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Adaptation of Engine Vibration Characteristics for Diagnostics of Mechanical Defects

Abstract: An engine vibration and noise signal being applied for the engine combustion assessment contains also information on: a valve clearance, head gasket damage and wearing out of elements of a vehicle driving system. As the engine mileage increases the wearing out of driving system elements also increases, and in consequence the characteristics of vibration and noise generated by individual sub-assemblies are changing. Diagnosing of defects can be performed on the grounds of the model-based vibroacoustic signal by comparing the measured signal with this model. However, this model should be adapted after each changes of driving system elements and after each engine overhaul. Thus, it should be easily and fast automatically identifiable. The problem of changing vibration characteristics was illustrated on the example of the new Ford Fiesta engine and Fiat Punto engine of a considerable mileage (400 000 km). Time histories and vibration spectra for the engine in a good working condition and for the engine with the damaged exhaust valve were presented. Methods of generating the base model and its identification were proposed.

Key words: *reciprocating engine, vibroacoustic model, exhaust valve, engine vibration spectrum*

Adaptacja charakterystyk drganiowych silnika dla potrzeb diagnozowania uszkodzeń mechanicznych

Streszczenie: Sygnał drgań i hałasu silnika jest wykorzystywany do oceny spalania w silniku ale niesie też informacje o luzie zaworowym, uszkodzeniu uszczelki głowicy i zużyciu elementów zespołu napędowego pojazdu. W miarę wzrostu przebiegu silnika rośnie zużycie elementów układu napędowego, a co za tym idzie, zmieniają się charakterystyki drgań i hałasu generowane przez poszczególne podzespoły. Diagnozowanie uszkodzeń można przeprowadzać na podstawie modelu bazowego sygnału wibroakustycznego przez porównanie sygnału zmierzonego podczas eksploatacji silnika z tym modelem. Jednak model ten powinien ulec adaptacji po każdorazowej wymianie elementów zespołu napędowego i każdym remoncie silnika. Musi więc być łatwo i szybko identyfikowalny, najlepiej w sposób automatyczny. Problem zmiany charakterystyk drganiowych przedstawiono na przykładzie drgań nowego silnika Ford Fiesta i silnika Fiat Punto o znacznym przebiegu (400 tys. km). Przedstawiono przebiegi czasowe i widma drgań dla silnika sprawnego i z wypalonym zaworem wylotowym. Zaproponowano metody generowania modelu bazowego i jego identyfikacji.

Słowa kluczowe: *silnik spalinowy, model wibroakustyczny, zawór wylotowy, widmo drgań silnika*

1. Introduction

There is a group of mechanical defects, which - not only - are not detected by the On-Board Diagnostics (OBD) but also even camouflaged by the engine control system. As an example the pressure decrease in a cylinder, caused by a leakage of valves, rings or a head gasket puncture, can be used. Such defects cause an automatic change of control parameters, but the on-board diagnostic system does not react [1, 3, 8].

The performed investigations revealed that it is possible to define defect symptoms on the basis of the signal of the engine head vibration. It was indicated in papers [2, 3, 8] that for the defective exhaust valve the resonance frequency of the valve impact into its seat is shifted. It should be added, that examinations were performed on the run-in engine but of a short mileage. Whereas during the engine exploitation its vibration characteristics are changing, spectral lines are broadening, new components are adding, etc.

In addition, the diagnostics on the symptom basis is only possible for the individual examined object. More useful and universal is the model-based diagnostics with taking into account the engine lifetime. However, it is not easy to model the engine vibration signal. The measured vibrations are a mixture of periodic waves due to the rotating components and transient waves due to the reciprocating components of the engine and pressure forces. Strong transients come from exhaust and inlet valve operations, fuel injection, combustion, piston slap.

