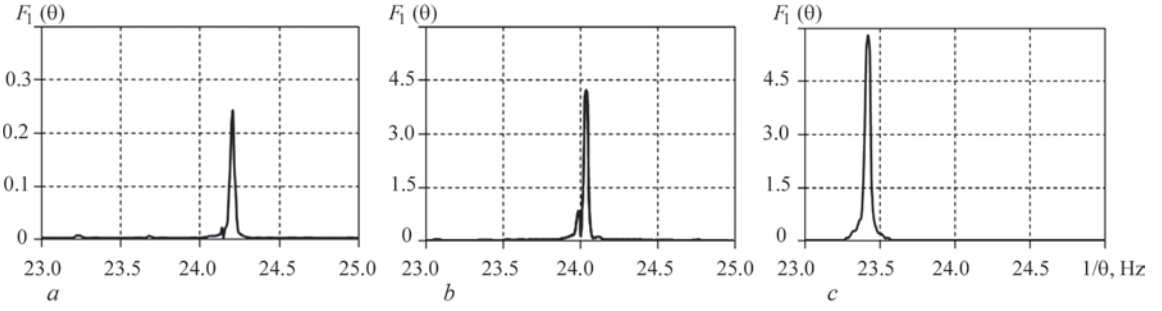

Figure 5. Dependence of quadratic functional of first order on test frequency for three stages of development of defect of gear tooth

culated values of the main frequency of deterministic oscillations are close to the values obtained by means of tachometer measurement, namely 24.192; 24.047 and 23.412 Hz.

Following from the calculation values of the basic frequency there were calculated the amplitudes of harmonics of deterministic constituent of vibration that are presented on Figure 6.

First harmonics of spectra of the deterministic constituent can be interpreted as orders of harmonic of a shaft rotation frequency. Twenty fifth harmonic corresponds to the first harmonic of coupling frequency and frequencies of higher harmonics are linear combinations of frequencies of coupling and rotation frequency. On the first stage of defect development the amplitude of harmonic of coupling frequency is the largest. Increase of damage provokes domination of the harmonics of 6–9th orders, however a general view of amplitude spectra remains similar. Sum of amplitudes of the harmonics for levels of defect development equals 3.47, 7.44 and 10.50, respectively, whereas sum powers of the harmonics equal 0.36, 3.52 and 4.63. Calculated according to [3] values of indicator I_1 change from 2.14 to 3.03 and I_2 indicator from 9.87 to 12.8. Based on the sine and cosine Fourier coefficients [1] it is possible to calculate evaluation of PCRP mathematical expectation for all time moments $t \in \left[0, \hat{P}_1\right]$ (Figure 7).

On the assumption of [1, 17] and taking into account calculated values of the correlation function it is possible to make a conclusion that for set length of realization a standard deviation $\sigma\left[\hat{m}(t)\right]$ of evaluation of mathematical expectation is less than 0.01. Deterministic oscillations have a group structure and time intervals between the groups are close to a period of shaft rotation and each group consists of approximately eight oscillations.

Further analysis of condition of the gearbox was carried out based on the centered vibration signals obtained by means of subtraction from a signal of evaluation of PCRP mathematical expectation, i.e. $\mathring{\xi}(t) = \xi(t) - \hat{m}(t)$. Evaluations of correlation function of the centered signals (Figure 8) have a shape of slowly damped groups which follow one by one with

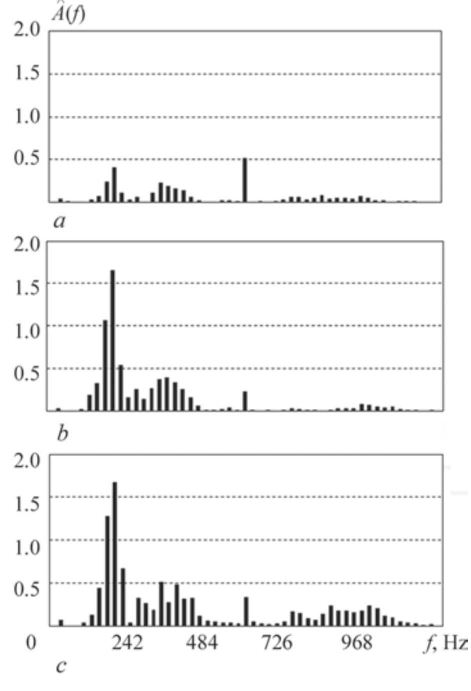

Figure 6. Amplitude spectra of oscillations deterministic constituent for three stages of development of defect of gear tooth

