APPLICATION OF VIBRATION SIGNALS IN THE DIAGNOSIS OF COMBUSTION ENGINES – EXPLOITATION PRACTICES

Zbigniew Stanik, Jan Warczek

Faculty of Transport, Silesian University of Technology
Krasińskiego Street 8, 40-019 Katowice
tel.: 0326034118
e-mail: zbigniew.stanik@polsl.pl, jan.warczek@polsl.pl

Abstract

Changes in operating properties of the internal combustion engine, for various reasons, may manifest themselves with similar symptoms. An example is the drop in engine power, which may be caused by malfunctioning of the system such as power supply, or excessive wear geometric kinematic pairs as the piston-crankshaft. Identification of the causes of malfunction is the basis for carrying out corrective action. In practice, the workshop frequent disability are different manifestations of the drive units having identical symptoms. An alternative to iterative repair methods is the introduction of diagnostic tools that will help identify causes of failure, without having to remove the individual motor units. These provisions comply with the method of vibration analysis. The vibration signals provide information about the technical condition of the object. The paper presents examples of applying the methods of vibration in the identification of changes in the technical condition of the engine, which confirm their usefulness in identifying sources of failure. During the process of investigations, time courses of vibration accelerations were recorded with piezoelectric transducer mounted at half height of the first cylinder, perpendicular to its axis. The worked out method is based on vibration signals recorded at engine operation. The dominant amplitude components of time courses are strongly connected with air- fuel mixture ignition as well as with kinetic pairs of the engine.

Keywords: *vibration diagnostics, combustion engine*

1. Introduction

Combustion drive units which are commonly applied in modern cars can be classified as typical mechatronic systems. Steering system of the combustion engine, which employs the set of data received from a number of sensors, creates the steering sequence in accordance with the assumed algorithm and activates the actuators. Such procedure controls the parameters of the engine performance. It helps make efficient use of energy stored in the fuel and simultaneously maintain high level of environmental protection by reducing the amount of toxic components in waste gases. In order to ensure the correct functioning of such system it is necessary to maintain all its elements in nominal technical condition. OBD, which functions as an expert system supporting the work of a car mechanic, detects all failures of the system elements. Unfortunately, many failures which occur at combustion engines operation are not identified by the on board diagnostic systems. It happens frequently in practice that the system identifies the failure, but misinterprets the signals sent by the sensors which in consequence confuse the user. An example which illustrates the above might be the case of a two-mass flywheel failure diagnosed as the failure of a crankshaft sensor. In such a case it is the professional experience of a mechanic who decides about the repair method. There are, however, cases reported from practice, where neither experience nor on board diagnostic systems the basis for precise diagnosis. Then the application of alternative diagnostic methods such as vibroacoustic methods, which feature the best usefulness, might be the right solution. One of many advantages of such methods is their non-invasive character (without dismantling) which reduces the costs of diagnosis. In the paper the authors attempt at presenting the vibration methods in the diagnosis of piston combustion engines. The methods confirm their usefulness in identifying the sources of failures.

2. The object and investigation method

During the operation of modern combustion engines some cases of defectiveness occur when different failures are manifested with identical symptoms. Such cases of malfunctioning as e.g. power drop or uneven rotational speed are identified by OBD but their interpretation is not correct. The occurrence of such a phenomenon calls for iterative repair method which, due to considerable costs, is often not the optimal. The investigations carried out by the authors aimed at working out such vibration measures which would identify various failures. The investigations were performed with the use of four-cylinder ZI engine working in operational conditions. The assumed investigation goal was accepted on the basis of statistical analysis of operational cases which resulted in cars calling at service points. During the experiments the failure was modelled where the valve timing belt was shifted precisely in the same way as it happens during emergency engine start without a starter. The change of timing phases relative to crankshaft angle point can take the values of total multiplication factors n of a cog belt pitch which was n = 0,1,2 respectively. In case of the engines with faulty set valve timing, the symptoms are very similar to these which can be observed in case of extensive damping of waste gases outflow caused by impurities or partial damage of catalytic insert. Another model type of a failure was gradual reduction of wastes flow through the engine exhaust system. The Fig. 1 shows the view of this type of catalytic converter damage detected at iterative repair.

