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DIAGNOSIS OF INDUSTRIAL GEARBOXES CONDITION BY VIBRATION AND TIME-FREQUENCY, SCALE-FREQUENCY, FREQUENCY-FREQUENCY ANALYSIS

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Preliminary Note – Prethodno priopćenje

In the article methods of vibroacoustic diagnostics of high-power toothed gears are described. It is shown below, that properly registered and processed acoustic signal or vibration signal may serve as an explicitly interpreted source of diagnostic symptoms. The presented analysis were based on vibration signals registered during the work of the gear of a rolling stand working in Katowice Steel Plant (presently one of the branches of Mittal Steel Poland JSC).

Key words: mechanical engineering, gear, acoustic signal, diagnosis

Dijagnoza stanja industrijskih zupčanika pomoću vibracijske, vermensko frekvencijske, skalno frekvencijske, frekvencijsko frekvencijske analize. U članku se opisuju metode vibroakustične dijagnostike zupčanika visoke snage. Dalje je pokazano, da ispravno registrirani i obrađeni akustični signal ili vibracijski signal može poslužiti kao eksplicitno interpretirani izvor dijagnostičkih simptoma. Predstavljene analize temeljile su se na vibracijskim signalima registriranima tijekom rada zupčanika valjačkog stana u pogonu u čeličani Katowice (trenutno jedan od ogranaka tvrtke Mittal Steel Poland JSC)

Ključne riječi: strojarstvo, zupčanik, akustički signal, dijagnoze

INTRODUCTION

Residual phenomena are inseparable phenomena during the work of a technical object, and among them there are vibrations and noise [1,2]. The evaluation of the technical condition on the basis of research is known under the name of vibroacoustic diagnostics.

The basis for the research on the use of vibroacoustic signals in the diagnostics of the object technical condition is the creation of symptoms measures, which will enable to define the condition precisely.

Vibroacoustic diagnostics uses, as source of information about the condition of the tested object the dynamic parameters, describing the appearance and the propagations of the vibroacoustic disturbance both in a tested object and in the outer environment [3].

The vibroacoustic signal includes both information required about the processes in progress in a technical object and the unnecessary information from the point of view of diagnostic aim, the, so called, information noise. A very important issue here is the right reconstruction of the information model of a given object condition, being the basis to treat it as the information carrier.

In the vibroacoustic diagnosis of the technical objects lots of various signal analysis methods are used [4].

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RESEARCH OBJECT

Tests were conducted on 10 single-stage and double stage gears with additional meshing of the roll cage. In the power transmission system of the cages the asynchronous engines with the power of 200 kW were applied. The rotational speeds of the input shafts are constant for each gear and are included in the range from 380 to 800 rotation/minute. In the course of research the measurements of vibration accelerations in three directions were conducted and the impulse signals were registered, consistent with the rotations of the input shaft which served for synchronic averaging. The measurements of the gearbox vibrations were conducted during idle running and with a load during rolling.

Registration and processing of the vibration signals was conducted with the use of an analysis-measurement system which is presented in Figure 1.

Diagnostic signals were processed in the Matlab-Simulink environment. The applied measurement method enabled the synchronic averaging of the vibration signals with the rotations of the input shafts. The changes of the diagnosed gearboxes condition have significant influence on the structure of the vibroacoustic signal.

TIME-FREQUENCY ANALYSIS

In vibroacoustic diagnostics such methods of signal analysis are used, which enable to analyse simultaneously in time domain and frequency domain. They are

