

DIAGNOSIS OF THE WEAR OF GEARS IN THE GEARBOX USING THE WAVELET PACKET TRANSFORM

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The paper presents research aimed at diagnosing early cases of wear of gears tooth surface in the gearbox based on measurements of vibration signals and their processing using the wavelet packet transform. Analysis concerned the vibration signals recorded in a test bench experiment, during which the wear of gears teeth increased (pitting and spalling). The studies allow conclusions to be drawn that the processing of vibration signals using the wavelet packet transform allows the detection of early cases of wear of the working surface of the teeth on the basis of an analysis of selected details of wavelet decomposition and vibration measures.

Key words: gearbox, wear, condition monitoring, vibration

INTRODUCTION

Gearbox are popular devices that have many industrial applications, including in the automotive industry. The use of appropriate toughened materials with suitably chosen hardness gradation of the wheel and pinion, their machining and hence the high-precision of production, ensures the long life of a gear. Adoption of these assumptions also ensures low noise and trouble-free operation [1,2].

During operation, however, there can be an accelerated wear of the gearbox elements [3-7]. The accelerated wear is influenced by the incorrect preparation of gears in the machining process as well as during heat treatment, too high values of the instantaneous load (overload) of the gearbox, operation in a highly polluted environment.

The causes of gearbox wear described above may lead to its damage [6,7], of which the most common is pitting (spalling).

Measurements and processing of vibration signals are testing and analysis methods that are used to evaluate the technical condition of machinery and equipment during normal operation [3-9]. An important direction of current research is the development of new diagnostic methods, including for the wear of gears.

The paper presents the results of gearbox tests, whose purpose is to diagnose early cases of wear in the surfaces of the gear teeth. The paper discusses the assumptions of the experiments carried out, the method of measuring the vibration, and presents a method for processing vibration signals, which allows for diagnosing early cases of wear of gears, along with sample results. The results presented are a continuation of diagnostic tests of gears, presented in [6].

BENCH TESTS

Tests were conducted on a power circulating gear testing machine FZG (DIN 51354). Measurements of the velocity of transverse vibration of the gear shaft using a laser vibrometer and vibration acceleration of its housing by means of a piezoelectric transducer were performed. Measurements were performed with a 25,6 kHz sampling frequency. The tests were performed with a load of $Q = 3,1$ MPa. Figure 1 shows a diagram of the measuring system.

For bench test, a pair of gears was selected with spur teeth (Table 1) made in accuracy class 5 (DIN 3964 B4) and a hardness of 37 - 40 HRC.

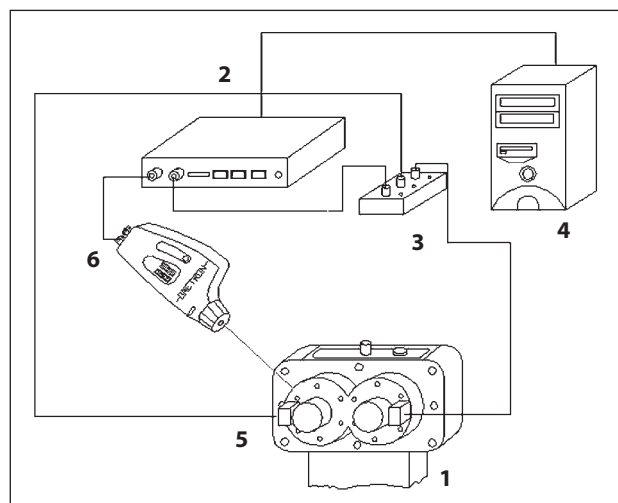


Figure 1 The diagram of measurement system:
1 – the examined gearbox, 2 – DSTP signal analyzer (SigLab), 3 – logic system, 4 – PC, 5 – sensors of shaft's position, 6 – laser vibrometer or piezoelectric transducer

Table 1 Geometrical parameters of gears

Parameters	Value
Distance between the centers of two gears a_w	91,5 mm
Face width b_w	20 mm
Module pitch m_n	4,5 mm
Number of pinion teeth z_1	16
Number of wheel teeth z_2	24
Normal pressure angle α_{on}	20 °

During the bench tests, the moment of onset and development of the wear on the working surface of the teeth was observed, and four series of vibration measurements were performed (before the occurrence of wear and during three phases of wear). Figure 2 shows sample images of phase 1 and phase 3 of wear of the surfaces of two gears.

Wear of the tooth surface occurred in the form of loss of material with a small depth (pitting), the area of which increased from the initiation site to the remaining parts of the tooth. Increase of surface wear did not occur uniformly on all the teeth. Spalling of the surface of the teeth presented a typical progression, which is caused by the hydraulic action of oil.