Fig. 1. The catalytic converter damage caused by overheating

During the process of investigations, time courses of vibration accelerations were recorded with piezoelectric transducer mounted at half height of the first cylinder, perpendicular to its axis. Exemplary part of the recorded signal is presented in Fig. 2.

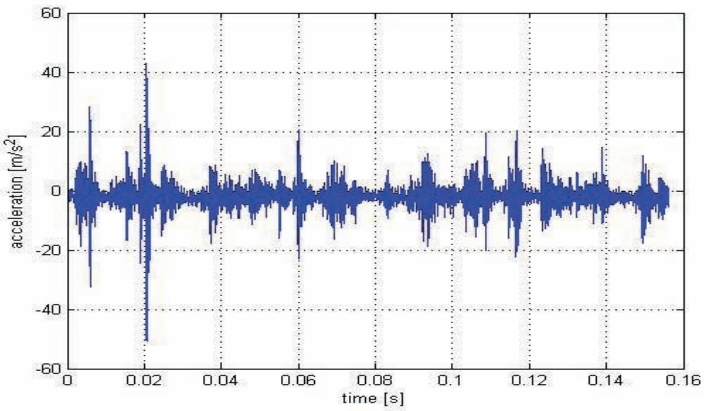

Fig. 2. Part of vibration acceleration signal recorded upon the engine case at half height of the first cylinder

The worked out method is based on vibration signals recorded at engine operation. The form of these time courses is complex and contains a lot of information. The dominant amplitude components of time courses are strongly connected with air- fuel mixture ignition as well as with kinetic pairs of the engine. The mechanical vibrations produced are transmitted by mechanical structures and reach the place where the sensor is mounted. Modal properties of the engine elements are revealed in vibrational signal and constitute kind of a resonance structure. In order to reduce the effect of non-modelled failures of vibration sources, the investigations were carried out on the same engine operating in stable temperature conditions at constant rotational speed.

3. The applied analysis method

The bulk of information carried by vibration signals is practically unavailable in time. In its wide sense the signals recorded can be classified as stationary, but the choice of shorter time windows will require the application of time-frequency methods of analysis. Therefore, the spectrum analysis of long signal fragments (min 20 rotations of a crankshaft) as well as the time-frequency analysis in time windows which roughly correspond to single operational cycles was performed simultaneously. Continuous wavelet transform was used to determine time-frequency distribution. The wavelet transformation helps obtain information about both time and frequency structure of the analyzed signal due to the fact that in this transformation wavelet function can be either lengthened or shortened. Narrow wavelets enable the analysis of high-frequency signal components and at the same time long term base functions reveal slow change features of the signal.
Continuous wavelet transformation of the signal can be defined as:

$$CWT_x(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\Psi\left(\frac{t-b}{a}\right)dt, \tag{1}$$

where:

Ψ(t) - wavelet family,

a - scale parameter $a \in R^{+} / 0 \wedge a \sim \frac{1}{f}$,

$\frac{1}{\sqrt{a}}$ - the scaling factor normalizing the wavelet energy,

b - translation parameter in time domain $b \in R$.

The wavelet transform represents the correlation between the analysed signal and a scaled function *Ψ(t)* respectively. The idea of wavelet transformation is to decompose a signal *x(t)* into wavelet coefficients $WT_x(a,b)$ with the use of a wavelet function. As the result of such transformation wavelet coefficients that are function of scale and time location are obtained. With the change of scale parameter, *a* and time shift parameter, *b* respectively, the time-frequency distribution is obtained. Base function of wavelet transformation is subjected to scaling and translation, which helps obtain wavelets of diverse life time and centre frequencies. When current value of wavelet centre frequency is considered then the frequencies corresponding to the analysed scale ranges can be determined. The best results are obtained when wavelets the shape of which matches the primary signal features are used. Long-time signal fragment was subjected to spectrum analysis which a-synchronically averaged the distribution of Power Spectrum Density with FFT algorithm defined as:

$$PSD(f) = \frac{1}{n}\sum_{i=1}^{n} \lim_{\Delta f \to 0} \frac{1}{\Delta f}\left[\lim_{T\to\infty} \frac{1}{T}\int_{0}^{T} x^2(t,f,\Delta f)dt\right], \tag{2}$$

where:

x(t, f , Δf) - signal component in frequency range from *f* to *Δf*,

T - signal observation time significant for correct estimation of power spectrum density distribution,

n - number of averaged distributions of power spectrum density.

