AVERAGED WAVELET POWER SPECTRUM AS A METHOD OF PISTON – SKIRT CLEARANCE DETECTION

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Summary

Vibration of engine block and head is caused by many input functions and their structure changes together with the occurrence of mechanical damage, wear and tear, and anomalies occurring in the combustion process. Due to the above reasons, the vibration signal measured on an engine block or head is of complex nature, it is non-stationary and contains transient components. In such case, the traditional methods, such as Fourier analysis are of little use; it is necessary to apply processing methods as far as time and frequency are concerned.

This paper presents an attempt to define the clearance in the piston – cylinder system based on the vibration acceleration signal. A single-cylinder Diesel engine and a four-cylinder engine with spark ignition (SI) were tested. In order to obtain damage sensitive symptoms, the vibration acceleration signals were analyzed with use of a continuous wavelet transform (CWT). Based on the wavelet analysis, the averaged wavelet power spectra (ASWPS) were defined, which reflect the energy distribution on a scale being the frequency function. Based on the results obtained, it has been shown that the averaged wavelet distribution of signal energy can be useful in diagnosing clearance in the piston – cylinder system.

Keywords: combustion engines, diagnostics, wavelet transform, clearance in the piston – cylinder system.

UŚREDNIONE FALKOWE WIDMO MOCY JAKO METODA DIAGNOZOWANIA LUZU W UKŁADZIE TŁOK-CYLINDER

Streszczenie

Drgania bloku i głowicy silnika są spowodowane wieloma wymuszeniami, a ich struktura zmienia się wraz z pojawianiem się uszkodzeń mechanicznych, zużycia eksploatacyjnego oraz występowania anomalii w procesie spalania. Z powyższych powodów sygnał drganiowy mierzony na bloku lub głowicy silnika ma złożony charakter, jest niestacjonarny i zawiera składowe impulsowe. W takim przypadku tradycyjne metody takie jak analiza Fouriera są mało przydatne, konieczne staje się stosowanie metod przetwarzania w dziedzinie czasu i częstotliwości.

W artykule przedstawiono próbę określania luzu w układzie tłok – cylinder na podstawie sygnału przyspieszeń drgań. Badaniom podano jednocylindrowy silnik z zapłonem samoczynnym (ZS) i czterocylindrowy silnik z zapłonem iskrowym (ZI). W celu uzyskania symptomów wrażliwych na uszkodzenie sygnały przyspieszeń drgań analizowano za pomocą ciągłej transformaty falkowej (CWT). Na podstawie analizy falkowej określono uśrednione falkowe widma mocy (ASWPS), które odzwierciedlają rozkład energii w dziedzinie skali będącej funkcją częstotliwości. Na podstawie uzyskanych wyników można stwierdzić, że uśredniony falkowy rozkład energii sygnału może być przydatny w diagnozowaniu luzu w układzie tłok – cylinder.

Słowa kluczowe: silniki spalinowe, diagnostyka, transformata falkowa, luz w układzie tłok cylinder.

1. INTRODUCTION

For the detection of mechanical defects in motor vehicles, operating processes are used as information carriers, in which the processing of one energy type into another or its transfer takes place. The carrier of information on the technical condition of combustion engines, which is used more and more frequently, is a vibroacoustic signal [2, 3, 4, 5, 7, 8, 10]. The diagnostic systems used in the modern combustion engines [9] aim at locating the element or system which, due to natural wear or damage, cannot further perform its function as specified by the manufacturer.

From the point of view of their effects, mechanical damages can be divided into:

– damages causing the increase of toxic compounds emission or the increase of fuel consumption,
– damages having direct influence upon the safety of driving.

- non-emmission damages of the power transmission system, imparing the vehicle’s dynamics.

Increasing requirements concerning the durability and reliability of combustion engines and the minimisation of costs and disadvantageous influence upon the environment necessitate the acquiring of information on their condition during operation. Introduction of the obligation of manufacturing motor vehicles compliant with the OBDII standard resulted in the possibility of accessing data stored in the programmers of individual systems. Owing to this solution, new possibilities of diagnosing the technical condition of those systems arise [9]. The main sources of vibrations and noise generated by the piston combustion engine, are thermodynamic processes taking place in it, including the combustion process, percussion phenomena in the piston – cylinder system and operation of the timing gear system. Combustion of the material filling the cylinder is a quickly-changing process and it occurs in a small range of the crankshaft rotation angle corresponding to the piston location close to its top dead point (GMP). The impulse nature of inductions initiates the vibrations of the resonant engine structure. Vibration acceleration signal are registered on the head and engine block may be used in tests aiming at limiting vibroactivity of combustion engines and they are a good source of diagnostic information on the condition of various engine kinematic pairs.