The average percentage wear of the working surface was calculated using Metillo software and are presented in Table 2.

Table 2 The average percentage wear of the gear teeth working surface

No of wear phase / -	1	2	3
Surface wear / %	1,08	3,57	10,38

SIGNAL PROCESSING METHOD

Discrete wavelet packet transform was used for processing vibration signals [10].

In developing the calculation method, it was assumed that signal processing will be performed for the

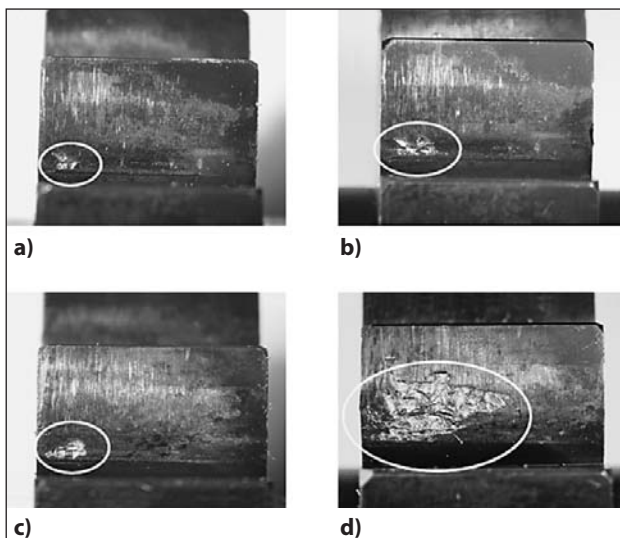


Figure 2 Examples of wear on gear surfaces - phase 1 and phase 3: a) - b) tooth 1, c) - d) tooth 2

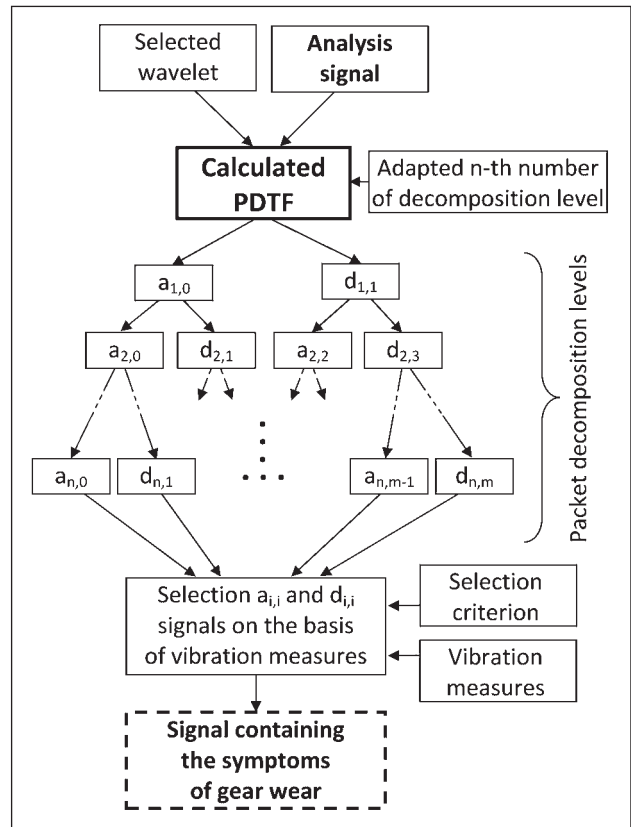


Figure 3 The method of processing of a vibration signal

raw vibration signal of the gearbox, not subjected to pre-filtering and synchronous averaging. Figure 3 contains the calculation algorithm.

This method requires providing such information as the type of wavelet and the number of decomposition levels. Vibration measures of individual details are calculated on the basis of the signals received on the last decomposition level. The values of vibration measures and analysis of the dynamics of their changes allows selecting the details, which will be used for further signal processing. In the process of reconstruction [10], a new signal is obtained, which contains only those component spectra that carry information about the occurring tooth wear.

To evaluate the wear of the working surface of the teeth, calculations of two measures were adopted: the 4th order central moment denoted M4 (1) and the root mean square of vibration signal denoted RMS (2).

$$M4 = \frac{1}{n} \sum_{i=1}^n (s_i - \bar{s})^4 \tag{1}$$

$$RMS = \sqrt{\frac{1}{n} \sum_{i=1}^n (s_i)^2} \tag{2}$$

s_i - instantaneous signal value, \bar{s} - mean signal value, n - number of samples.