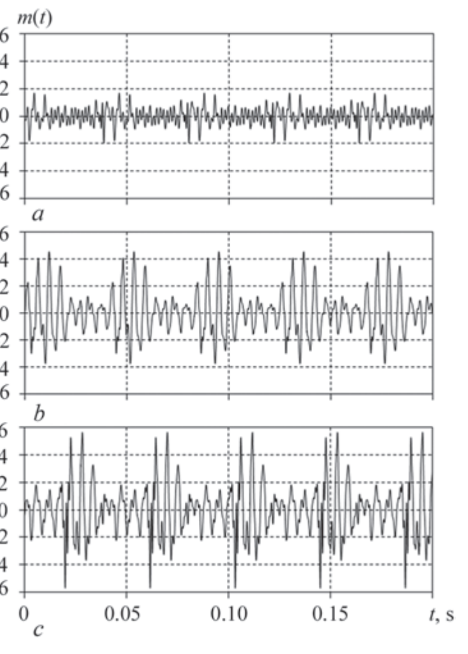

Figure 7. Evaluations of mathematical expectation of vibration signal for three stages of development of defect of gear tooth

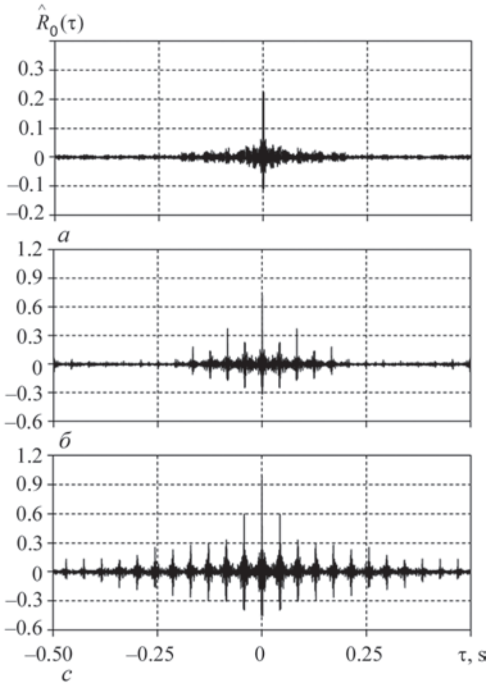

Figure 8. Evaluations of correlation function of stochastic constituent of vibration for three stages of development of defect of gear tooth

rotation period. These groups become clearly noticeable for the second (Figure 8, *b*) and third (Figure 8, *c*) stages of defect development. The values of evaluation with increase of a shear τ decrease to fluctuations of small power, so deterministic oscillations are completely separated from vibration signal.

Spectral densities of the stochastic constituent of vibration signals contain only continuous constituent of a signal (Figure 9, 10). A comb-like shape of evaluations of the spectral densities indicates a narrow-band modulation of bearing harmonics of PCRP of low- and high-frequency range. This means that the modulating processes can be represented in form of sum of low-frequency and high-frequency narrow-band constituents which can be modeled using Rice's representation [5]. The conclusions on correlations or absence of correlations between these constituents in the range of low- and high-frequency areas can be made only based on the results of PCRP-analysis.

Dependencies of LSM functional [3] on a test frequency for each stage of failure of gear tooth contain a clearly determined peak (Figure 11) in a point which is considered as evaluation of a period of dispersion or main frequency. The evaluated values of main frequency f_0 equal 24.196, 24.075 and 23.423 Hz.

