TAKING ADVANTAGE OF EMPIRICAL MODE DECOMPOSITION IN DIAGNOSING GEAR FAULTS

Bogusław ŁAZARZ, Henryk MADEJ, Piotr CZECH

Department of Automotive Vehicle Construction, Faculty of Transport, Silesian University of Technology
ul. Krasińskiego 8, 40-019 Katowice, e-mail: boguslaw.lazarz@polsl.pl, henryk.madej@polsl.pl,
piotr.czech@polsl.pl;

Summary

The study presents the application of empirical mode decomposition as a tool useful in diagnosing faults in gears. The method is a modern algorithm used for non-linear and non-stationary signals. Using this algorithm, it is possible to decompose a signal into a finite sum of component called intrinsic mode functions (IMF). For each IMF, the number of extremes and the number of transitions through zero is equal or different, by maximum one, and the mean value of envelope determined by the signal extremes equals zero. In practice, natural signals do not meet these conditions.

In the experiment, a gearbox operating in a circulating power system was used, with 16 and 24 pinion and wheel teeth, respectively. The measurements were carried out for a non-damaged gear and for a gear with a modelled fault, operating at various rotational speeds and under different loads.

Keywords: diagnostics, gears, empirical mode decomposition.

WYKORZYSTANIE EMPIRYCZNEJ DEKOMPOZYCJI SYGNAŁU W DIAGNOSTYCE USZKODZEŃ PRZEKŁADNI ZĘBATYCH

Streszczenie

W opracowaniu przedstawiono zastosowanie empirycznej dekompozycji sygnału jako narzędzia przydatnego w diagnostyce uszkodzeń przekładni zębatych. Metoda ta jest nowoczesnym algorytmem stosowanym dla sygnałów nieliniowych i niestacjonarnych. Wykorzystując ten algorytm można rozłożyć sygnał na skończoną sumę składowych zwanych funkcjami wewnętrznymi (IMF). Dla każdego IMF liczba ekstremów i liczba przejść przez zero jest równa bądź różna o maksimum jeden, a wartość średnia obwiedni określonej przez ekstrema sygnału równa się zero. W praktyce naturalne sygnały nie spełniają tych warunków.

W eksperymencie wykorzystano przekładnie zębatą pracującą w układzie mocy krążącej o licznie zębów zębnika i koła odpowiednio 16 i 24. Pomiary przeprowadzono dla przekładni nieuszkodzonej oraz z zamodelowanym uszkodzeniem, pracującej przy różnych prędkościach obrotowych i różnych obciążeniach.

Słowa kluczowe: diagnostyka, przekładnie zębate, empiryczna dekompozycja sygnału.

1. INTRODUCTION

The development of engineering creates a higher and higher demand for modern means of diagnostics. Changes in the condition of diagnosed gears have a significant influence on the vibroacoustic signal structure. The recorded vibroacoustic signals are processed in order to obtain measures which would be symptoms signifying the intensity and degree of wear [1, 5]. The main aim of diagnosing machines is to detect damages in their early phase. A particular significance in diagnostics is attributed to non-invasive methods, comprising the vibroacoustic diagnosis methods [1, 4, 5]. They utilise the vibration and acoustic signal as information medium. The fault symptoms contained in the signal are difficult to identify based on raw measurement data. A number of signal analysis methods are used for analysing WA signals and identifying, on their basis, the fault in a gear.

In gearboxes, we deal with modulation phenomena, where high-frequency meshing signals or resonance frequency of gear components are the carrying signals. There are many reasons of amplitude and frequency modulation in gears. During the gear operation, wear and degradation processes occur, which influence the parameters of modulating signals. A confirmation of this is the fact that an analysis of the signal envelope in the frequency bands connected with mesh is one of the most effective methods of diagnosing gears used in practice. Appropriate signal processing in time and frequency domains allows determining the modulation degree of carrying signals.

2. DESCRIPTION OF THE MODE DECOMPOSITION ALGORITHM

The authors decided to check the usefulness of empirical mode decomposition (EMD) in gearbox diagnostics, in an experiment.