2. AVERAGED WAVELET POWER SPECTRUM (ASWPS)

The vibration signal measured on engine block or head is complex, non-stationary and contains transient components, and therefore, traditional methods, such as Fourier analysis, are of little use here. In recent years, diagnostic methods are developed which use signal analysis in time and frequency respect (Wigner—Ville distribution – WV) or in respect of time and scale, being a frequency function – continuous wavelet transform (CWT) [1] defined by the following equation:

$$CWT_x(a,b) = C_{ab} = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \psi^* \left(\frac{t-b}{a} \right) \cdot x(t)\,dt \,, \quad (1)$$

where:

a – means scale parameter,
b – value of the analysing function shift,
$\psi(t)$ - analysing wavelet,
$x(t)$ – signal analysed.

Characteristics obtained by means of wavelet transformation are called scalograms or time and scale characteristics and they are usually presented as SD or 3D charts. The time axis of the characteristics corresponds to the time shift the base wavelet is subject to, whereas another axis contains the values of scale which are the frequency function. Similarly to spectogram which is the square of *STFT* Fourier transformation module, the scalogram is the square of wavelet transformation module, that is, time-scale representation:

$$S_x^{SCAL}(a,b) = \left| CWT_x(a,b) \right|^2 = \left| C_x(a,b) \right|^2 . \quad (2)$$

Based on this transformation, it is possible to determine the so-called scale wavelet power spectrum used for the evaluation of energy change of the signal analysed in selected scopes of scale and crankshaft rotation angle:

$$E(a) = \int_{b_1}^{b_2} \left| C_x(a,b) \right|^2 db = \int_{b_1}^{b_2} S_x^{SCAL}(a,b)\,db \,. \quad (3)$$

where:

b_1, b_2 – limits of integration, corresponding to the analysed scope of time or crankshaft rotation angle.

Based on the spectrum so determined, it is possible to define the signal energy in a selected range of scale $a_1 \div a_2$ and the crankshaft rotation angle $b_1 \div b_2$:

$$E = \int_{a_1}^{a_2} E(a)\,da = \int_{a_1}^{a_2}\int_{b_1}^{b_2} S_x^{SCAL}(a,b)\,dadbb \,. \quad (4)$$

3. ANALYSIS OF SI ENGINE SIGNALS

During the tests of a vehicle equipped with a spark ignition engine of 1.2 dm^3 capacity acceleration of vibration was recorded in the function of time and the crankshaft rotation angle. In the measurements, a DPA crank angle encoder produced by Kistler and ICP vibration acceleration converters produced by PCB were used together with an SV006 signal amplifier. Three converters were used, two of them were located close to the fourth cylinder. One of them allowed recording vibration in a direction perpendicular to the cylinder axis and the other one – paralelly. The third sensor was placed on the head near the first cylinder and it allowed recording the vibrations parallel to the cylinder axis. The signals were recorded with use of an eight-channel NI PCI-6143 data acquisition card, controlled with a programme developed in the Lab View 7.1 environment.

Fig. 1 shows the courses of vibration accelerations, recorded in the direction perpendicular to the cylinder axis and simultaneously, perpendicular to the piston pin axis in case of an engine operating with a rotational speed of 2500 RPM. The measurements were performed before and after the repair of the engine, consisting of replacement of the pistons worn out.

Based on the tests results analysis it was stated that the repair performed did not influence the peak values of vibration accelerations (Fig. 1). It did not influence the root-mean-square value of vibration accelerations, calculated based on the root-mean-square values of 23 cycles of engine's operation (Fig. 2).