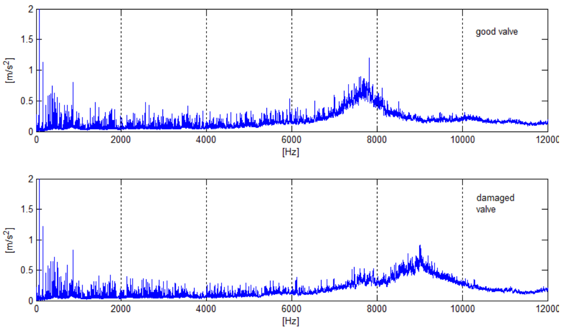
All these causes that the mathematical model of the process is very complicated, non-linear, of many parameters and thereby difficult for identification. Therefore the empirical model of the digitally processed vibration signal was applied in the hereby paper.

2. Investigation method and vibration characteristics

Examinations performed for two spark ignition engines, Ford Fiesta of a mileage of 2000 km and Fiat Punto of a mileage of 400 000 km, were compared. The head engine vibration signal at the 1-st cylinder and the additional synchronising signals such as of the crankshaft position sensor, of the ignition coil, and of the engine load were recorded. Tests were performed during driving the car at the stable speed for various rotational speeds and loads. Frequency of signal sampling in both cases was 25 kHz. Valve defect was constituted by the valve head cut 3 mm long. The accurate description of investigations can be found in [2, 3, 4].

The comparative analysis of two investigated states of the engine valve can be performed in the fastest way by means of the Fourier transform. The averaged spectra of head engine vibrations: Ford and Fiat with valves in a good working condition and defective ones are presented in Fig. 1.

a)



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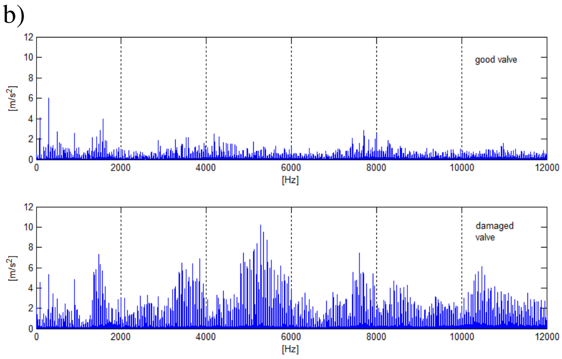
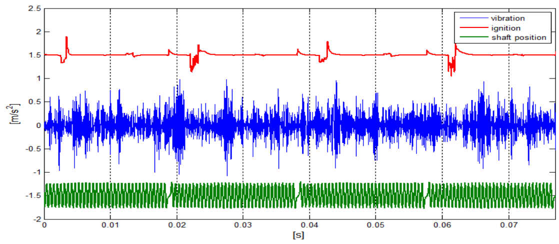


Fig.1. Averaged spectra of head engine vibrations in the horizontal direction at the engine speed of 3000 rpm for the exhaust valve in a good working condition and defective (of the 1-st cylinder):
a) Ford of a mileage of 2000 km
b) Fiat of a mileage of 400 000 km

The characteristics of Ford and Fiat cars presented in Fig.1 are very different. Amplitudes of vibration components depend on the type of engine, its lifetime, as well as on the place of the vibration sensor attachment. When in the new Ford engine the exhaust valve is defective, the resonance frequency shifting in the direction of higher frequencies is clearly seen. For the Fiat engine the resonance frequency is not clearly seen, however when the exhaust valve is damaged amplitudes of broadband vibrations are increasing. Vibration responses on pulse trains caused by the internal combustion engine operation are seen in all spectra. When the engine is highly worn out these responses are intensified by the valve defect.