Decomposition of the diagnostic signal $x(t)$ into a finite sum of components called intrinsic mode functions (IMF) is conducted in accordance with the algorithm [2÷5]:

- identification of local minimums $l(t)$ of signal $x(t)$,
- identification of local maximums $u(t)$ of signal $x(t)$,
- determination of the mean value from the envelope of minimums and maximums $m_1(t)$,
- determination of the first component, $h(\tau)$, from dependence:

$$h_1(t)=x(t)-m_1(t) \quad (1)$$

- identification of local minimums $l(t)$ of signal $h_1(t)$,
- identification of local maximums $u(t)$ of signal $h_1(t)$, etc.

The algorithm repeats until:

- the number of extremes and reversals of the function sign equals or differs by not more than one,
- the mean value of local minimums and maximums equals zero.

The value determined is called the first intrinsic mode function:

$$IMF_1(t)=h_1(t) \quad (2)$$

Next, this value is removed from the tested base signal $x(t)$, yielding the first remainder, $r_1(t)$:

$$r_1(t)=x(t)-IMF_1(t) \quad (3)$$

The remainder is treated as the tested base signal, $x(t)$, and the whole process is repeated from its beginning.

The process of empirical mode decomposition is completed when the remainder $r_N(t)$ is constant or monotonic.

The result of application of the algorithm described is the sum of subsequent intrinsic mode functions and the remainder:

$$x(t)=\sum_{i=1}^{N} IMF_i(t)+r_N(t) \quad (4)$$

In order to illustrate the operation of the EMD algorithm, a model signal was created:

$$\begin{aligned} x(t) &= 2\cdot\sin\left(2\cdot\pi\cdot 15\cdot t\right)+ \\ &+4\cdot\sin\left(2\cdot\pi\cdot 15\cdot t\right)\cdot\sin\left(2\cdot\pi\cdot 0{,}1\cdot t\right)+ \\ &+\sin\left(2\cdot\pi\cdot 15\cdot t\right) \end{aligned} \quad (5)$$

The signal so modelled was then subjected to an empirical decomposition analysis, the results of which are shown in Fig. 2.

3. OBJECT OF RESEARCH

The object of research was a gearbox working in a circulating power system, comprising an electric motor, a belt transmission, the tested gearbox, a closing gear and a tightening clutch. The 15 [kW] electric motor drove the closing gear through the belt transmission. The gearbox load was controlled with a lever with weights, a tightening clutch and torsional shafts. The gear speed was set by means of a frequency converter, which controlled the work of the electric motor. The tested and closing gears had identical ratios and identical axle bases. Parameters of the tested toothed wheels are compiled in Table 1.

Table 1. Parameters of the tested toothed wheels

Parameter	Value
number of pinion teeth	$z_1 = 16$
number of wheel teeth	$z_2 = 24$
angle of teeth line inclination	$\beta = 0^o$
addendum modification coefficient for the pinion	$x_1 = 0{,}8635$
addendum modification coefficient for the wheel	$x_2 = -0{,}5$
nominal pressure angle	$\alpha = 20°$
nominal module	$m_n = 4{,}5$ mm
transverse contact ratio	$\varepsilon_\alpha = 1{,}32$
addendum coefficient	$h_{ao} = 1$
tip clearance coefficient	$c_o = 0{,}25$
wheel width	b = 20 mm

In the experiment, measurements were performed of the wheel shaft's transverse vibration speed for a gear without faults and for a gear with a defect in the form of a crack in a tooth root at a depth of ΔX=1 [mm] (Fig. 1).

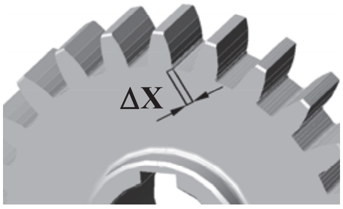

Fig. 1. The modelled wheel defect in the form of a crack in the tooth root

The measuring system consisted of shaft's angular position sensors, a logical unit, a laser vibrometer, a signal analyzer and a computer. Measurement of the wheel shaft transverse vibration was performed in the direction of the force acting between the teeth, using a laser vibrometer, Ometron VH300+. The selected measurement direction allowed recording in the best way the vibration signal modulations occurring in the case of faults of gear components. The logical unit together with two shafts' angular position sensors allowed precise determination of the moment of meshing of the same pair of teeth. The recorded vibration speed signal and the reference signal from the logical unit were processed in a DSPT SigLab analyzer. The measured signals were recorded in a PC.

The measurements were performed for a gearbox operating at two rotational speeds of the wheel shaft:

- n=900 [r.p.m.],
- n=1800 [r.p.m.],

and under two loads:

- Q=2.58 [MPa],
- Q=3.85 [MPa].