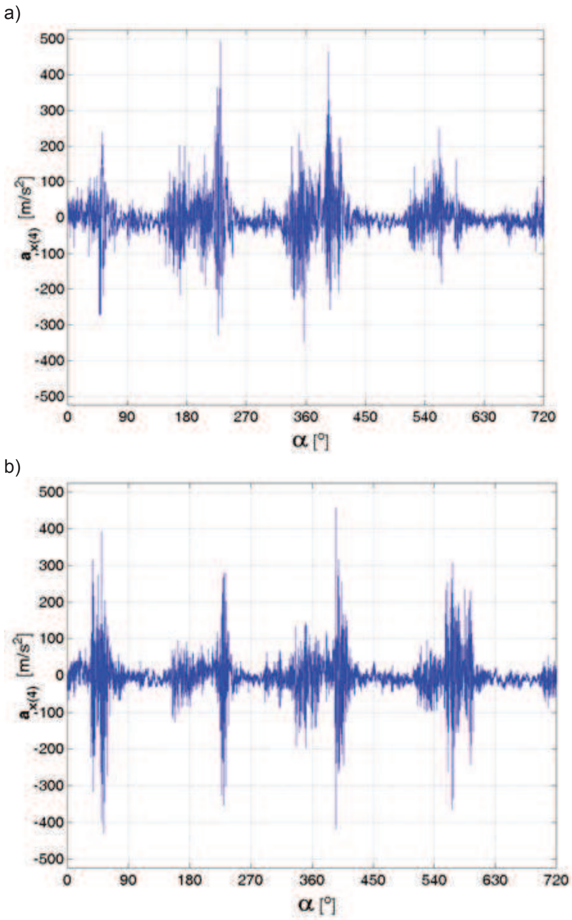

Fig. 1. Course of the vibration accelerations recorded on the fourth cylinder in the direction perpendicular to the cylinder axis and simultaneously perpendicular to the piston pin axis: a) before engine repair, b) after engine repair

Similarly, the results of the spectrum analysis of vibration signal in the scope of low frequencies from 0 to 500 Hz do not show significant differences in the bands connected with the induction frequency equaling 83.34 Hz (Fig. 3). It is possible to note a small amplitude change in the spectrum of vibration acceleration recorded after the engine repair in the band connected with the ignition. Spectrum analysis was conducted for the time course comprising fifteen full working cycles of the engine tested.

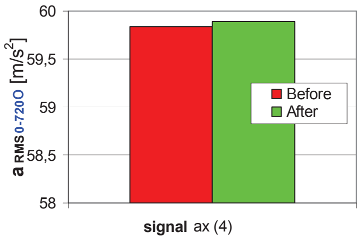

Fig. 2. Comparison of root-mean-square value calculated based on the vibration accelerations registered on the fourth cylinder in the direction perpendicular to the cylinder axis before and after the engine repair

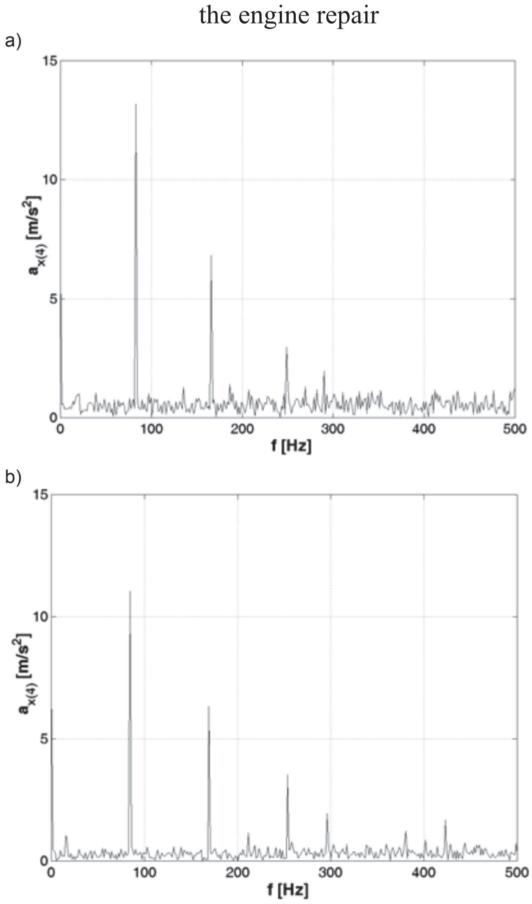

Fig. 3. Spectra of vibration accelerations recorded on the fourth cylinder in the direction perpendicular to the cylinder axis before (a) and after (b) repair of the engine

