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Vibroacoustic diagnostics of gear drives by using of wavelet analysis

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Abstract

For last ten years wavelet-transform has found wide application in vibroacoustic signal processing. The wavelet-analysis gives unique possibilities to recognize local features of investigated signal. Following researches have been realized: sequentially it was recorded vibration signal generated during operation of machine tool gearbox unit with a serviceable and damaged tooth gears; spectrum analysis and wavelet-transform of the measured signals were made; confirmation of wavelet-analysis efficiency in vibroacoustic diagnostics are obtained.

Key words: *diagnostics, gearing, damage, vibration, signal, spectrum, wavelet*

1. INTRODUCTION

The most widespread mechanisms in machine-building industry are involute tooth gearings. While operation tooth gears wear out and get damages. Excessive increase of gears damages can lead to infringement of normal work and drive breakage.

Gearing operation is accompanied by periodic impacts at an entry of teeth pairs in engagement that generates vibroacoustic fluctuations. Amplitude depend on such factors, as type of teeth, gears rotation speed, loading, manufacturing and assemblage accuracy, it also depend on presence of operational damage and it degree. These factors except the last can be considered during designing, manufacturing, assembling and by selecting of gear drive operating modes. Last factor can be revealed at the control and drive diagnostics during operation.

Vibroacoustic fluctuations are characterized by high frequencies, small amplitudes of vibration displacement and considerable vibration acceleration. Vibroacoustic signal has the difficult structure and contains information concerning of tooth gears condition. Also there is a noise which interferes with accurate decoding of the information containing in a signal. Besides, there are distortions during diagnostic signal transiting through channels from a source to the detector. An initial signal is the short impulse generated in a gear-and-pinion set through impact. Detector perceives not this signal but a damped oscillation. Therefore at diagnostics system engineering it is necessary to select such way of signal processing which minimizes influence of noise [1].

2. SPECTRUM ANALYSIS OF VIBROACOUSTIC SIGNAL

Spectrum analysis is one of the most often applied classical signal processing methods of vibroacoustic diagnostics which allows to describe frequent structure of a measured signal. It’s based on Fourier-transformation which uses sines and the cosines as basis functions presented by a complex exponential curve.

According to demands at the analysis of complex nonstationary signals, it is possible to note certain "disadvantages" of the Fourier-transform:

- poor information content in the analysis of nonstationary signals; full lack of possibilities of the analysis of signal singularities (discontinuities, differentials, peaks, etc.) because they are "blurring" in a frequent area on all spectrum;

- the classical algorithm of Fourier-transform basically does not allow a possibility to analyse signal frequency characteristics at any moment of time;

- using Fourier-transform it is possible to investigate a nonstationary signal or only in a time area or only in the frequent area; does not allow to define what frequencies are contained in a signal at a certain period of time

These disadvantages have led to appearance of window Fourier-transform at first and then were developed methods of wavelet-transform.

For time localisation of spectral components it is necessary to construct time-and-frequency representation of a signal [2]. I. Daubechies in the publication [3] has displayed fundamental limitations of the Fourier-transform regarding representation of nonstationary signals and signals with sharp differentials of amplitude. These serious limitations have been overcome by using the special mathematical apparatus of any signals representation based on wavelets.

3. WAVELET ANALYSIS

The wavelet apparatus is founded on a generalized conception of signals ***s(t)*** in a vector space in the form of basis functions $\boldsymbol{\psi_{a,b}(t)}$ multiplied by coefficients $\boldsymbol{C_{a,b}}$:

$$s(t) = \sum_{a,b} C_{a,b}\psi_{a,b}(t) \tag{1}$$

where ***a, b*** is time scale and time localisation.

Such functions $\boldsymbol{\psi_{a,b}(t)}$ are extremely localised in frequent area and degenerated in a vertical line on a spectrum, but are not localised in a time area [4]. Ability of wavelets-spectrograms to discover artefacts of signals has no precedents in the spectrum analysis. Wavelets are localised both in time and in frequent areas. Discrete and continuous a wavelet-transform has found wide application in vibroacoustic signal processing. In particular wavelet analysis allows unique possibilities to recognise smallest local singularities of a signal.

Direct continuous wavelet-transformation of the signal ***s(t)*** is made by formal analogy to a Fourier-transform by an evaluation of wavelets-coefficients:

$$C_{a,b} = \int_{a,b} s(t)\psi_{a,b}\left(\frac{t-b}{a}\right)dt \tag{2}$$

Result of a signal wavelet-transform (2) is the two-dimensional matrix of coefficient values $\boldsymbol{C_{a,b}}$, allocated in space **(*a, b*)**. This array gives the information about variation in time of the processed signal wavelet-components with different scale and it is called as a spectrum of wavelet-transform coefficients or as scale-time (time-and-frequency) spectrum or simply wavelet-scalogram.

