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PTNSS–2011–SC-084

Detection of the engine head gasket defects on the basis of vibration signal

Abstract: The results of the analysis of the engine vibration acceleration signal measured for the original and for the damaged engine head gaskets are presented in the paper. Examinations were performed in the Fiat Punto car with a four-cylinder SI engine. Vibration and synchronizing signals were recorded during the car driving at a constant speed since it has an essential influence on characteristics of the engine vibration signal. The spectral analysis of the vibration signal indicated amplitude increases within the broad frequency band: 5–25 kHz, with a maximum at 8 kHz. However, the spectrum can only serve as an indicator that a certain leakage or damage appears in the engine. More precise information can be found on the basis of the time-frequency analysis. The wavelet analysis was performed by means of the Morlet wavelet. It turned out that such filtration allows for a distinct separation of vibration responses corresponding to the gasket leakage. Then the filtered signal envelope was determined and its average values for the engine with the original and with the damaged head gasket were estimated. It is clearly seen, that this measure increases twice when the damaged gasket is checked and thus that allows to formulate the diagnosis.

Key words: *spark ignition engine, vibration signal, diagnosing, engine head gasket, wavelet analysis*

Wykrywanie uszkodzenia uszczelki głowicy silnika na podstawie sygnału drgań

Streszczenie: W referacie przedstawiono wyniki analizy sygnału przyspieszenia drgań silnika pomierzonego dla nowej i uszkodzonej uszczelki głowicy silnika. Badania przeprowadzono na samochodzie Fiat Punto z silnikiem czterocylindrowym o zapłonie iskrowym. Rejestrowano sygnał drgań głowicy silnika i sygnały synchronizujące w czasie jazdy samochodem ze stałą prędkością, ponieważ ma ona istotny wpływ na charakterystyki sygnału drgań silnika. Przeprowadzona analiza widmowa sygnału drgań wykazała wzrost amplitud w szerokim paśmie częstotliwości 5–25 kHz, z maksimum dla 8 kHz. Jednak widmo może być tylko indykatorem, na jego podstawie można jedynie stwierdzić, że w silniku występuje nieszczelność lub uszkodzenie. Dokładniejszych informacji może dostarczyć analiza czasowo-częstotliwościowa. Wykonano analizę falkową przy użyciu falki Morleta. Okazało się, że przeprowadzenie takiej filtracji pozwala na wyraźne wyseparowanie odpowiedzi drganiowych związanych z nieszczelnością uszczelki. Następnie wyznaczono obwiednię sygnału przefiltrowanego i wyznaczono jego wartość średnią dla silnika z nową i uszkodzoną uszczelką głowicy. Widać wyraźnie, że miara ta wzrasta dwukrotnie przy badanym uszkodzeniu, co pozwala na sformułowanie diagnozy.

Słowa kluczowe: *silnik spalinowy, sygnał drgań, diagnozowanie, uszczelka głowicy silnika, analiza falkowa*

1. Introduction

Occasionally, the compression in the cylinder cause a leakage in the gasket and the gasket will have to be replaced, or severe damage can take place (a "blown" head gasket). This problem has been exacerbated by the use of aluminum rather than iron cylinder heads; while lighter than iron, aluminum has a much greater thermal expansion rate, which in turn causes a great deal more stress to be placed on the head gasket.

If the gasket fails, a variety of problems can occur, from compression loss (leading to power reduction, or a rough engine), to exhaust gases being forced into the cooling system, leading to the engine overheating and increased engine wear due to the motor oil being mixed with antifreeze. Coolant can leak into the cylinders, causing the exhaust to issue steam and the catalytic converter to be damaged. If a very large amount of coolant does this, hydrolock can occur, causing extensive engine damage. Sometimes, all that may happen when a head gasket is blown is excessive steam erupting from the tailpipe; yet the engine may act and drive like normal, until all the coolant is gone and the engine overheats. A damaged head gasket can cause compression to leak between cylinders.

The condition of a head gasket is typically investigated by checking the compression pressure with a pressure gauge, or better, a leak-down test or noting any indication of combustion gasses in the cooling system on a water-cooled engine.

The maintenance method of diagnostics of engine head gasket defects by means of the analysis of engine vibrations, recorded during car driving, is proposed in the hereby paper.