These values also insignificantly differ from the main frequency evaluations of mathematical expectations of vibrosignals. The clearly defined peak on a diagram on Figure 11, *a* corresponds to early stage of defect appearance. Taking into account powers of the peaks on Figure 11, *b*, *c* the conclusion is made on a

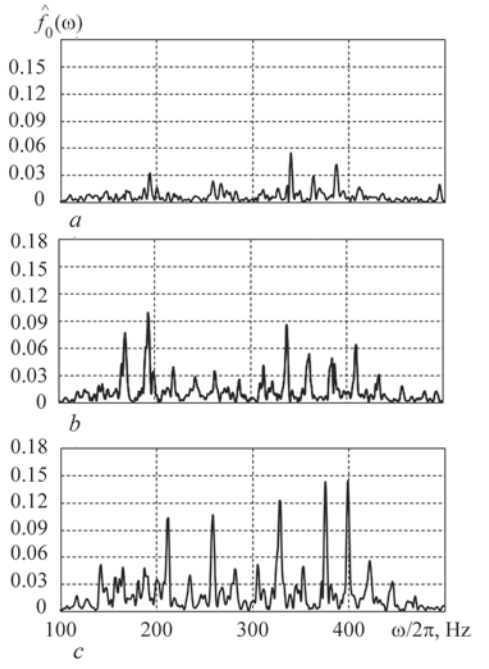

Figure 9. Evaluations of spectral densities of stochastic constituents of vibration in area of low frequencies for three stages of development of defect of gear tooth

presence of developed defect. An amplitude spectrum of change of dispersion in time (Figure 12) was calculated having the information about $\hat{f}_0$ value.

Figure 13 shows the statistics diagrams

$$\left|\hat{R}_k(0,\theta)\right| = \left[\left[R_k^c(0,\theta)\right]^2 + \left[R_k^s(0,\theta)\right]^2\right]^{\frac{1}{2}}.$$

As can be seen from Figure 13, the diagrams contain no dominating extremums based on which it is difficult to make any conclusions as for defect development.

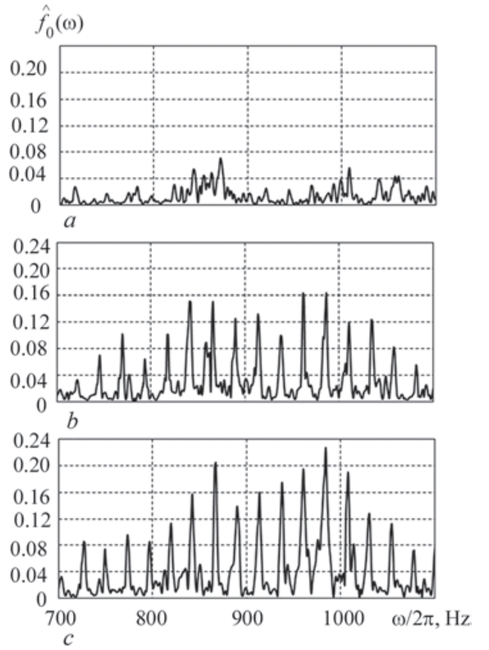

Figure 10. Evaluations of spectral densities of stochastic constituents of vibration in high-frequency area for three stages of development of defect of gear tooth

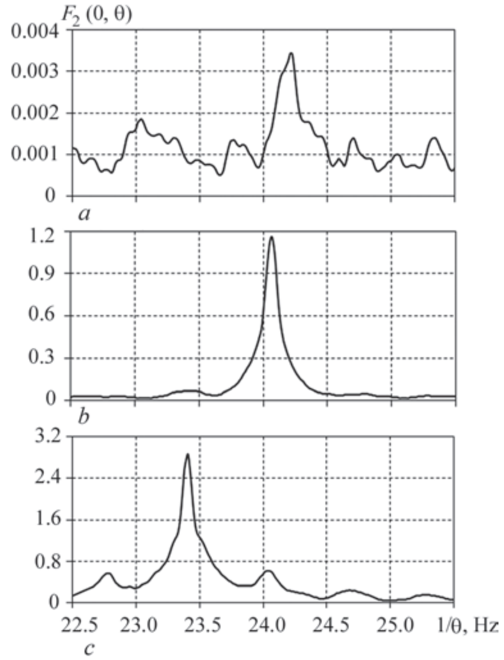

Figure 11. Dependencies of quadratic functional of second order on test period for three stages of development of defect of gear tooth