4. Investigation results of the engine in diverse technical condition

Figure 3- 7 present the images obtained in the domain of frequency and time for the applied methods of signal processing. The results obtained for the signals recorded upon the engine in nominal technical conditions enable to determine the dominant spectrum components. Three local maximum values are found within the analyzed frequencies and their position is shown in Fig. 3.I.a. Low –frequency maximum value corresponds to the phenomena connected with the course of conversion process where chemical energy stored in the fuel is converted into mechanical energy. Structural vibrations induced by impulse forces present at the time of engine operation are noticed in the range of higher frequencies.

a) b)

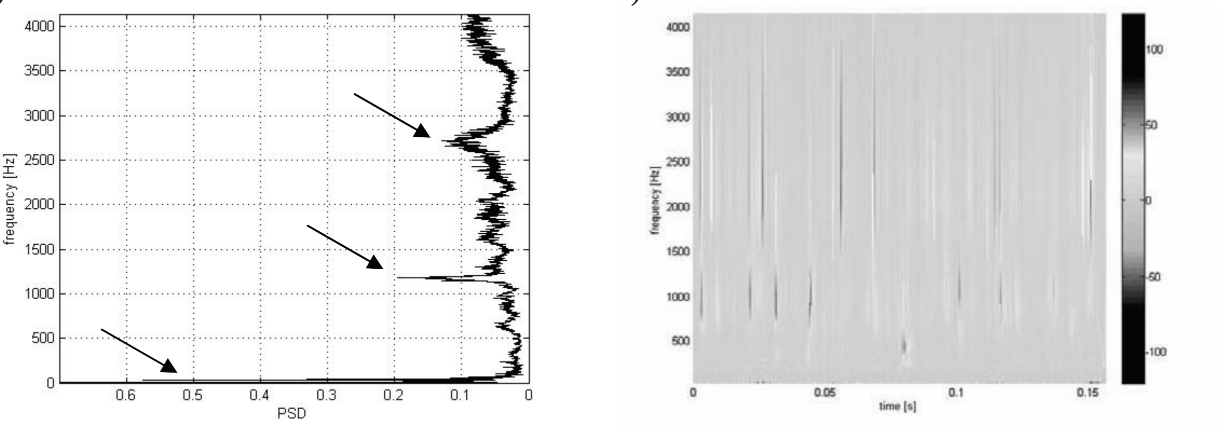

Fig. 3. I. The results obtained for the engine in nominal technical conditions: a) – frequency distribution of power spectrum density of the vibration acceleration signal, b) - time-frequency distribution of wavelet coefficients ,view 2D

a) b)

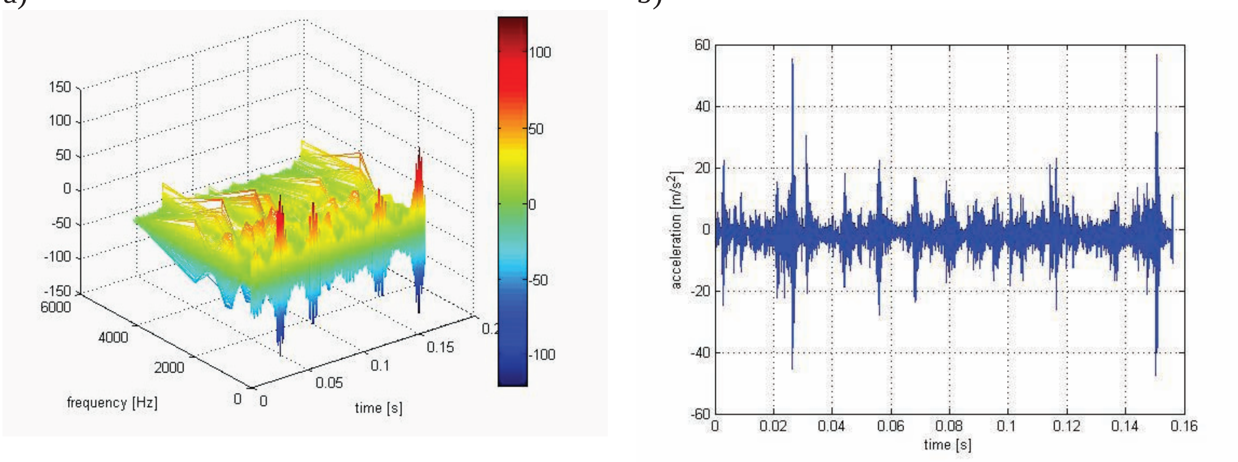

Fig. 3. II. The results obtained for the engine in nominal technical conditions: a) – 3D wavelet distribution of vibration acceleration in a selected frequency band, b) – fragment of the analysed signal