It is possible to realise the analysis and synthesis of a local singularity of any signal by means of wavelets. The selection of concrete wavelet and transform (continuous or discrete) completely depends on task in view character and on a concrete investigated signal. Different signals go right to be analysed by different ways and criterion of success is simplicity of received signal decomposition [5].

The wavelet-transform allows to look at investigated process from other point of view. At the analysis of nonstationary signals wavelet locality gives the major advantage in comparison with Fourier-transform because local singularities of a signal give hardly noticeable components of a Fourier-spectrum. It is practically impossible to discover these singularities, their place and character [5].

4. RESULTS OF RESEARCH

Purpose of research is development of a signal processing technique and definition of estimation criterion of multishaft gearbox technical condition and also detection of damage kind, degree of damage and its localisation.

In this section presented spectrum and wavelet analysis of vibroacoustic signal measured during operation of machine tool gearbox unit of universal lathe CH-401/501. Rotation speed of output shaft was ***32, 400, 1000 min***$^{-1}$. It has been at first measured vibroactivity of healthy drive. Then on the second shaft was established the wheel (***z=43***) with one tooth chipping and measurements have been repeated. Value of tooth damage gradually increased and was ***25, 50 and 75%*** (Fig 1.).

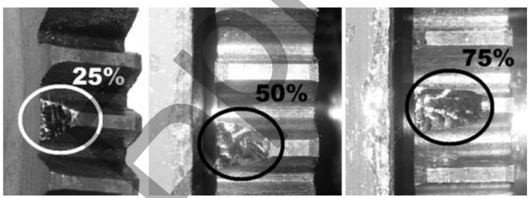


Figure 1 – Tooth chipping of experimental wheel

4.1 *Spectrum analysis*

The fragment of a vibrosignal generated by gearbox with damaged wheel and its spectrum is featured in Fig 2. During measurements the wheel with a local damage rotated with frequency $\boldsymbol{f_o \approx 14,82}$ ***Hz*** and frequency of teeth linkage was $\boldsymbol{f_z \approx 637,1}$ ***Hz***. The spectrum analysis was made on the basis of classical Fourier-transform by the program VibroAnalizator developed in common BSTU (Brest State Technical University) and BSU (Belorussian State University).

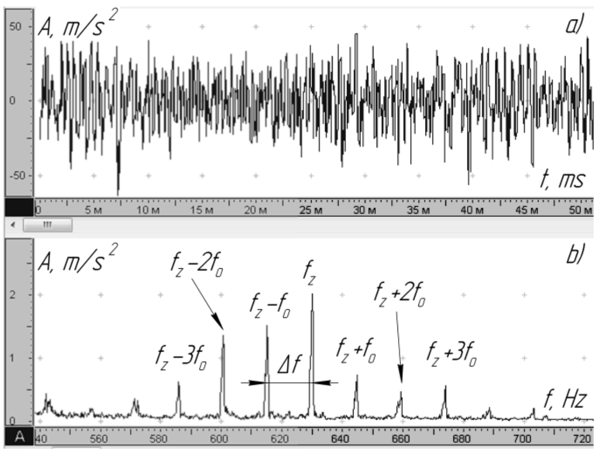


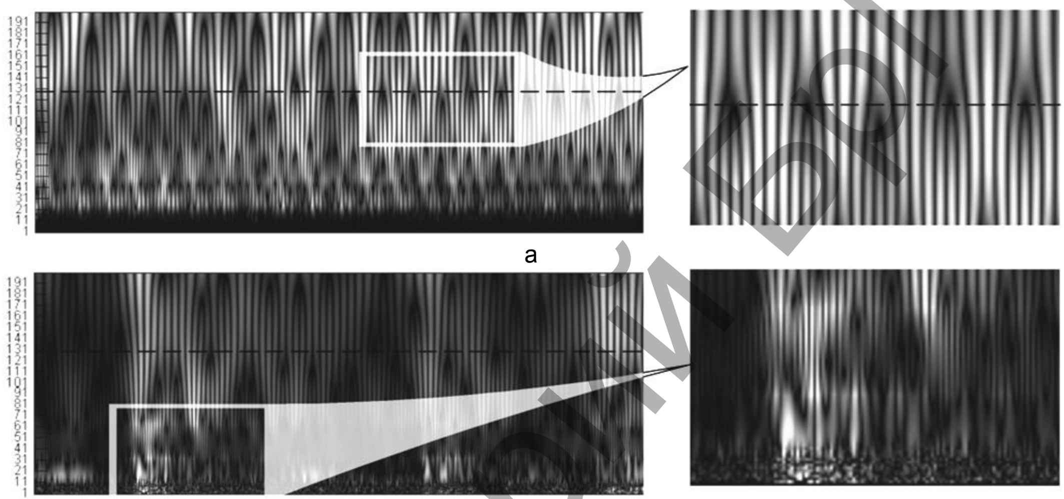
Figure 3 – Signal (**a**) and its spectrum (**b**)