RESULTS AND DISCUSSION

On the basis of the vibration signals recorded at different wear values of the working surface of the teeth, they were processed using the method of decomposition of vi-

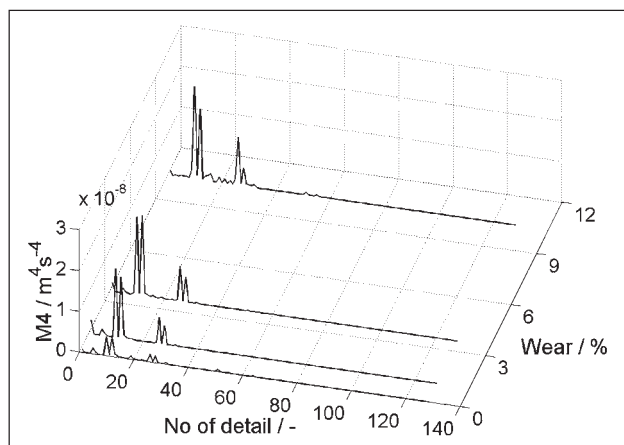


Figure 4 Example change of the value of measure M4 calculated for the subsequent details of wavelet distribution in varying degrees of tooth wear - transverse vibration velocity of the gear shaft

bration signal presented in the paper. The following calculation assumptions were made: wavelet - Daubechies 2, the number of decomposition levels - 7 (128 details) and the signal evaluation measures M4 and RMS.

The result of the calculation of measure M4 (Figure 4) of vibration signals on the last decomposition level indicates that for the selected details there is an increase in its value with the increase of wear of the tooth surface.

In further tests, on the basis of the calculated values of measure M4, the details that clearly include information about tooth wear were selected, according to the criterion:

$$M4(p_{1j}) < M4(p_{2j}) < M4(p_{3j}) < M4(p_{4j}) \quad (3)$$

where:

$M4(p_{ij})$ - value of measure M4 in the measurement of p_{ij} , $i=1 \div 4$, j - the number of the decomposition detail.

Details were selected as a result of this analysis that in the process of reconstructing the signal formed a new signal (filtered signal) containing information about tooth wear.

Figure 5 shows a comparison of the spectra of the raw vibration signal, and the signal obtained by calculation with use of the presented method for the detection of tooth wear.

After selection, the signal has low energy components of the vibration signal spectrum occurring between its main components, which include harmonic frequencies of the meshing ($f_z = 720$ Hz) with sidebands. These results are consistent with the results presented, for example, in [6].

Figure 6 includes the calculated measures M4 and RMS of raw vibration signals and after selection.

The calculations show that the use of selection allows for detecting even minor wear of the teeth's working surface, irrespective of the vibration measurement point.

Comparing the percentage increase of measure M4 and RMS, it can be concluded that each of them allows

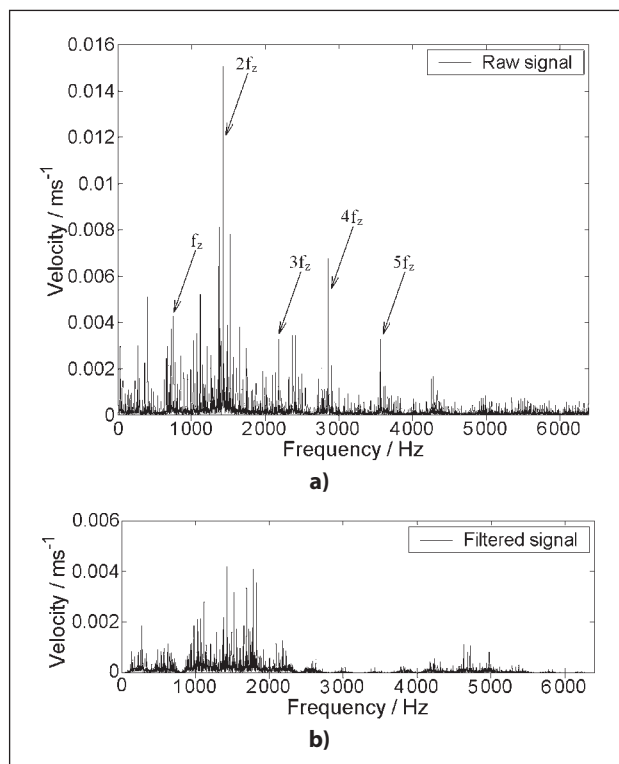


Figure 5 Example spectra of transverse vibration velocity of the shaft - tooth wear of 10,38 %: a) raw signal b) filtered signal