2. Description of examinations

Examinations were performed during road tests on the Fiat Punto of 400 000 km. mileage. Series of engine vibration measurements for various rotational speeds and loads were performed. Technical specifications of the engine are as follows:

engine type	FIRE 1.2 MPI, four-stroke, gasoline,
displacement	1242 cm^3,
maximum power	54 kW at 6000 rpm,
maximum torque	106 Nm at 4000 rpm,
cylinder diameter x piston stroke	50,8 x 78,9 mm

The main measuring path included the piezoelectric vibration sensors B&K Delta Shear type 4393 of a frequency range: 0.1 – 16500 Hz, resonance frequency 55 kHz and work temperatures from -74 to +250°C, fixed with a joint screwed into the engine side at cylinder 1, and the portable device for recording data B&K PULSE type 3560E. Accelerations of engine block vibrations were recorded in the vertical and horizontal directions with a frequency of 65536 Hz, which means the frequency encompassing the sensor resonance frequency range. Apart the engine vibration signal also the crankshaft position signal, throttle position and signals from the ignition coil at 1 and 4 cylinder were recorded. Additional signals enabled the identification of engine timing.

Signals of 1-minute duration were recorded during driving for stable condition of engine with a constant speed at 2000, 3000, 4000 rpm and constant load on the highway. Small speed fluctuations were eliminated during further analysis. Maintaining the constant rotational speed of the engine is essential, since this parameter has a significant influence on the vibration amplitude. Small fluctuations of the load have meaningless influence on vibration characteristics [2].

A crack of a gasket was simulated by the cut, which is seen in Figure 1.

Fig.1. The defected head gasket
Rys.1. Uszkodzona uszczelka głowicy

Instantaneous waveforms of engine head vibrations during two working cycles are presented in Figure 2. Valve operations, mainly vibration responses to closing inlet valves are clearly seen in the diagram. Operations of exhaust valves, at the proper valve clearance, are usually not seen in the time history of head vibrations. However, the times of vibration responses to impulse forces, related to engine operations caused by the resonance occurrence, can become longer, due to the damage. Additionally, vibrations of a resonance character and significant amplitudes – not being responses to any forces occurring at the normal engine operations – manifest themselves when the gasket is damaged. Thus, they are symptomatic for the defect under examination.

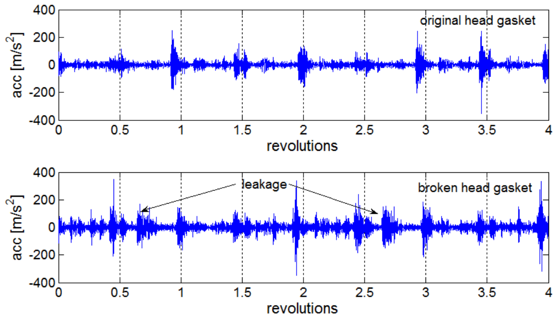


Fig.2. Instantaneous waveforms of engine head vibrations for the original and defected head gasket for 3000 rpm during 4 revolutions of the crank shaft
Rys.2. Chwilowe przebiegi czasowe drgań głowicy silnika dla oryginalnej i uszkodzonej uszczelki głowicy przy prędkości obrotowej wału korbowego 3000 obr/min podczas 4 obrotów wału

3. Wavelet analysis and enveloping

The spectral analysis (Fig. 3) indicates that for the damaged gasket there is the amplitude increase within the broad frequency band: 5–25 kHz, with the maximum at approximately 8 kHz. However, a spectrum can only serve as an indicator that a certain leakage, damage or knock combustion appears in the engine.

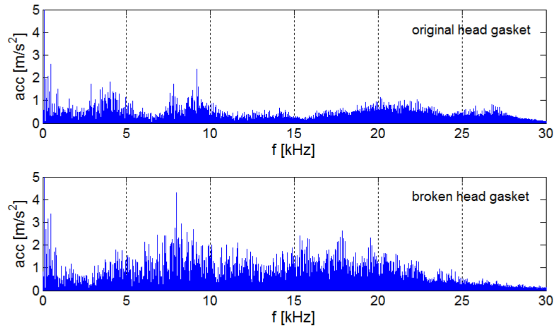


Fig.3. Averaged vibration spectrum of the engine head for the original and defected head gasket
Rys.3. Uśrednione widma drgań głowicy silnika dla oryginalnej i uszkodzonej uszczelki głowicy

More precise information can be obtained from the time-frequency analysis. The wavelet analysis was performed by means of the Morlet wavelet. Wavelet transforms are inner products between signals and the wavelet family, which are derived from the mother wavelet by dilation and translation. Let $\psi(t)$ be the mother wavelet, the daughter wavelet will be $\psi_{a,b}(t)=\psi(t-b)/a$, where a is the scale parameter and b is the time translation. By varying the parameters a and b, we can obtain different daughter wavelets that constitute a wavelet family. Wavelet transform of the signal x(t) is to perform the following operation [6]:

$$W(a,b)=\frac{1}{\sqrt{a}}\int x(t)\psi^{*}_{a,b}(t)dt \qquad (1)$$

where '*' stands for complex conjugation.