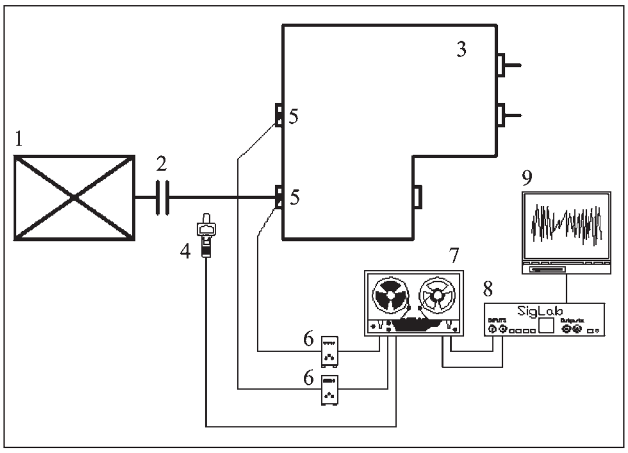

Figure 1 Diagram of the measurement system of toothed gears of the rolling stands drives, where: 1 – engine, 2 – clutch, 3 – tested gear, 4 – rotational speed sensor, 5 – measurement points, 6 – preamplifier BK2626, 7 – measurement recorder BK7003, 8 – signal analyser SigLab50-21, 9 – computer

used for time variable signals in the sense of amplitude and frequency; that is for the non-stationary signals [3]. In the group of such methods one finds the Short Time Fourier Transform STFT, defined as:

$$STFT(b,f)=\int_{-\infty}^{+\infty} w(t-b)\cdot x(t)\cdot e^{-j2\pi ft}\,dt$$

where:

$w(t-b)$ – window function shifted in time domain,

b – given shift of window function.

Time signal is divided into smaller parts, and then for each of them the Fast Fourier Transform FFT is calculated. The side-by-side configuration of the marked spectra creates the time-frequency map. STFT can be treated as a comb of simultaneously working filters [3].

Figure 2 presents the marked STFT of the difference signal of toothed gears vibrations in rolling stands drives.

In this method, the use of the wide window increases the resolution in frequency domain, and decreases in time domain. For a narrow window the effect is reverse.

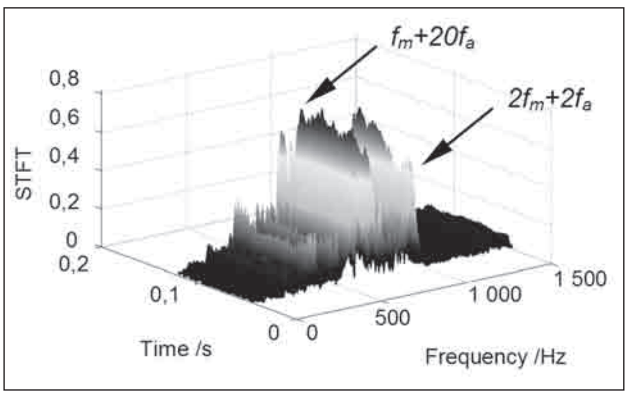

Figure 2 STFT distributions of the vibration difference signals of toothed gears in rolling stands drives during rolling – gear classified for repair, f_a, f_m – shaft rotation, meshing frequency

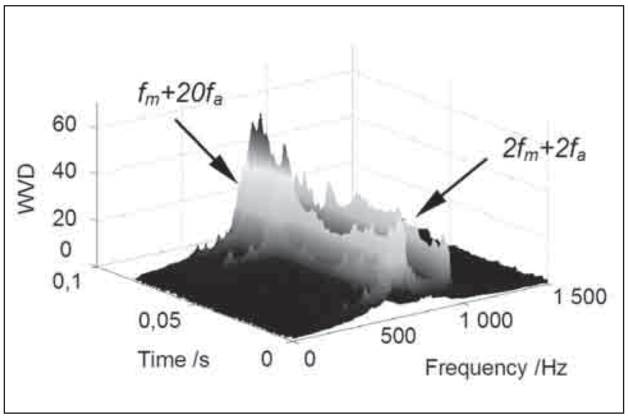

Figure 3 Pseudo Wigner Ville distribution of the difference signals in toothed gears vibrations of the rolling stands gears during rolling – gear classified for repair, f_a, f_m – shaft rotation, meshing frequency

The transform which lacks this disadvantage is the Wigner–Ville distribution and its pseudo transform with the applied Choi–Wiliams window:

$$WVD(t,f)=\int_{-\infty}^{+\infty} w(\tau)\cdot x\left(t+\frac{\tau}{2}\right)\cdot x^{*}\left(t-\frac{\tau}{2}\right)\cdot e^{-j2\pi f\tau}\,d\tau$$

where:

$x^*(t)$ – complex time signal, compressed with $x(t)$,

$w(\tau)$ – symmetric weight function, similar to window function in STFT.