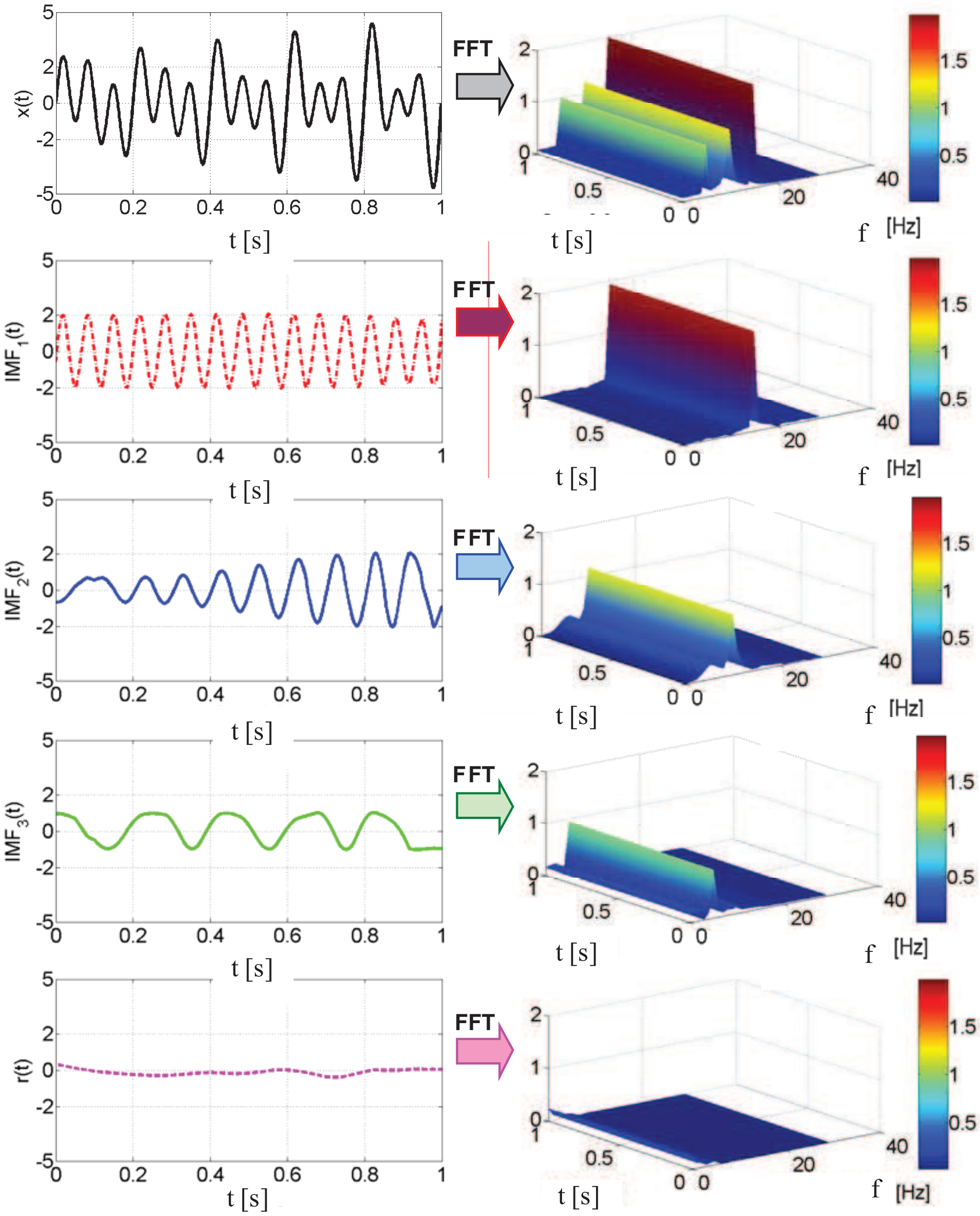

Fig. 2. EMD and spectrum decomposition for the model signal

4. EXPERIMENT RESULTS

In order to check the usefulness of EMD analysis for diagnosing the condition of gearboxes, the recorded vibration speeds were subjected to the operation of a decomposition algorithm. Some examples of the results are shown in Fig. 3÷10.