In the studies described in papers [7, 8], a nonaveraged wavelet power spectrum was applied for clearance detection in the piston – cylinder system of Diesel engine. Due to the existence of a stochastic constituent of the vibration signal and, for example, the possibility of misfiring, this method may lead to untrue conclusions. For this reason, in this article, a method of diagnosing clearance in the piston – cylinder system has been suggested, which method is based on the averaged scale - wavelet power spectrum (ASWPS), determined according to the diagram presented in Fig. 4. Using the Morlet wavelet, a wavelet transform was calculated based on 23 full engine's working cycles. Next, the scope of analysis was narrowed to the crankshaft rotation angle of 350-420°, since in this scope the piston hits the cylinder wall. Fig. 5 shows the scale wavelet power spectra (SPWT) of 23 engine's working cycles before and after its repair: In order to enable easier comparison of spectra obtained for the conditions before and after the engine repair, they were averaged. It is possible to see in Fig. 6 that after the repair, the values of constituent amplitudes of obtained spectra decreased. The energy of CWT coefficients, calculated from the dependence 4 on the basis of SWPS (Fig. 7) was proposed to be the diagnostic measure. The measure proposed is sensitive to the clearance change in the piston – cylinder system (Fig. 8).

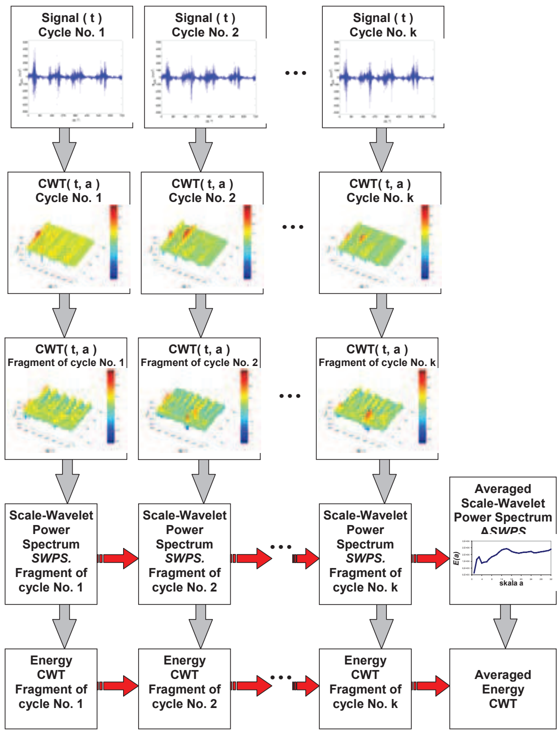

Fig. 4. Diagram of calculating the Averaged Scale Wavelet Power Spectrum (ASPWT)

4. ANALYSIS OF DIESEL ENGINE SIGNALS

In order to check the usefulness of the method suggested, another object of analysis were vibration signals of a single-cylinder Diesel engine with direct injection, produced by Ruggerini of 477 cm^3 capacity and of 91mm cylinder diameter. In the tests, the following items were recorded:

- pressure inside the cylinder,
- vibration accelerations of engine wall blocks in the direction parallel to the cylinder axis and perpendicular to the cylinder axis and simultaneously in the direction perpendicular to the piston pin axis,
- crankshaft rotation angle and GMP (top dead point) of piston,
- engine's torque,
- subatmospheric pressure in the suction manifold.

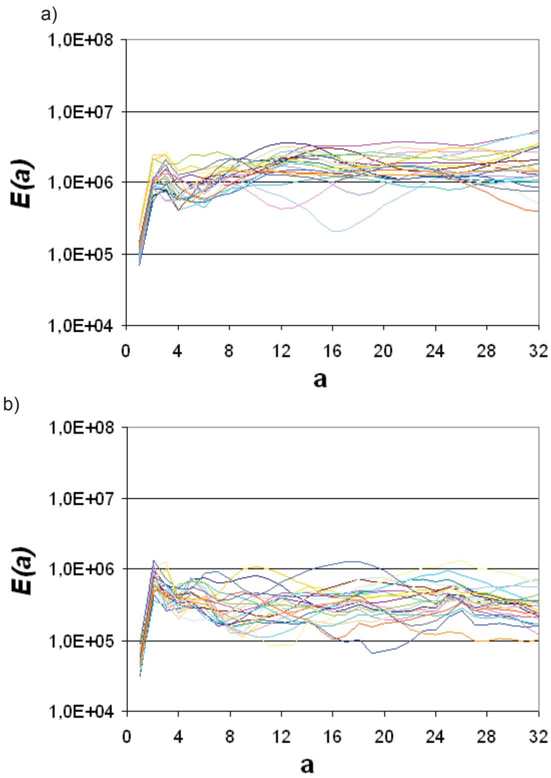

Fig. 5. Scale wavelet power spectra (SPWT) – measurement on the fourth cylinder in the direction perpendicular to the cylinder axis: a) before, b) after repair of the engine