The comparison of STFT method with the WVD method taking into account their advantages and disadvantages was presented in [3].

Wigner–Ville Distribution for the difference signal of the toothed gear vibrations in rolling stands drives during rolling is presented in Figure 3.

WAVELET ANALYSIS

Wavelet analysis consists of signal decomposition and presenting it in the form of linear combination of basic functions, called wavelets [2]. The feature which distinguishes this method of signal analysis from other methods is the multi-stage signal decomposition, variable resolution in time and frequency domain and possibility to use basic functions other than harmonic functions.

Continuous wavelet transform is defined as follows:

$$CWT(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}\psi\left(\frac{t-b}{a}\right)\cdot x\left(t\right)dt$$

where:

$y_{a,b}(t)$ – the analyzing wavelet,

a – the scale parameter, $a \in R^+$, $a \neq 0$,

b – the time parameter, $b \in R$.

Wavelet frequency is regulated by the parameter of scale a, whereas using parameter b one can test the local properties of the time runs.

This method, due to the possibility of adjustment of the window width to the analysed frequency range enables testing the non-stationary signals. For the long-

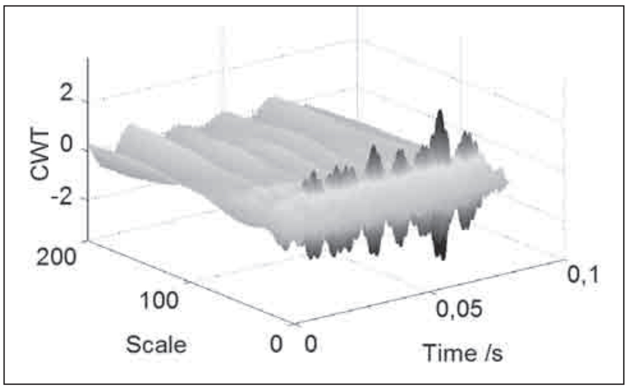

Figure 4 CWT distribution of toothed gears vibration signals of rolling stands drives during idle running – gear classified for repair

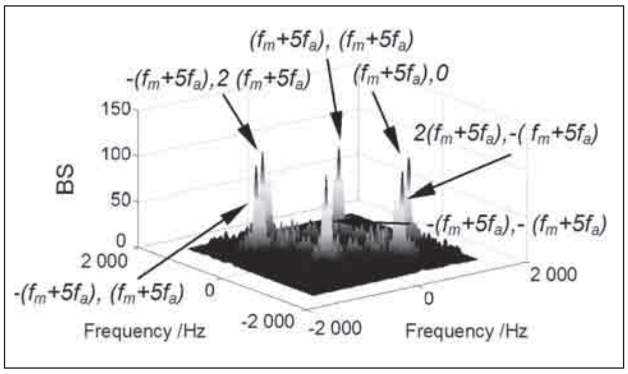

Figure 5 Bispectrum distributions of the vibration difference signals of toothed gears in rolling stands drives during idle running – gear classified for repair, f_a, f_m – shaft rotation, meshing frequency

term variation runs the window expands in time domain, whereas with high frequencies it narrows preserving a constant surface area. The proper choice of the basic wavelet and the array of the scale value determine the correctness of the diagnosis process of the object technical condition with the use of wavelet analysis.

The CWT distribution of toothed gears vibration signals in rolling stands drives, in time of idle running is presented in Figure 4.

BISPECTRUM ANALYSIS

Low-energy changes of a modulating character accompanying the early stages of elements malfunction in power transmission systems are possible to be traced with the use of bispectrum analysis [1].