From the *x(t)* base signal components obtained, spectra were determined. Based on the so determined spectra, the signal energy was defined for subsequent decomposition levels. The results obtained are presented in Figs. 11÷14 and in Table 2. In order to depict better the differences in the energy determined from the spectra between the good and poor condition of the gearbox, the results were referred to the good condition, which was assumed to equal 100%.

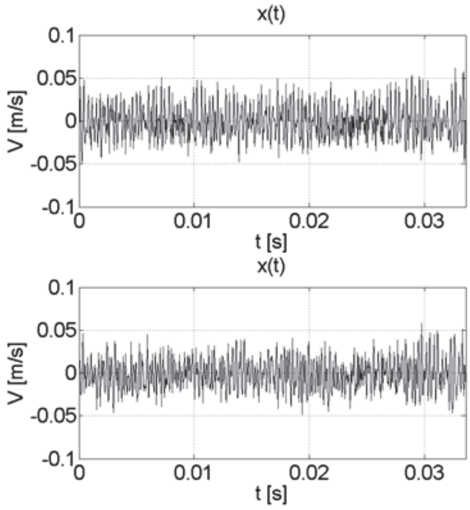

Fig. 3. Recorded signal for the gearbox without faults (a), and with a crack at the tooth root (b)

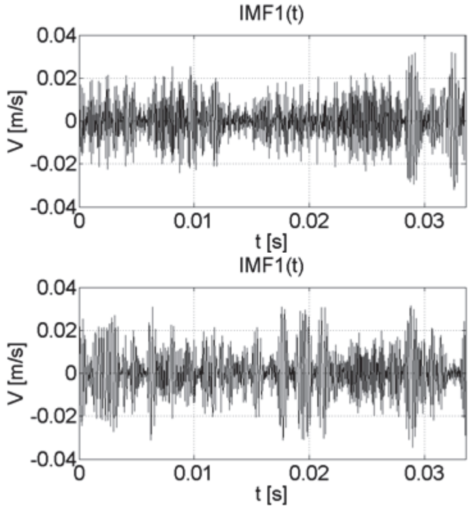

Fig. 4. IMF1 for the gearbox without faults (a), and with a crack at the tooth root (b)

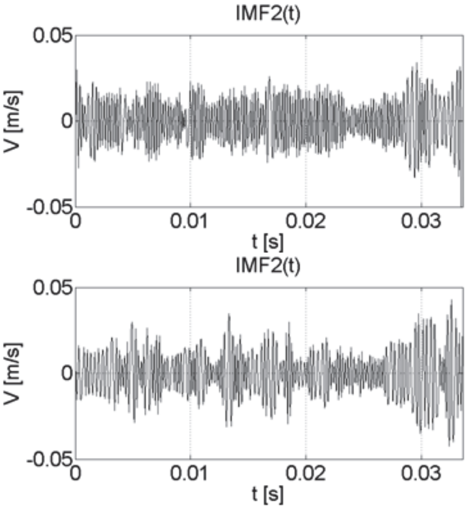

Fig. 5. IMF2 for the gearbox without faults (a), and with a crack at the tooth root (b)

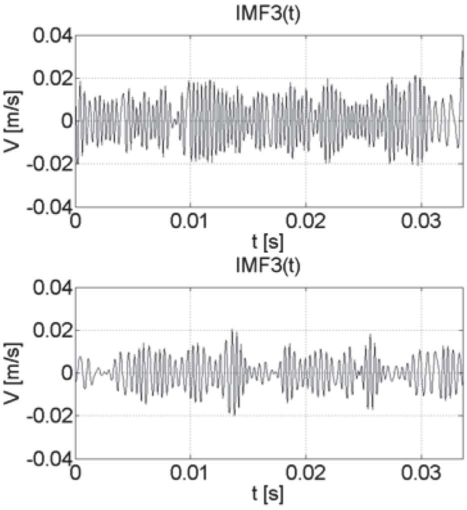

Fig. 6. IMF3 for the gearbox without faults (a), and with a crack at the tooth root (b)

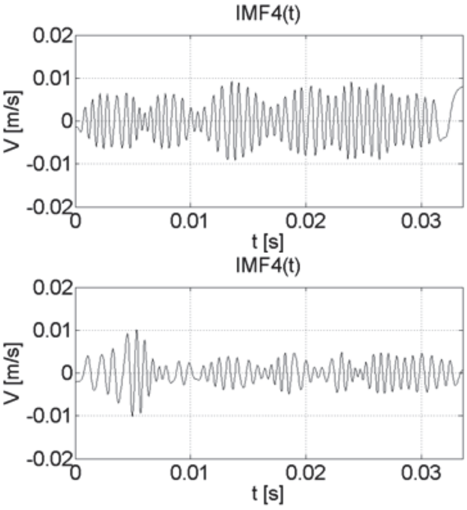

Fig. 7. IMF4 for the gearbox without faults (a), and with a crack at the tooth root (b)