Power spectrum density does not provide time information contained in the signal which seems essential from the point of view of cyclostationary character of engine case vibrations. Time-frequency distribution obtained after continuous wavelet transformation makes the analysis of the changes in signal energy complex structure possible. The wavelet distributions obtained for the tested engine in its nominal technical condition are presented in Fig. 3.I.b and 3.II.a. Variable energy distribution of the vibration signal typical for these types of objects is clearly visible.

Fig. 4 and 5 present the effect of incorrect valve-timing phases positioning caused by the shift of a cog belt, upon the form of determined distributions. The bigger the error the lower the local values of the vibration signal power in the defined ranges of structural resonances.

a) b)

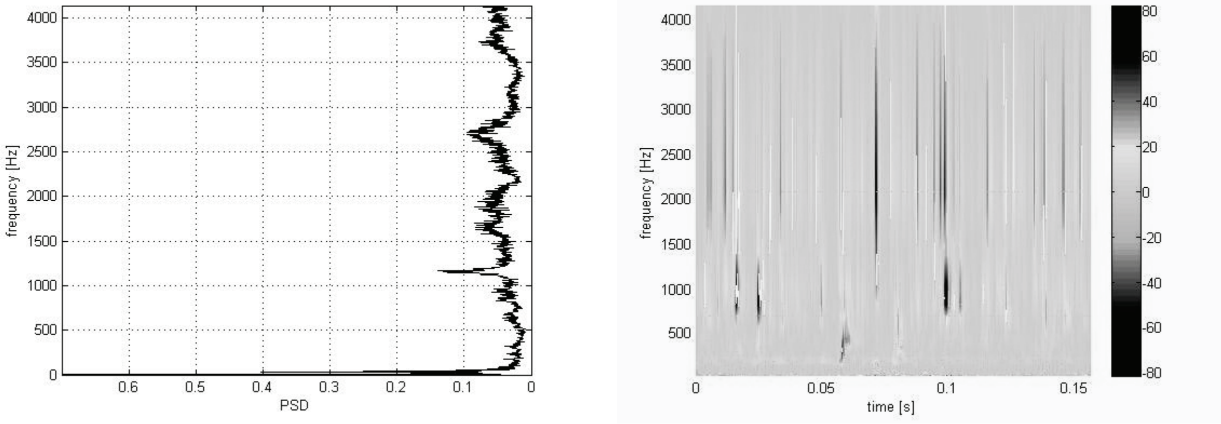

Fig. 4. I. The results obtained for shift of a cog belt by one tooth a) – frequency distribution of power spectrum density of the vibration acceleration signal, b) - time-frequency distribution of wavelet coefficients ,view 2D

a) b)