In a signal plot (Fig 2a.) are visible splashes of the amplitudes which sources to define it is impossible without additional processing. Such graph allows to judge the common level of vibration only. On a spectrum (Fig 2b.) the peak with teeth linkage frequency $\boldsymbol{f_z}$ is visible and it enclosed by side frequencies with an interval equal to rotational frequency of the second shaft $\boldsymbol{f_o}$. These are indications of a signal frequency modulation in the presence of damage in a gear-and-pinion set. Intervals of side bands $\Delta f = f_o$ allow to judge that the damaged wheel is arranged on the second shaft.

4.2 *Wavelet analysis*

With the aid of VibroAnalizator vibrosignal synchronous accumulation was made for separation of the components generated by gearbox unit elements established on everyone shaft. Then signal was exported for the further processing in the MatLab. By means of plug-in Wavelet Toolbox it is made continuous wavelet-transformation of the given signal. Wavelet Morley with center frequency f_c***=0,8125 Hz*** is used. In Fig 3. illustrated wavelet-scalogram of the synchronous signal of second shaft. Axis ***X*** – time localisation ***b*** (time analogy), axis ***Y*** – time scale ***a*** (frequency analogy).

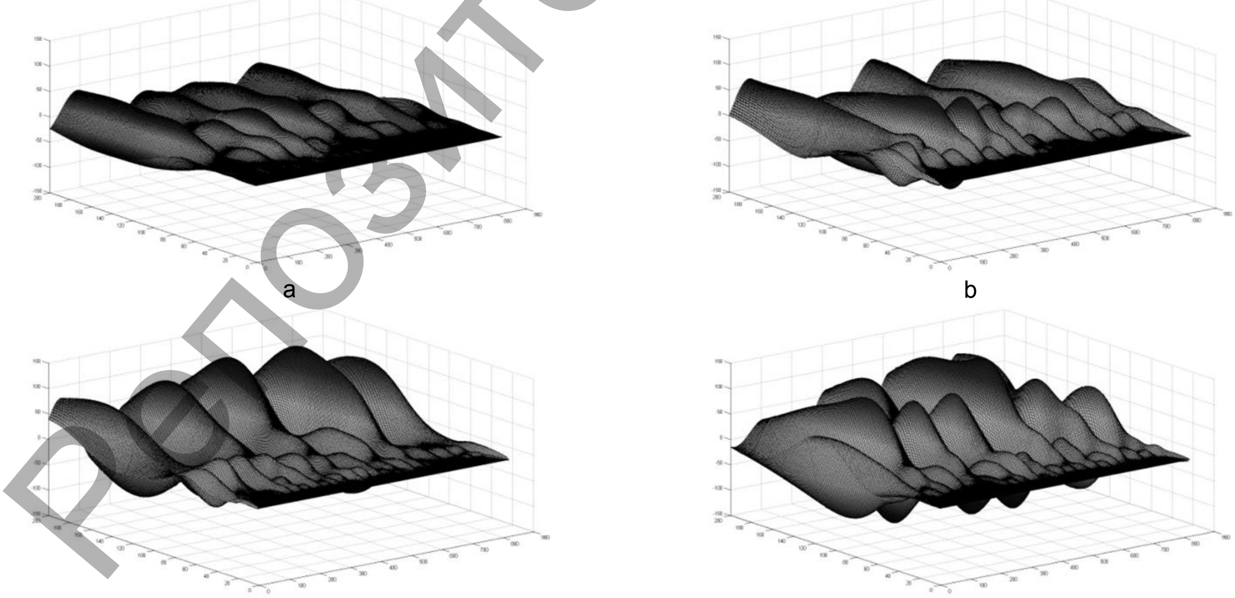
It is possible to mark an explicit modification of the pattern between. Regularity of the wavelet-scalogram at a serviceable tooth gear was replaced by non-regularity at appearance of one tooth chipping. Also have considerably increased coefficients $C_{a,b}$ practically for all time scales ***a***, that confirms the impact theory according to which impact impulse generates broadband damped oscillations. The amount of dark areas in Fig 3a. at a scale ***a≈130*** corresponds to amount of teeth of the damaged wheel. There were high-frequency components in a vibrosignal at tooth chipping presence. It is possible to see in Fig 3b. in a range of scales ***a≈1…30***.



a

b

Figure 3 – Wavelet-scalogram of synchronous vibroacoustic signal of second shaft measured at gearbox unit operation with serviceable (**a**) and damaged wheel (**b**)



a b

c d

Figure 4 – Three-dimensional plot of wavelet-coefficients: tooth chipping 0% (**a**), 25% (**b**), 50% (**c**), 75% (**d**)

Three-dimensional plots of wavelet-coefficients with identical limits along axes are presented in Fig 4. Where axis ***X*** - time localisation (time analogy), ***Y*** - time scale ***a*** (frequency analogy), ***Z*** - wavelet-coefficients $C_{a,b}$ (amplitude analogy).