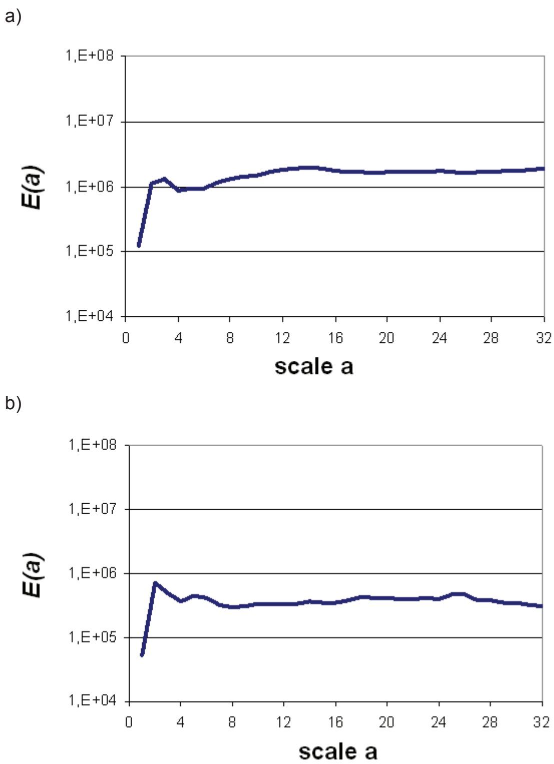

Fig. 6. Averaged scale wavelet power spectra (ASPWT) – of 23 engine's operating cycles in the direction perpendicular to the cylinder axis:
a) before, b) after repair of the engine

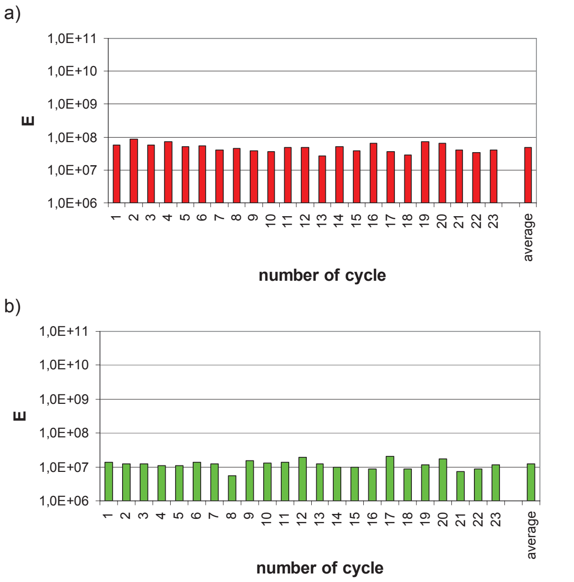

Fig. 7. Energy of CWT coefficients of 23 cycles of engine operation - measurement on the fourth cylinder in the direction perpendicular to the cylinder axis: a) before, b) after repair of the engine

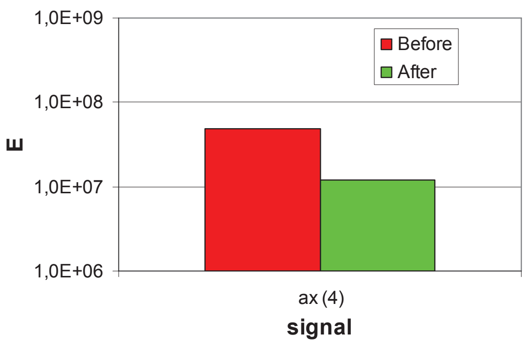

Fig. 8. Average energy of CWT coefficients of 23 engine's operating cycles - measurement on the fourth cylinder in the direction perpendicular to the cylinder axis

During the tests, the engine operated with a rotational speed of about 1250 [r.p.m.] and was loaded with torque of 2.8 [Nm].

The measurements were conducted for three clearance values: nominal clearance, double nominal clearance and four times nominal clearance. For the selected experimental clearance values, the compression pressure on the same level was kept.