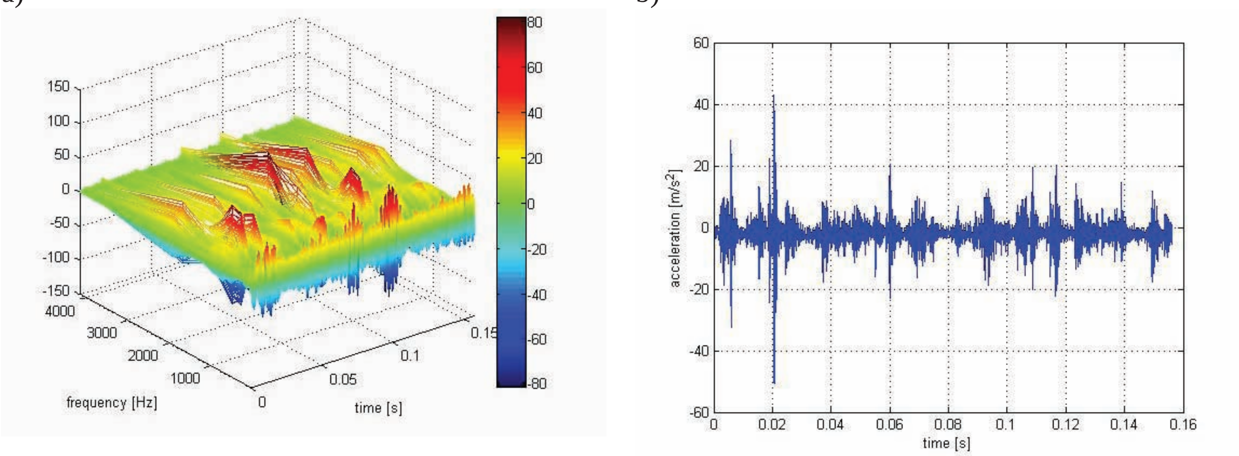

Fig. 4. II. The results obtained for shift of a cog belt by one tooth a) – 3D wavelet distribution of vibration acceleration in a selected frequency band, b) – fragment of the analysed signal

a) b)

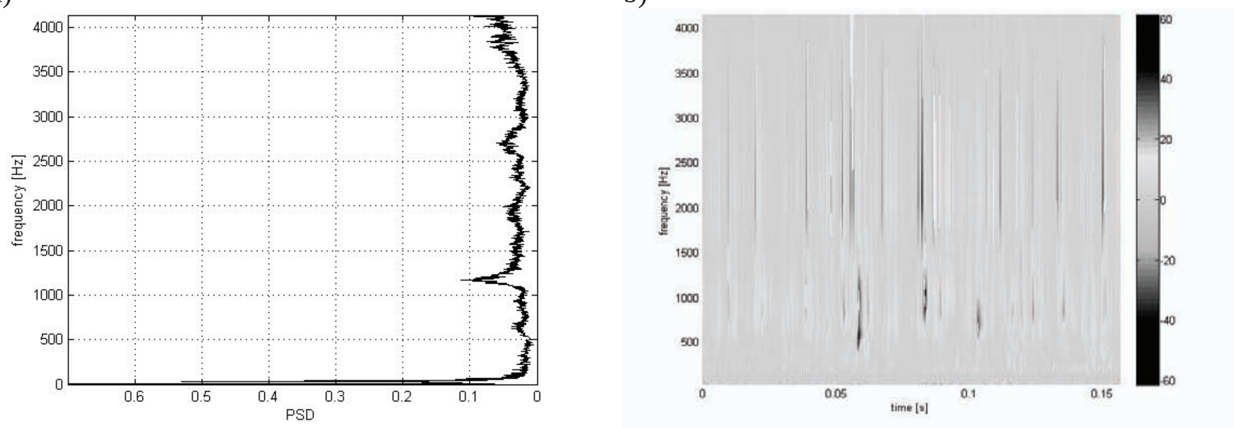

Fig.5.I. The results obtained for shift of a cog belt by two teeth : a) – frequency distribution of power spectrum density of the vibration acceleration signal, b) - time-frequency distribution of wavelet coefficients, view 2D

a) b)