Since valve damages occur mostly in engines of a long lifetime, a symptom of frequency shifting is either not present or is not much visible. The amplitude increase in the spectrum can have various reasons. Apart from the valve damage, it can mean another leakage in the engine or a knock combustion. Thus, time histories of head engine vibrations should be verified by imposing them on time histories of the synchronizing signals (Fig.2).

a)



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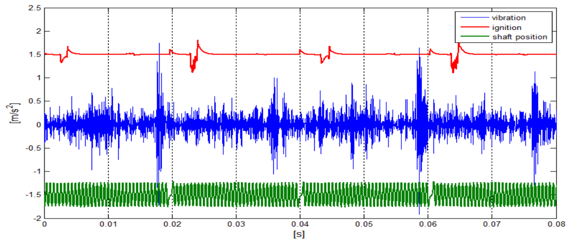

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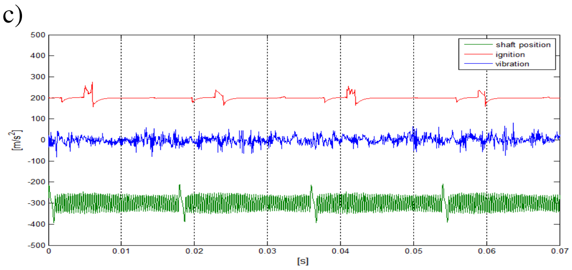

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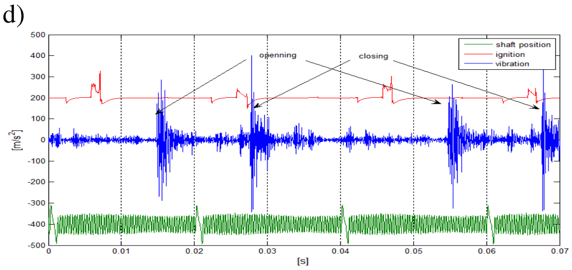


Fig.2. Vibration waveforms of engine head during two working cycles at the engine speed of 3000 rpm
a) Ford - exhaust valve in a good working condition
b) Ford – defective exhaust valve
c) Fiat – exhaust valve in a good working condition
d) Fiat – defective exhaust valve

It is difficult to separate vibrations related to operations of exhaust valves when valves are in a good working condition, whereas they are clearly seen when valves are damaged, both in the Ford and Fiat engine.

3. Adaptation of vibration characteristics and determination the measures

In order to be universal the model should be capable of self-adaptation for various engines being in various worn out states. First of all, the basic model recorded for the new run-in engine must exist. This model should automatically update itself after each engine overhaul or exchange of element. The model must be determined for the selected rotational speed of the engine, since vibration characteristics significantly depend on this parameter.

Base measures of the vibration signal constituting the reference in the diagnostic process are determined on the grounds of this model. The procedure of the engine mechanical defects diagnostics on the grounds of the adaptive model of the head engine basic vibration signal is presented in Fig.3.

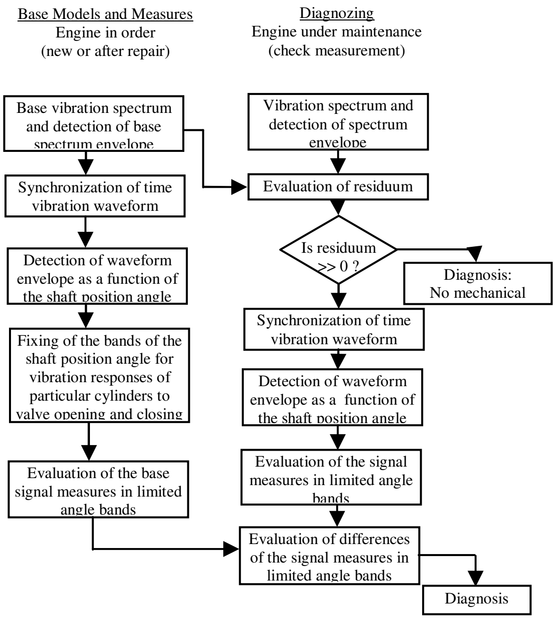


Fig.3. Diagnostic procedure of the selected engine mechanical defects on the grounds of the vibration signal base model

During the car drive at a constant speed the signals of head engine vibrations and synchronising signals are recorded. The vibration signal undergoes preprocessing, which means that it is high-pass filtered and processed from the time domain into the crankshaft rotation angle domain. The amplitude spectrum is determined, which envelope constitutes the reference for the control measurements during the further engine maintenance. The time signal is synchronised, and its envelope is also the base for the control measurements.