Amplitude spectra of dispersion $\hat{V}(k\hat{f}_0)$ (Figure 12) slowly drop down with increase of frequency that is especially typical for two last stages of defect development. Spectral constituents distributed on frequency for more than 280 Hz are weakly correlated. Therefore, the low-frequency and high-frequency modulations are non-correlated. An indicator is formed for this peculiarity consideration:

$$I_4 = \frac{\Delta\hat{R}_0(0) + \sum_{k=1}^{L_2} \hat{V}\left(k\hat{f}_0\right)}{\hat{R}_0^{(i)}(0)}, \quad (2)$$

where $\Delta\hat{R}_0(0) = \hat{R}_0^c(0) - \hat{R}_0^{(i)}(0)$. Indicator I_4 has the following values, namely 1.29, 13.82 and 30.72, respectively, for each stage of defect development. Significant increase of I_4 indicator is an evidence of its high sensitivity to change of condition of gear pair.

It should be noted that the indicators used in the work differ from the indicators of cycle stability. A condition of gearbox is described by relationship of a power of change in time of mathematical expectation or dispersion to the initial quantities of these values, but not to an averaged by time dispersion for each condition. The latter significantly changes with defect development. Therefore, it is reasonable to take into account these changes as it was shown above.

Figure 14 shows the diagrams of dispersion change in time. These changes contain a significant projection caused by defect of gear tooth in a time interval which equals a nonstationarity period. These projections are particularly strong for two last stages when a defect of tooth is well developed and close to failure.

A failure of gear tooth was verified after a regular check of the gearbox by a group of maintenance staff (Figure 15). A relative standard deviation of evaluation of correlation function $\sigma_r[\hat{R}(t,0)]$, calculated by [1, 4] for set length of realization is less than 0.04.

Specific features of the damage can also be determined based on the analysis of correlation functions of stochastic constituent of vibration signal (Figure 16).

In this case the correlation oscillations are a superposition of damped waves with close frequencies $\mu_0 \pm k\omega_0$, where μ_0 is the resonance frequency of gear pair.

PCRP methods of vibration analysis proposed in [1, 4] for early defect detection differ from the meth-

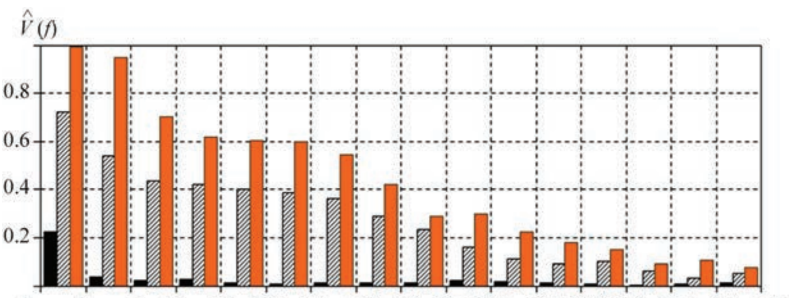

Figure 12. Amplitude spectrum of periodic changes of dispersion for three stages of development of defect of gear tooth

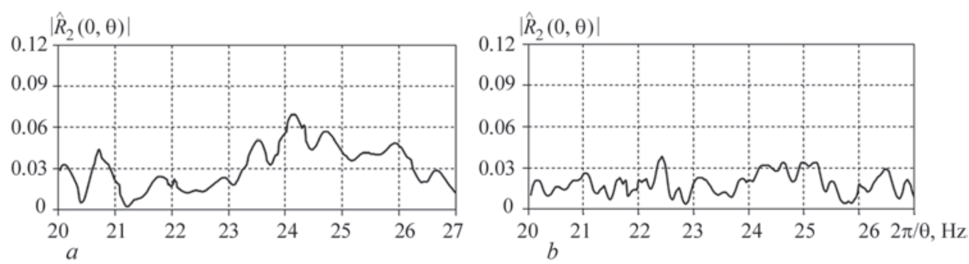

Figure 13. Dispersion of constituents of first (*a*) and second (*b*) functional for first stage of defect development