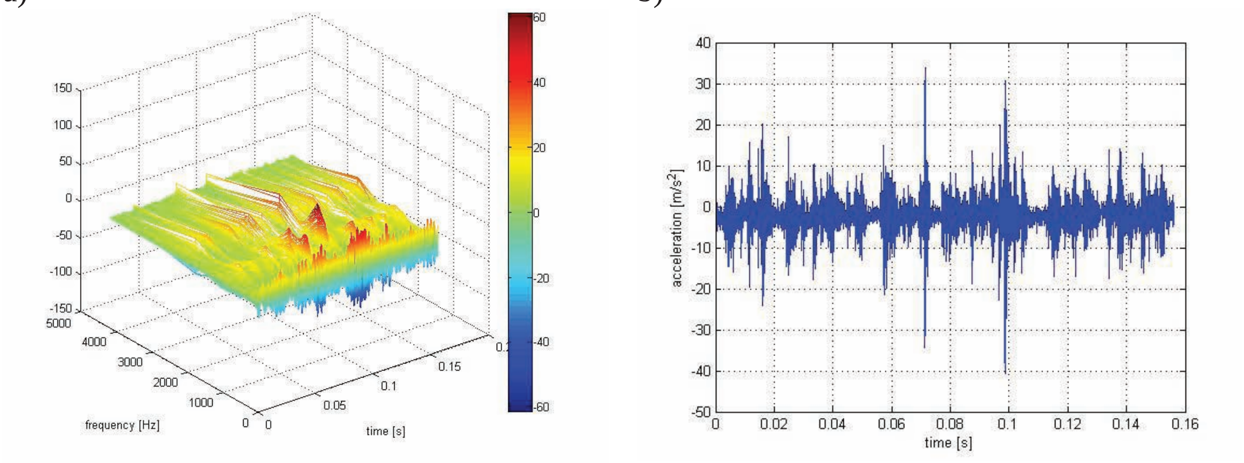

Fig. 5. II. The results obtained for shift of a cog belt by two teeth: a) – 3D wavelet distribution of vibration acceleration in a selected frequency band, b) – fragment of the analysed signal

a) b)

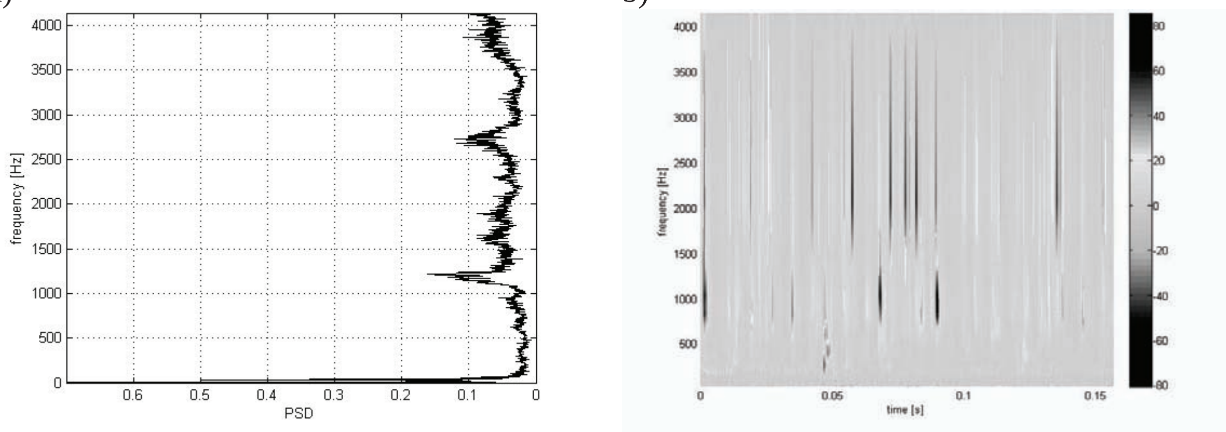

Fig. 6. I. The results obtained at the reduced surface area of the exhaust channel cross section by 75%: a) – frequency distribution of power spectrum density of the vibration acceleration signal, b) - time-frequency distribution of wavelet coefficients, view 2D

a) b)