The diagnostic system storage retains the spectrum and time-history envelopes, which mathematical descriptions constitutes the base models. The ways of engine vibration signal modelling are given in [5-7]. On the grounds of base models the characteristic base measures needed for the defects diagnostics are determined.

On the grounds of engine data the angle-time ranges of vibration response for impulse force (from: opening and closing of valves, ignition, closing of injectors) can be determined. The response starts at the determined angle of rotation of the crankshaft and ends after the determined time (this means that for different rotational speeds it ends within another angle range).

For ranges, in which the vibration response occurs correspondingly for the opening and closing of exhaust valve the averaged square values are calculated according to the equation:

$$x_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i} \qquad (1)$$

where:

x_i - amplitude of the i-th sample of the vibration signal envelope in the determined range of the vibration response,

N – number of samples in the determined range of the vibration response.

The diagnostics idea is based on comparing the vibration signal - measured in the determined time intervals (e.g. monthly) or for the determined mileage – with the base model.

4. Method verification

The procedure methodology can be illustrated on the basis of the exhaust valve defect of the Fiat engine. The averaged spectrum of vibrations of the engine head with the defective valve was compared to the base spectrum of the engine in a good working condition (Fig.4).

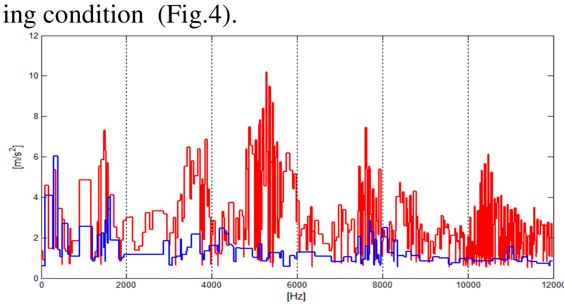


Fig.4. Comparison of the envelopes of the averaged spectra of the engine head vibration acceleration for the valve in a good working condition (blue) and for the defective one (red).

However, on the grounds of the difference between the current spectrum envelope and the base envelope one can only state that the difference is a large one, broad-band and that the further vibration signal analysis as a function of the crankshaft angle of rotation should be performed.

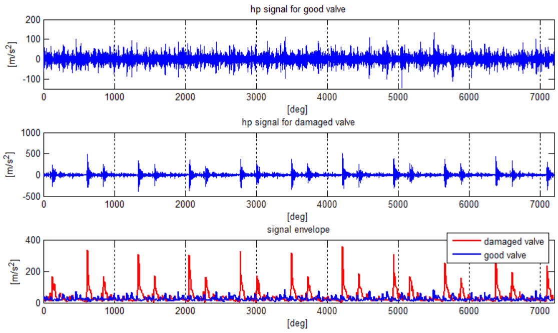


Fig.5. Time histories of head engine vibration: base and with a defective valve, and the comparison of their envelopes in 10 operating cycles of engine

Time histories of instantaneous vibration during 10 cycles of engine operations for the engine in a good working condition and for the engine with the defective exhaust valve are shown in Fig.5. Envelopes of both time histories are compared in the lower figure. It can be stated that they significantly differ on the maximum amplitude and that the signal is cyclostationary. The next step is synchronous averaging of the signal envelope (Fig.6). The envelope averaging is the more justified operation than the signal averaging since in this case even the smallest time shifting of the instantaneous signal can cause an error.

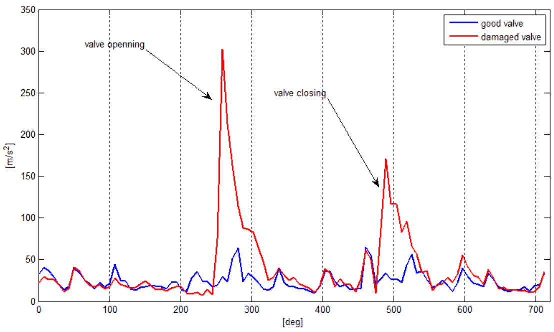


Fig.6. Synchronously averaged signal of the vibration envelope for the base state and for the engine with the defective exhaust valve

The determined time intervals, during which the vibration responses on impulse forces such as opening and closing of the exhaust valve occur for individual cylinders, are presented in Fig.7.