Observing the presented in Fig. 9 averaged wavelet power spectra (ASPWT) of the signals registered in two mutually perpendicular directions, it can be noted that the amplitudes of those spectra in the whole scope of scale increase together with the increase of clearance in the piston – cylinder system. Similarly, the energy of CWT coefficients changes (Fig. 10).

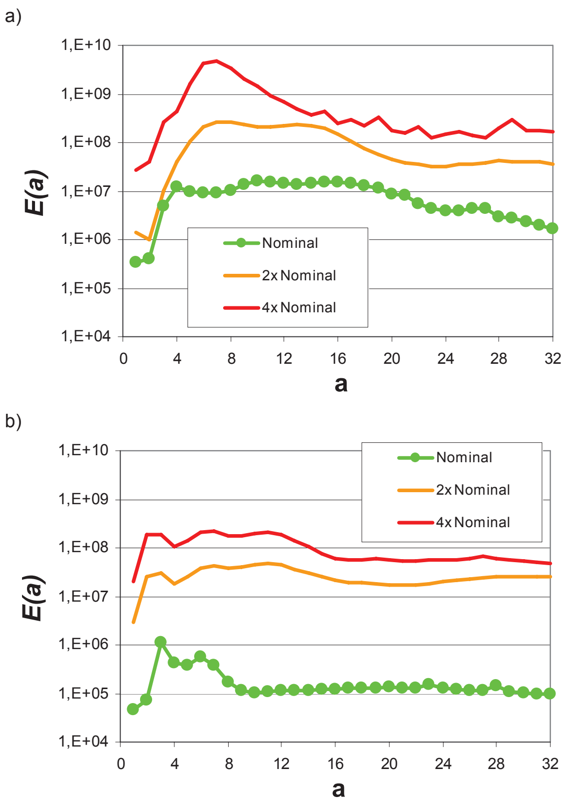

Fig. 9. Averaged scale wavelet power spectrum (ASPWT) – 30 cycles of engine operation: a) of vibration acceleration signal of engine block, b) of head

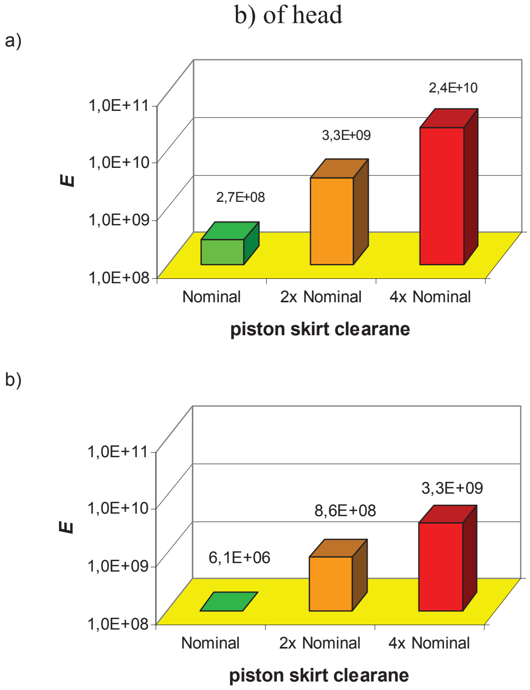

Fig. 10. Average coefficient CWT energy of vibration accelerations signal a) of engine block, b) of head

5. CONCLUSIONS

Based on the research and analyses performed, the following conclusions have been formulated:

- Based on an appropriate phase and spectrum analysis, it is possible to determine appropriate measures of vibration signal, sensitive to operational wear of the piston – cylinder system.
- In case of both engines, the suggested measure, based on the averaged wavelet power spectrum (ASWPS) was sensitive to the clearance change in the piston – cylinder system.
- Using the vibration signals in diagnosing mechanical combustion engines is more effective when applying signal decomposition by means of time-frequency (scale) representations.
- Differences in the obtained spectra for the tested engines may be caused by:
  - a different number of cylinders – SI engine has 4 cylinders, whereas Diesel engine has 1 cylinder,
  - maximal pressures in combustion chamber - SI and Diesel engines,
  - construction of the engine – SI engine is cooled with liquid and Diesel engine is cooled with air.
- It seems reasonable to develop appropriate algorithms supplementing OBD systems, allowing the detection of mechanical defects in engines, which can be masked by electronic control devices of the contemporary automotive vehicles.

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