If a daughter wavelet is viewed as a filter, wavelet transform is simply a filtering operation [5]. Morlet wavelet is one of the most popular non-orthogonal wavelets [3]. The definition of Morlet is:

$$\psi(t)=\exp\left(-\beta^{2}t^{2}/2\right)\cos(\pi t) \qquad (2)$$

where β is the shape coefficient.

It is a cosine signal that decays exponentially on both the left and the right sides. This feature makes it very similar to an impulse. It has been used for impulse isolation and mechanical fault diagnosis through the performance of a wavelet de-noising procedure [7].

A daughter Morlet wavelet is obtained by time translation b and scale dilation a from the mother wavelet, as shown in the following formula:

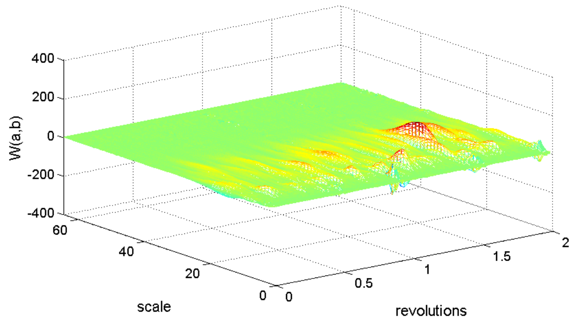
$$\psi_{a,b}(t)=\psi\left(\frac{t-b}{a}\right)= = \exp\left[-\frac{\beta^{2}(t-b)^{2}}{2a^{2}}\right]\cos\left[\frac{\pi(t-b)}{a}\right] \qquad (3)$$

where:
a – the scale parameter for dilation
b – the time translation.

It can also be looked at as a filter. To identify the immersed impulses by filtering, the location and the shape of the frequency band corresponding to the impulses must be determined first. Scale a and parameter β control the location and the shape of the daughter Morlet wavelet, respectively.

Figure 4 illustrates Morlet wavelet filtering of vibration signal.

a)



b)

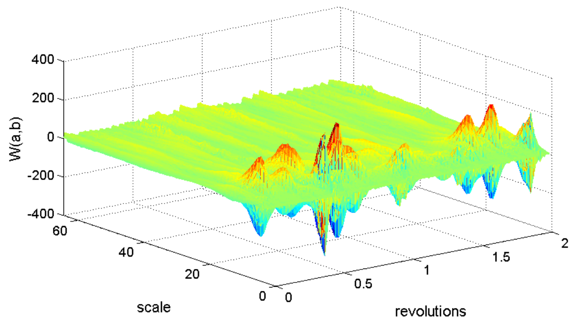


Fig.4. Continuous wavelet decomposition of vibration signal for a) original and b) defected head gasket

Rys.4. Ciągła transformata falkowa sygnału drgań dla a) oryginalnej i b)uszkodzonej uszczelki głowicy silnika

For the engine in good working order (Fig.4a) the vibration related with closing of the inlet valve are dominant. They are performed by the Morlet wavelet, of a scale a=4, which corresponds to a pseudo-frequency 18 kHz. On the other hand, vibrations related to the gasket damage were found after the signal filtering at a scale a=9, which corresponds to a pseudo-frequency of 8125 Hz (Fig.4b). Both frequency ranges are seen in the amplitude spectrum of the signal but it is not known, in which moment of the engine working cycle they occur. Therefore the synchronisation and further analysis of vibration signals are so important.