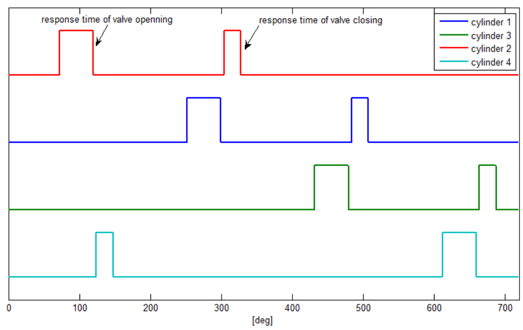
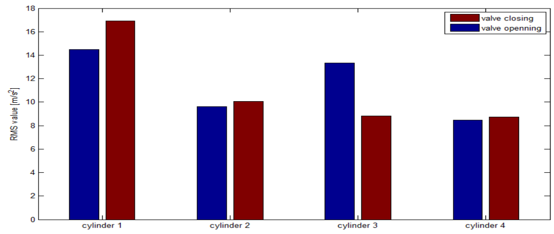


Fig.7. Sequences of time windows determining limits for vibration responses on opening and closing of the exhaust valve of individual cylinders

Basing on Eq. (1) the RMS vibration measures characteristic for the valve opening and closing, both base measures and the control ones for the engine with the defective exhaust valve were calculated (Fig.8).

a)



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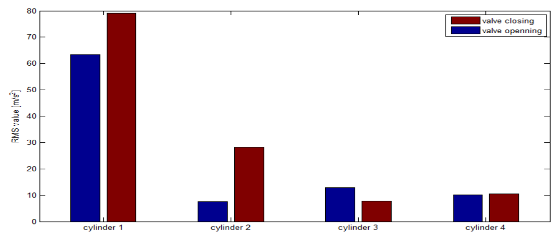

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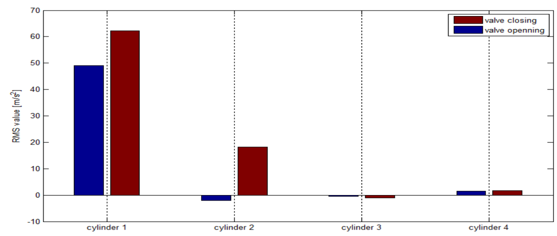

Fig.8. Measures of the engine vibration response on opening and closing of exhaust valve:
a) Base measures
b) Measures for the engine with the defective exhaust valve at the 1st cylinder,
c) Difference (a-b)

Since vibrations are measured at the 1-st cylinder, the base measures for this cylinder are larger than for the remaining ones (which are at a similar level). However, for the defective valve vibration measures are increasing more than 4 times. The measure for closing the valve of the 2-nd cylinder is also increasing because the time window of closing the exhaust valve of the 2-nd cylinder overlaps the prolonged vibration response for opening the exhaust valve of the 1-st cylinder. Such situation occurs in case of the defect. This information should be taken into consideration at performing diagnostics.

5. Conclusions

The presented method of diagnosing the selected mechanical defects of the internal combustion engine based on the vibration signal model can be applied for diagnostics of e.g. valve defect, not proper valve clearance, head gasket defect, etc. This method was verified by the example of the exhaust valve - of the high mileage engine - defect. The selected vibration measure in the case of the defect increased 4 times. This increase would be even higher in case of utilizing the resonance frequency of the vibration sensor [4]. The presented hereby method with some modifications can be applied for on-board diagnostics and constitute the supplementation of the existing OBD systems.

Nomenclature/*Skróty i oznaczenia*

OBD On-Board Diagnostics/*diagnostyka pokładowa*

RMS Root-mean square value/*wartość średniokwadratowa*

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