In the notion of the bispectral analysis, a third-order cumulant is used, described with the dependence:

$$C_3(\tau_1,\tau_2)=E\left[x(t)x(t+\tau_1)x(t+\tau_2)\right]$$

where:

E – expected value.

Higher-order cumulants, known also as semi-invariants are the measures of the size of signal changes around its mean value. They also possess the ability to expose the existence of non-linearity in a signal.

Bispectrum is a function of two frequencies defined as transform FFT from third-order cumulant:

$$BS(f_1,f_2)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}C_3(\tau_1,\tau_2)e^{-j2\pi(f_1\tau_1+f_2\tau_2)}d\tau_1 d\tau_2$$

Bispectra take complex values including the information concerning the amplitude and the signal phase.

The influence of the toothed gear condition in a rolling stand on the bispectrum distribution is presented in Figure 5.

NON-DIMENSIONAL DISCRIMINANT VALUES

Changes in the condition of the diagnosed transmissions toothed gear have a significant influence on the vibroacoustic signal structure. The registered vibroacoustic signals have to be converted by using appropriate signal measures so that they constitute symptoms showing wear intensity and advancement. In order to analyse signals registered during the test residual signal and difference signal have been used residual signal and difference signal. The residual signal *r(t)* is obtained by removing the bands which contain rotation components of shafts, their harmonics as well as mesh frequency components and their harmonics. The difference signal *d(t)* is obtained in a similar way but the removed bands in the area of mesh frequencies and their harmonics are much wider and cover the sidebands connected with gear rotation frequencies.

In order to assess the dynamic condition of a rolling stand transmission toothed gear, non-dimensional discriminants [5,6] have been used, calculated on the basis of signals of vibrations synchronically averaging:

$$FM0=\frac{A_{PP}}{\sum_{k=1}^{n}A_k}$$

$$FM4=\frac{\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^4}{\left[\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^2\right]^2}\qquad NA4=\frac{\frac{1}{N}\sum_{n=1}^{N}\left(r_n-\bar{r}\right)^4}{\left[\frac{1}{N}\sum_{n=1}^{N}\left(r_n-\bar{r}\right)^2\right]^2}$$

$$M6A=\frac{\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^6}{\left[\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^2\right]^3}\qquad M8A=\frac{\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^8}{\left[\frac{1}{N}\sum_{n=1}^{N}\left(d_n-\bar{d}\right)^2\right]^4}$$

where:

N – sampling point number,

A_{pp} – peak-to-peak value,

A_k – amplitude of gear mesh harmonics,

$d(t)$ – average signal value *d(t)*,

$\bar{r}(t)$ – average signal value *r(t)*,

In Table 1 values of selected non-dimensional discriminants have been compared. Values crest factor *CF* and kurtosis *K* have also been presented to show comparison.

M6A and *M8A* discriminants calculated on the basis of vibration signals of the transmission toothed gear qualified for repair show a big increase in value (by approx. 100-200 %), irrespective of load. Simultaneously, static measures *CF* and *K* change only by approx. 9-36 %.

Table 1 **Discriminant values**

	idle running		under load	
	good condition	bad condition	good condition	bad condition
CF	4,0	4,5	3,9	2,9
K	3,3	3,6	2,8	3,8
FM0	14,2	11,4	2,1	4,5
FM4	2,8	3,3	2,6	3,3
NA4	2,8	3,2	2,6	3,5
M6A	11,9	21,2	9,7	19,4
M8A	63,3	215,1	45,0	150,7

CONCLUSION

From the number of vibroacoustic signals analysis methods applied in diagnostic practice only some are presented in this paper in reference to the analysis methods of time-frequency, time-scale and frequency-frequency domain. Those analyses are the starting point in defining the diagnostic measures for particular diagnosed cases [4]. The damage descriptors of particular elements of power transmission systems built on their basis are used in forming the complete diagnostics systems. The most recently designed diagnosis systems work according to methods of artificial intelligence.

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Note: The responsible translator for English language is Dr Michel Bouquet, POLIGLOCI, Katowice, Poland