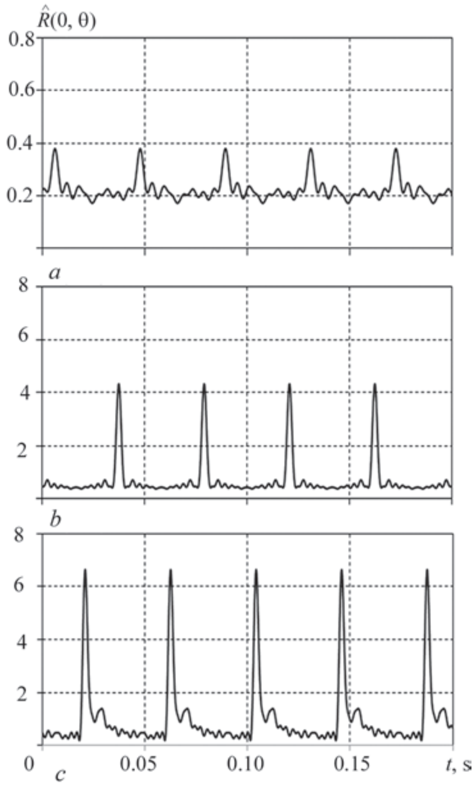

Figure 14. Evaluations of dispersion function of stochastic constituents of oscillations for three stages of development of defect of gear tooth

ods of so-called cycle stationary analysis being traditionally used in literature [5–10].

The cycle stationary analysis includes the calculation of cyclic autocorrelation function depending on time and shear and its 2D Fourier transformation, search of correlated harmonics, calculation of coherence functions and their integration, determination of so-called informative band of frequencies and different developed procedures of final consideration, etc. [11–18].

The PCRP analysis is carried out in a frequency-time area without transition into double-frequency area. A time structure of vibration signal was investigated based on expansion of moment functions of the first and second orders in Fourier series. The amplitude spectra of deterministic constituent of vibration and time changes of power for stochastic part are used for description of conditions of machines. Analysis in a stationary approximation is carried out for determination of the general properties of spectral content of oscillations and identification of frequency interval for detection of the hidden periodicities.

Effective methods of determination of the hidden periodicities of first and second order developed in [1, 4] provide identification of a period of deterministic oscillations and a period of time changes of moment functions of the second order for each separate realization with necessary accuracy. This provides the

Figure 15. Photo of driving gear tooth of gearbox

possibility to get the evaluations of corresponding amplitude spectra, which can be used as a basis for evaluation of technical state of machine. An amplitude spectrum of dispersion is determined by modulus of correlation constituents (cyclic functions) in a point with shear $\tau = 0$:

$$\left|R_k(0)\right| = \int_{-\infty}^{\infty} f_k(\omega)d\omega \quad k = \overline{1, L_2}.$$

An amplitude of separate harmonics of k series is a sum characteristic of correlation of spectral harmonics, frequencies of which are displaced for $k\omega_0$. Summarizing amplitudes of all series a sum characteristic is obtained for all possible correlations of spectral

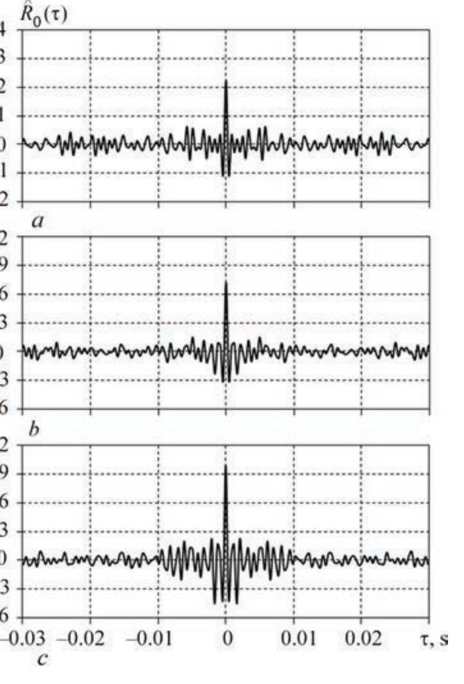

Figure 16. Dependencies of correlation functions of stochastic constituent of vibration signal for three stages of development of defect of gear tooth