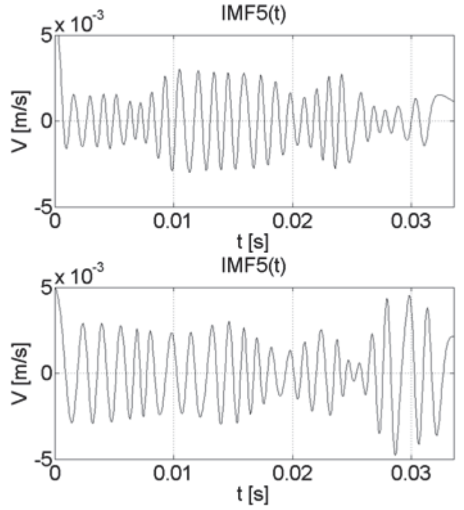

Fig. 8. IMF5 for the gearbox without faults (a), and with a crack at the tooth root (b)

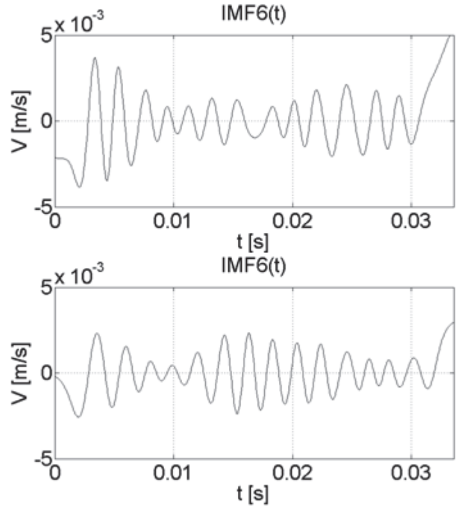

Fig. 9. IMF6 for the gearbox without faults (a), and with a crack at the tooth root (b)

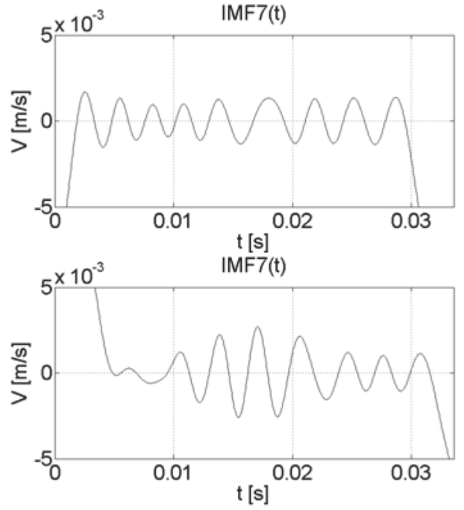

Fig. 10. IMF7 for the gearbox without faults (a), and with a crack at the tooth root (b)

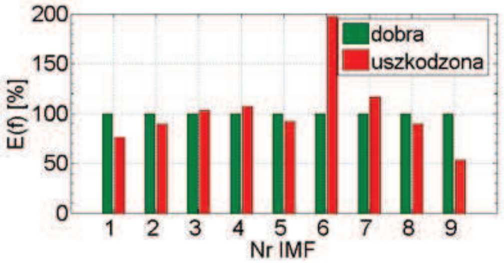

Fig. 11. Spectrum energy
(n=900 [r.p.m.], Q=2.58 [MPa])

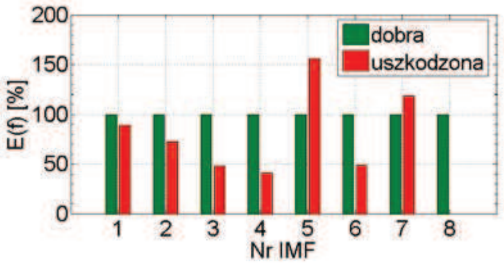

Fig. 12. Spectrum energy
(n=1800 [r.p.m.], Q=2.58 [MPa])