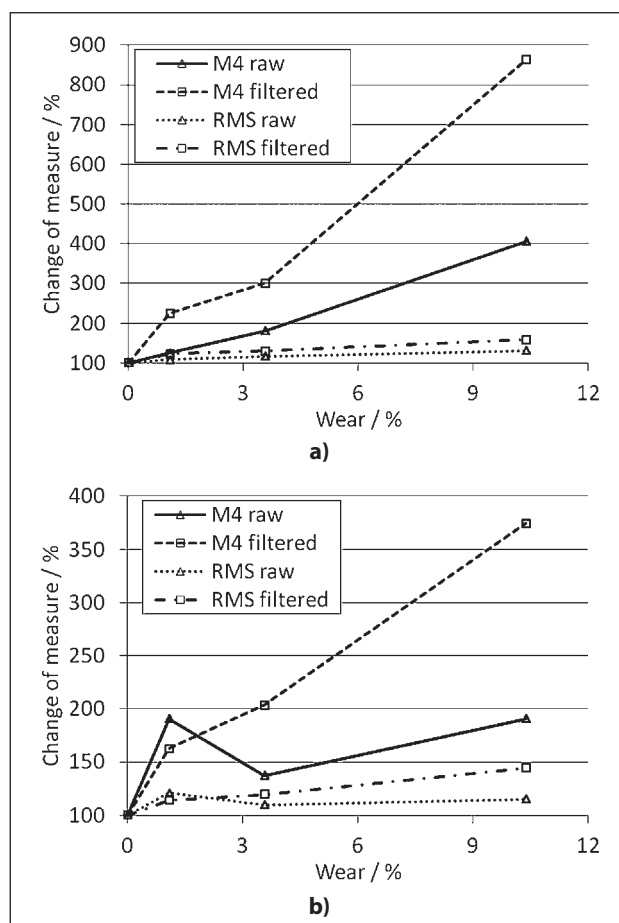


Figure 6 Comparison of changes in the value of measures M4 and RMS raw vibration signal (denoted as raw) and filtered signal (denoted as filtered) depending on the wear of the surface of gears: a) transverse vibration velocity of the shaft, b) housing vibration acceleration signal

for detecting the wear of the working surface of the teeth, however, M4 shows much greater sensitivity and growth dynamics.

CONCLUSIONS

The studies allow conclusions to be drawn that the processing of vibration signals using the wavelet packet transform allows the detection of early cases of wear of the working surface of the teeth on the basis of an analysis of selected details of wavelet decomposition and vibration measures.

Decomposition of vibration signals and calculated measures make it possible to filter the signals and select only those details that include vibrational symptoms of changes in the surface of the gear teeth. The increase in the value of the adopted vibration measures RMS and M4 made it possible to even detect the first phase of tooth wear (wear of 1,08 %), and therefore, these measures are sensitive to the change in the surface of gear teeth.

REFERENCES

- [1] A. Wilk, H. Madej, T. Figlus: Analysis of the possibility to reduce vibro activity of the gearbox housing, *Eksploatacja i Niezawodność – Maintenance And Reliability*, 50 (2011) 2, 42-49.
- [2] T. Figlus, A. Wilk: Comparison of the sound pressure measurement and the speed measurement of the gearbox vibrating surface, *Transport Problems*, 7 (2012) 1, 37-42.
- [3] F. Chaari, W. Bartelmus, R. Zimroz, T. Fakhfakh, M. Hadjar: Gearbox vibration signal amplitude and frequency modulation, *Shock Vibrat.*, 19 (2012) 4, 635-652.
- [4] P. Czech: Diagnosis of industrial gearboxes condition by vibration and time-frequency, scale-frequency, frequency-frequency analysis, *Metalurgija*, 51 (2012) 4, 521-524.
- [5] N. Sawalhi, R.B. Randall: Gear parameter identification in a wind turbine gearbox using vibration signals, *Mechanical Systems and Signal Processing*, 42 (2014) 1/2, 368-376.
- [6] T. Figlus, A. Wilk: Application of analysis of envelope's spectrum for gearbox diagnosing, *International Review of Mechanical Engineering*, 6 (2012) 6, 1350-1355.
- [7] S. Guoji, S. McLaughlin, X. Yongcheng, P. White: Theoretical and experimental analysis of bispectrum of vibration signals for fault diagnosis of gears, *Mechanical Systems and Signal Processing*, 43 (2014) 1/2, 76-89.
- [8] B. Gajdzik, R. Wieszala: Measurements of the communication noise level on the internal roads of the manufacturing metallurgical enterprise, *Metalurgija*, 51 (2012) 3, 369-372.
- [9] Ł. Konieczny, R. Burdzik, B. Łazarz: Application of the vibration test in the evaluation of the technical condition of shock absorbers built into the vehicle, *Journal of Vibroengineering*, 15 (2013) 4, 2042-2048.
- [10] S. Mallat: A theory for multiresolution signal decomposition: the wavelet representation, *IEEE Transaction on pattern analysis and machine intelligence*, 11 (1999), 674-693.

Note: The responsible translator for English language is A. Nowak, Chorzów, Poland