Table 1. Stages of defect development

Indicator	Stage				
	Initial	Small	Medium	High	Dangerous
I_2	$I_2 < 0.5$	$0.5 \le I_2 < 2.0$	$2.0 \le I_2 < 4.0$	$4.0 \le I_2 < 10.0$	$I_2 \ge 10.0$
I_4	$I_4 < 2.0$	$2.0 \le I_4 < 10.0$	$10.0 \le I_4 < 20.0$	$20.0 \le I_4 < 25.0$	$I_4 \ge 25.0$

harmonics of the stochastic constituent of oscillations, however, this analysis is carried out only in a cyclic frequency area in scope of harmonic analysis of Fourier series.

Averaged by time power of the stochastic oscillations, determined by $R_0(0)$, rises with defect development. It causes inclusion of value of increment $\Delta R_0(0)$ in (2) for the indicator of defect detection. Thus, it can be expected that indicator I_4 formed based on all coefficients of Fourier dispersion, will be sensitive as much as possible to change of state of gear pair.

The time changes of dispersion in a general case are not localized in a frequency area. The maximum difference of frequencies between correlated harmonics is determined by the largest number of dispersion harmonic.

It should be noted that a dispersion of cyclic statistics, which is used in the analysis of "bypass square" [12, 14, 19, 20] has $O(T^{-1})$ order, whereas a dispersion of evaluation of basic part has $O(T^{-3})$ order and LSM evaluation provides significantly higher signal-to-noise ratio. Since amplitude of each separate harmonic for $|R_k(0)|$ dispersion is always less than $R_0(0)$, i.e. $|R_k(0)| \le R_0(0)$, $\forall\, k = \overline{1, L_2}$, then LSM evaluation has an obvious advantage in a hidden periodicities search.

For known basic frequency a cyclic (constituent) evaluation can be considered as a signal filtering with a transfer function in form of comb reaching the peaks in points $f = k\hat{f}_0$, $\forall\, k = \overline{1, L_2}$. These peaks become sharper (narrower) with increase of realization length. Such an approach allows increase of processing accuracy and elimination of laborious procedures being usually used for improvement of the traditional methods based on discrete Fourier transformation [10, 11]. The amplitude spectrum of deterministic constituent of oscillations and, first of all, the amplitude spectrum of time changes of power of oscillations stochastic constituent characterize defect features. The indicators formed on this basis can be effectively used for analysis of state of machines and mechanisms. Following from the numerical results of processing of time series of vibration signals of WPG gearbox it is possible to outline the stages of defect development (Table 1).

It should be noted that an emergency stage of defect development is characterized with a quick growth of both indices. It is recommended to use both these indices on practice. It is noted that the numerical values of indices were obtained based on the analysis of signal in up to 1 kHz frequency range.

CONCLUSIONS

It is shown that the parameters of the first and second series of PCRP vibration in [0; $1.8f_p$] frequency band are sufficiently sensitive to changes of mechanism condition and in full provide successful detection of defects and monitoring of their development.

LSM functional was used for detection of hidden periodicities of second order. Its dependencies on test period have sharp peaks in the points which are taken as periods of dispersion time changes. Presence of such peaks of increase indicates nucleation and development of a local damage. The sum amplitude of dispersion harmonics was taken for comparison of different stages of defect development. At that values of amplitudes for harmonics, order of which is more than twelve, were insignificant. This means that the spectral constituents, frequency intervals between which are more than 280 Hz, are low-correlated and, therefore, low-frequency and high-frequency modulations are non-correlated.

Dispersion does not contain time changes at defect absence. Therefore, it is relevant to choose an initial value of zero correlation constituent $R_0(0)$, determining average power of stochastic constituent of vibration oscillations, for quantitative characteristic of a change of the mechanism condition. An average power rises in process of defect development, so this increase was taken into account in the formula for stochastic indicator of the mechanism condition. It is shown that change of this indicator significantly overwhelms change of the "deterministic" indicator. The latter is determined by a power of deterministic constituents of oscillations, at that the power of the latter significantly overwhelms the power of stochastic constituents. Obtained results provide allows recommending the proposed stochastic indicator for monitoring of WPG gearbox.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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