The synchronous averaging, which is aimed at removal noises from the signal, causes in this case the intensification of resonance vibrations. The averaged waveforms of the engine head vibrations, during one working cycle, for the engine with the original and damaged gasket are shown in Fig.5. Mainly the resonance vibrations related to the engine leakage are seen in the diagram. The signal was filtered by means of the Morlet wavelet, of a scale a=9 (Fig.6). Vibrations caused by the damaged gasket are even more visible. The signal envelope was determined, according to the equation [1]:

$$x_{ENV}(t)=\sqrt{x^{2}(t)+H[x(t)]^{2}} \qquad (4)$$

where $H[x(t)]$ is the Hilbert transform of the vibration signal $x(t)$ defined as:

$$H[x(t)] = x^2(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty} x(\tau)\frac{1}{t-\tau}d\tau \qquad (5)$$

and its time-history as a function of the crank shaft angle of rotation is illustrated in Figure 7.

a)

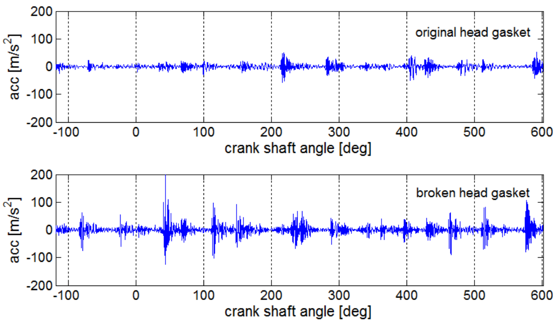
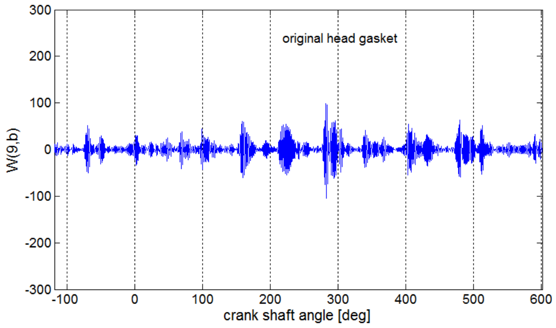


Fig.5. Synchronous averaged head vibration signal for original and defected head gasket

Rys.5. Uśredniony synchronicznie przebieg drgań głowicy silnika dla oryginalnej i uszkodzonej uszczelki głowicy

a)



b)

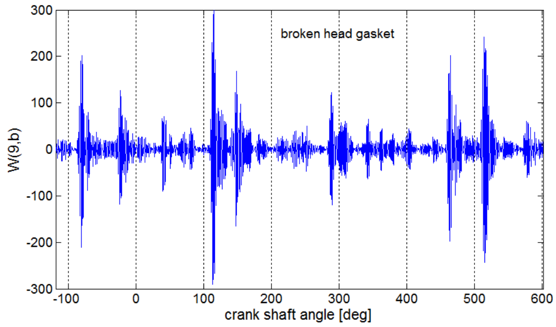


Fig.6. Filtered vibration signal with the Morlet wavelet for scale parameter a=9 for a) original and b) defected head gasket

Rys.6. Sygnał drgań filtrowany przy pomocy falki Morleta dla wsp.skali a=9 dla a) oryginalnej i b) uszkodzonej uszczelki głowicy

The envelope detection allows for the determination of diagnostic measures enabling the damage diagnostics. In order to eliminate the hypothesis of either a valve damage or its improper clearance the signal should be undergoing the further analysis, such as windowing of time history. In this case, all vibration responses to opening and closing of valves should be cut off [4]. Whereas in order to eliminate the hypothesis of a knock combustion the vibration response of the system caused by ignition in the cylinder should be also eliminated from the further analysis.

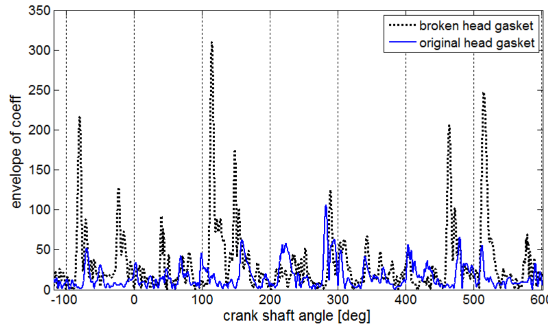


Fig.7. Comparison of the envelopes of the filtered signal for original and defected head gasket

Rys.7. Porównanie obwiednia sygnału przefiltrowanego dla oryginalnej i uszkodzonej uszczelki głowicy