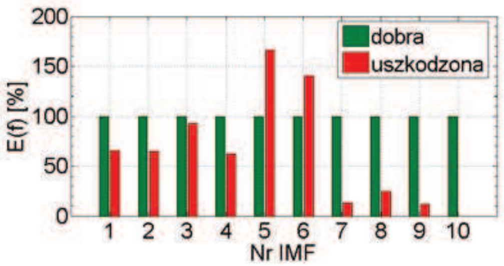

Fig. 13. Spectrum energy
(n=900 [r.p.m.], Q=3.85 [MPa])

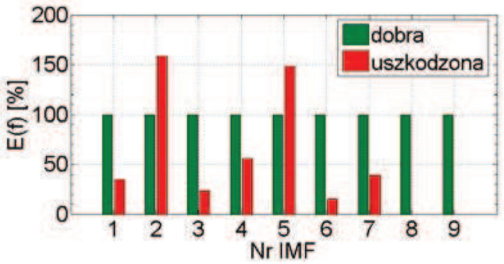

Fig. 14. Spectrum energy
(n=1800 [r.p.m.], Q=3.85 [MPa])

By comparing the results obtained, it can be noted that the percentage differences in the spectrum energy levels of signals *(x)t* measured for the good and for the damaged gear are below 20%. When observing the results (Figs. 11÷14) obtained for the subsequent decomposition levels, some levels can be found, for which the percentage differences are several times larger than when comparing the energy of the registered signals. Regardless of the gearbox operation parameters, the highest percentage increase of spectrum energy is observed for the sixth intrinsic mode function. The differences obtained reach up to 100%.

Table 2. List of energy from spectra

Operation parameters	**Signal**	**Spectrum energy for the gear:**	
		undamaged [%]	**damaged [%]**
n=900 [r.p.m.],Q= 2.58 [MPa]	X(f)	100	117,73
	IMF1(f)	100	75,835
	IMF2(f)	100	89,389
	IMF3(f)	100	103,15
	IMF4(f)	100	106,79
	IMF5(f)	100	91,682
	IMF6(f)	100	196,82
	IMF7(f)	100	116,63
	IMF8(f)	100	89,43
	IMF9(f)	100	53,367
n=1800 [r.p.m.], Q=2.58 [MPa]	X(f)	100	84,703
	IMF1(f)	100	88,884
	IMF2(f)	100	72,713
	IMF3(f)	100	48,352
	IMF4(f)	100	40,822
	IMF5(f)	100	155,79
	IMF6(f)	100	48,684
	IMF7(f)	100	118,21
n=900 [r.p.m.], Q=3.85 [MPa]	X(f)	100	109,46
	IMF1(f)	100	65,572
	IMF2(f)	100	64,588
	IMF3(f)	100	92,335
	IMF4(f)	100	62,319
	IMF5(f)	100	166,37
	IMF6(f)	100	140,03
	IMF7(f)	100	13,466
	IMF8(f)	100	25,079
	IMF9(f)	100	11,736
n=1800 [r.p.m.], Q=3.85 [MPa]	X(f)	100	81,395
	IMF1(f)	100	34,338
	IMF2(f)	100	158,61
	IMF3(f)	100	23,64
	IMF4(f)	100	56,05
	IMF5(f)	100	148,3
	IMF6(f)	100	15,184
	IMF7(f)	100	38,944

To sum up, a conclusion can be drawn that it is possible to effectively use the signal spectra energy for diagnosing gearboxes, after the application of empirical mode decomposition.

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Doctor habilitated **Bogusław ŁAZARZ**, is an associate professor of the Silesian University of Technology, Faculty of Transport, Department of Automotive Vehicles Construction at. He specialises in vibroacoustic diagnostics of gearboxes, modelling and computer-assisted design of power transmission systems with gears and in signal processing methods.

Doctor habilitated **Henryk MADEJ**, Eng, is employed as an associate professor of the Silesian University of Technology, Faculty of Transport, Department of Automotive Vehicles Construction. He deals with issues connected with vibroacoustics of machines, diagnosing combustion engines and gearboxes, automotive mechatronics, and metrology.

Dr **Piotr CZECH**, Eng., is an assistant professor at the Silesian University of Technology, Transport Faculty, Department of Automotive Vehicle Construction. He is the winner of the competition for the Prize of President of the Council of Ministers and for Fiat Prize. In his scientific work, he deals with using the artificial intelligence methods and signal processing methods in diagnosing components of power transmission systems.

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