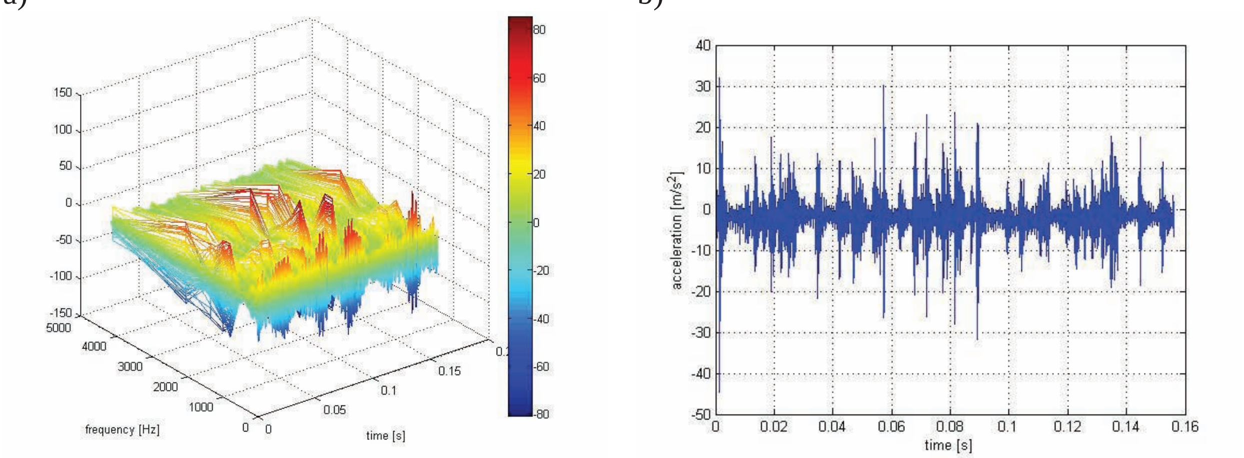

Fig. 6. II. The results obtained at the reduced surface area of the exhaust channel cross section by 75%: a) – 3D wavelet distribution of vibration acceleration in a selected frequency band, b) – fragment of the analysed signal

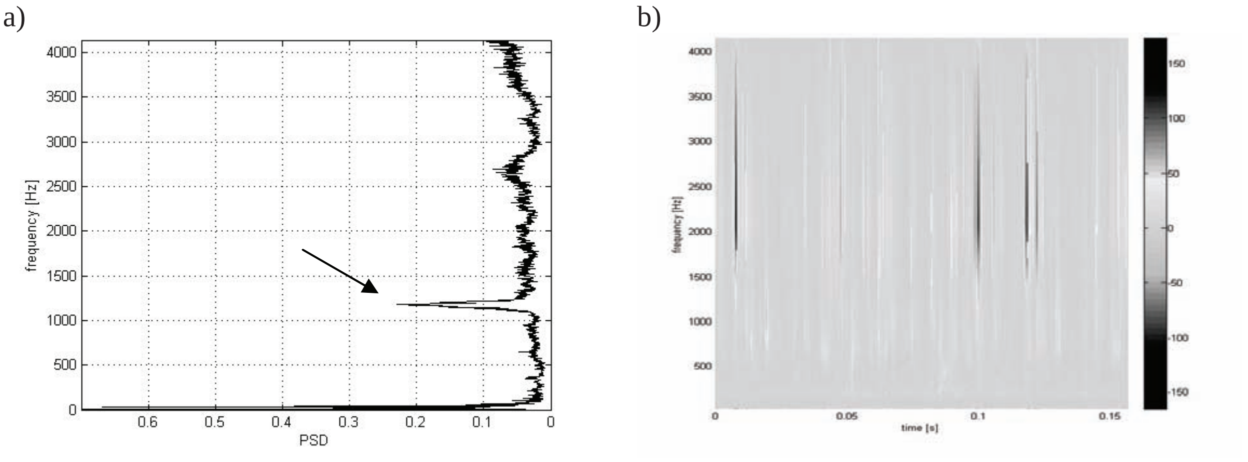

Fig. 7. I. The results obtained at the reduced surface area of the exhaust channel cross section by 85%: a) – frequency distribution of power spectrum density of the vibration acceleration signal, b) - time-frequency distribution of wavelet coefficients, view 2D

In the time-frequency distribution the signal energy is distributed around structural resonances in the analyzed frequency range but in a more uniform way. The reason is lower dynamics of mixture combustion in the chamber which leads to the decrease of frequency range of the vibrations. Vibration symptoms caused by increased damping of waste gases flow through the exhaust system are presented in Fig. 6 and 7.