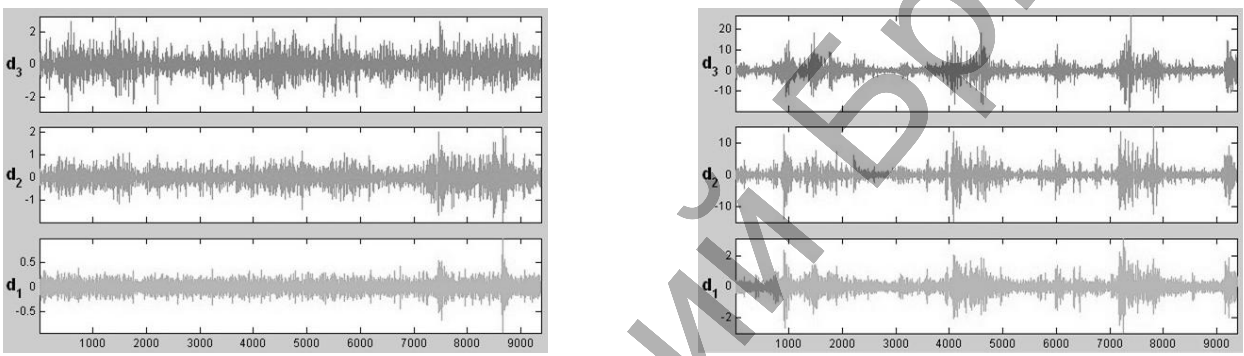
There is a visual difference of wavelets-coefficients plots in Fig 4. However it would be desirable to express this difference in numerical value to eliminate subjectivity of estimation. For this purpose it is possible to use at least three approaches: statistic characteristics, energy spectrum and stochastic characteristics [3].

4.3 *Statistics of wavelet-coefficients*

The fragment of Initial vibrosignal in ***200 ms*** generated by all drive and synchronous signals of 1, 2, 3, 4, 5th shafts have subjected to discrete decomposition by 4th order Daubechies wavelet to 3rd level. Plots of wavelet-coefficients (d_1, d_2, d_3) illustrated in Fig 5. are received as a result of discrete-transform of vibrosignals measured at operation of gear drive with serviceable wheel (Fig 5a.) and damaged wheel with tooth chipping ***75%*** (Fig 5b). There are three visible disturbance in curves d_i (Fig 5b.) which frequency of appearance corresponds to rotation frequency of the second shaft $f_o \approx 14,82$ ***Hz***. It allows to define location of damaged wheel.

Below statistic characteristics of wavelet-coefficients d_i of synchronous vibrosignals and signals without processing are considered. The average value of d_i is equal to zero as measured signals are random variable. Root-mean-square deviations of the received wavelets-coefficients d_i and initial signals (MatLab function "std") are calculated (Table 1).

We can see that standard deviations of wavelets-coefficients for the second shaft increase considerably at chipping occurrence. For the third shaft wavelets-coefficients vary slightly because of vibrations penetration. Therefore statistic characteristics can have diagnostic significance.



a b

Figure 5 – Details coefficients d_i of discreet wavelet-transform of vibrosignal measured at serviceable wheel (**a**) and at tooth chipping ***75%*** (**b**)

Table 1 – Statistic characteristics of wavelet-coefficients

Damage degree, %	Shaft 1 (synchronous signal)	Shaft 2 (synchronous signal)	Shaft 3 (synchronous signal)	Shaft 4 (synchronous signal)	Shaft 5 (synchronous signal)	Initial signal (measured)
00	3,13	4,13	1,75	4,62	4,17	2,43
25	4,27	9,88	2,19	4,2	3,84	7,67
50	4,08	9,62	2,66	4,52	4,33	7,51
75	4,4	10,74	3,65	4,6	4,33	8,11

5. CONCLUSION

Discrete and continuous wavelet-transform gives new possibilities in vibrodiagnostics, allows receiving absolutely new results which interpretation puts new problems for the researcher. This branch is rather young and is now at cycle of rapid development. In a kind of it appear more and more applications of wavelets.

Modern systems of computer mathematics are supplied by wavelet-transform functions and contain the big wavelets apparatus and also allow to design own wavelets for research of vibroacoustic signals features.

The present researches prove intelligence of wavelet-coefficients at diagnostics tooth gears; allow troubleshooting and evaluating a quantitative assessment of a damage degree.

However it is not necessary to neglect classical methods of signals analysis based on Fourier-transform which give the generalised representation of investigated system vibroactivity and allow localising damage.

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