After performing the time selection of the signal envelope the damage symptoms can be determined. The dimensional point parameters are:

a) average value of the signal envelope

$$\bar{x} = \frac{1}{T}\int_0^T x_{ENV}(t)dt \qquad (6)$$

b) RMS value of the signal envelope

$$x_{RMS} = \sqrt{\frac{1}{T}\int_0^T x_{ENV}^2(t)dt} \qquad (7)$$

c) max amplitude

$$x_{MAX} = \max(x_{ENV}) \qquad (8)$$

Non-dimensional point parameters include:

d) peak coefficient

$$C = \frac{x_{max}}{x_{RMS}} \qquad (9)$$

e) clearance coefficient

$$WL = \frac{x_{max}}{\left(\frac{1}{T}\int_0^T \sqrt{x_{ENV}(t)}dt\right)^2} \qquad (10)$$

f) shape coefficient

$$WK = \frac{x_{RMS}}{\bar{x}} \qquad (11)$$

g) impulse coefficient

$$WI = \frac{x_{max}}{\bar{x}} \qquad (12)$$

h) asymmetry coefficient

$$WA = \frac{\frac{1}{T}\int_0^T (x_{ENV}(t) - \overline{x})^3 dt}{\left(\sqrt{\frac{1}{T}\int_0^T (x_{ENV}(t) - \overline{x})^2 dt}\right)^3} \qquad (13)$$

i) kurtosis

$$K = \frac{\frac{1}{T}\int_0^T (x_{ENV}(t) - \overline{x})^4 dt}{\left(\sqrt{\frac{1}{T}\int_0^T (x_{ENV}(t) - \overline{x})^2 dt}\right)^4} \qquad (14)$$

More about the point discriminates can be found in [8].

Tabela 1. Parametry punktowe obliczone dla obwiedni sygnału falkowego przy aspółczynniku skali a=9, dla prędkości obrotowej wału korbowego 3000 obr/min

Table 1. Point parameters calculated for envelope of wavelet at scale a=9, for crank shaft speed 3000 rpm

Name of measure	Original head gasket	Defected head gasket
Average value	16,29	33,32
RMS value	22,29	53,54
Max value	106,12	310,12
Peak coefficient	4,76	5,79
Clearance coefficient	7,85	12,09
Shape coefficient	1,37	1,61
Impulse coefficient	6,51	9,31
Asymmetry coefficient	1,97	3,16
Kurtosis	7,98	15,04

Examinations revealed that several of these parameters, like x_{RMS}, $\overline{x}$, x_{MAX}, K, WA, increased at least twice for the damaged gasket.

4. Conclusions

The presented method of the engine vibrations signal analysis allows to detect the head gasket defects. Examinations were performed for the selected engine. The resonance frequency bands can be different for another engine. Therefore the frequencies singled out for this particular engine can not be considered as binding ones for other objects. Further time-frequency analysis as well as time-synchronizations are aimed at separating the vibration responses generated by various sources. The measures evaluated for wavelet signal envelope allow for two-state diagnosing of the head gasket: *good* or *damaged*. Limitation of this method constitutes the constancy of the engine rotational speed. The point discriminates were calculated for 3000 rpm. The defect symptom is many times larger than changes caused by fluctuations related to the rotational speed, load variability and a road surface unevenness. For another rotational speed the measures are different because of resonant character of vibrations caused by head gasket leakage. The solution of that problem is self-detection of the wavelet scale characteristic for the head gasket damage.

Further research referring to possibility to use the wavelet analysis for on-line head gasket diagnostics will comprise researches on adaptive diagnostic system.

Nomenclature/*Skróty i oznaczenia*

a scale parameter/*współczynnik skali*
acc acceleration of vibrations/*przyspieszenie drgań*
b translation in time/*przesunięcie w czasie*
C peak coefficient/*współczynnik szczytu*
ENV envelope of the signal/*obwiednia sygnału*
H[x(t)] Hilbert transform of the signal x(t)/*transformata Hilberta sygnału x(t)*
K kurtosis/*kurtoza*
RMS root-mean square value/*wartość średniokwadaratowa*
x(t) instanteous value/*wartość chwilowa*
$x_{ENV}(t)$ envelope of the signal/*obwiednia sygnału*
x_{MAX} max value/*wartość maksymalna*
x_{RMS} RMS value/*wartość średniokwadratowa*
$\overline{x}$ average value/*wartość średnia*
T average time/*czas uśredniania*
t time/*czas*
WA asymmetry coefficient/*współczynnik asymetrii*
WI asymmetry coefficient/*współczynnik impulsowości*
WK shape coefficient/*współczynnik kształtu*
WL clearance coefficient/*współczynnik luzu*
W(a,b) wavelet coefficient/*współczynnik falkowy*
β wavelet shape coefficient/*współczynnik kształtu falki*
τ shift in time/*przesunięcie w czasie*
$\psi(t)$ mother wavelet/*falka matka*
$\psi_{a,b}(t)$ daughter wavelet/*falka córka*

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