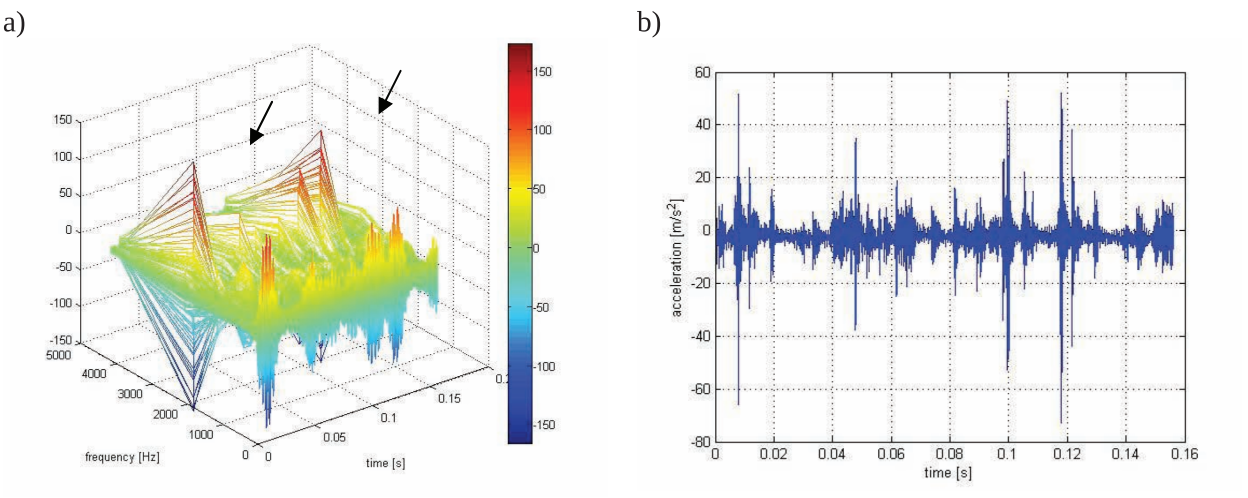

Fig. 7. II. The results obtained at the reduced surface area of the exhaust channel cross section by 85%: a) – 3D wavelet distribution of vibration acceleration in a selected frequency band, b) – fragment of the analysed signal

In case of the reduced surface area of the exhaust channel cross section by 75% in relation to the new system, the determined spectrum and time-frequency distribution do not differ significantly (Fig. 6). However, it should be stated that the investigations were performed for the engine idle run. Therefore, increased modelled damping of such amount of waste gases 'produced' in time did not effect the engine operation. Increased damping of waste gases flow generated by reduced cross section area of the exhaust channel by further 10% was reflected in higher total signal power for about 1200[Hz] and was accompanied by strong energy impulse for the highest analyzed frequency of structural vibrations (Fig. 7). The combination of two suggested methods of vibration acceleration signals analysis in the combustion engine block makes it possible to differentiate all reasons of failures which ,from the point of view of on board diagnosis, are not possible to be identified at present.

4. Conclusions

Modelled combustion engine failures resulted in very similar qualitative symptoms in course of engine operation. Application of the suggested methods of vibration acceleration signals analysis helped differentiate technical conditions and undertake effective maintenance decisions. The presented method might find its application at service points as an element supporting the diagnostic process of combustion engines. Such application is possible only after qualitative measures are defined and their boundary values for various design solutions of combustion engines are determined.

Acknowledgements

This works has been financed from budget source on science in years 2010-2013 as a research project.

References

[1] Łazarz, B., Madej, H., Peruń, G., Stanik, Z., *Vibration based diagnosis of internal combustion engine faults*, Diagnostyka Nr2(49), 2009.
[2] Zheng, G. T, Leung, A. Y. T., *Internal combustion engine noise analysis with time-frequency distribution*, Journal of Engineering for Gas Turbines and Power, Vol. 124, pp. 645-649, 2002.
[3] Madej, H., *Diagnozowanie uszkodzeń mechanicznych w silnikach spalinowych maskowanych przez elektroniczne urządzenia sterujące*, Biblioteka Problemów Eksploatacji, Katowice-Radom 2009.
[4] Dąbrowski, Z., Madej, H., *O użyteczności symptomów wibroakustycznych w nowoczesnej diagnostyce silników spalinowych*, Przegląd Mechaniczny, Nr 1, s. 32-35, 2007.
[5] Cempel, C., *Diagnostyka wibroakustyczna maszyn*, PWN, Warszawa 1989.
[6] Batko, W., Dąbrowski, Z., Engel, Z., Kiciński, J., Weyna, S., *Nowoczesne metody badania procesów wibroakustycznych*, ITE, Radom 2005.
[7] Lyon, R. C., *Understanding digital signal processing*, Prentice Hall PTR. 1st Edition, 1997.
[8] Madej, H., Stanik, Z., Warczek, J., *The vibroacoustic methods and their application in the diagnostics of the combustion engine's roller-bearing fittings,* J. KONES, Powertrain Transp., Vol. 17, No. 2, pp. 293-297, 2010