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Adaptive model of engine vibration signal for diagnostics of mechanical defects

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1. Introduction

The purpose of modelling the engine should be clearly stated. This work is dedicated to the development of the diagnostic model, which will enable one to find out the selected mechanical defects of the engine. These defects generate changes in the vibroacoustic signal characteristics. Leakage in the system engine valve – cylinder caused either by a valve defect (e.g. by an exhaust valve burnout) or by improper valve clearance are especially essential due to the frequency of their occurrence in the drive systems. Another type of leakage is caused by the defect of the engine head gasket. The adaptive system of controlling the internal combustion (IC) engine will try to manage such situations - in engines with spark ignition - by taking in an additional air-fuel mixture. In Diesel engines, a pressure decrease in cylinders will be compensated by additional operations of a turbo-compressor [1]. The on-board diagnostics (OBD) system in a majority of cases does not consider this defect as a fault since it is masked by the engine control system [2, 3].

The process of generating vibrations and noises in IC engine is very complicated. The observed vibrations are compositions of periodic waves related to operations of rotating elements and impulse responses corresponding to a piston plane-rotary motion as well as responses to gas pressures. Strong transient states in the vibroacoustic signal originate from operations of inlet and exhaust valves, injectors, combustion processes, piston strokes on cylinder sleeves, etc. Several publications concern investigations of vibroacoustic signals of IC engines [4-7].

Investigations carried out on spark ignition 4-cylinder engines: Fiat Punto, Renault K7J and Ford Fiesta indicate that a part of vibration responses is of a random character and has a broad amplitude spectrum, while other responses are distinctly resonant. These first ones are characteristic for responses for the exhaust valve closing, where vibrations from cycle to cycle of the engine operation are not repeatable. In the second type a narrow frequency range is dominating e.g. in responses for the inlet valve closing. Defects of valves and a head gasket are causing entering into the resonance zone and the natural intensification of vibrations [8]. Regardless of the response character (damping random vibrations or damping resonant vibrations) the time-frequency analysis [9], especially the wavelet analysis, provides good results.

During the modelling process of the engine the problem of selecting the abstraction (complexity) degree of the model occurs. Of course, it is possible to design one global model and expanding it, but in such case the complication degree will not allow to use it for the on-line (on-board) diagnostics.

Instead of the structural model, which is too complicated, the model of vibroacoustic signal propagation on a very high abstraction level is proposed in the presented study. The necessary condition of proper model operation is then its accurate formal identification. This model is created in an adaptive way, which means accelerated model identification and adjusting the model to the given type of drive system and its working time.

Designing this model requires performing a series of measurements in the selected points of the drive system as well as other additional synchronising signals during normal vehicle maintenance, that is, during driving at a steady speed and without abrupt load changes. The base model takes into account the influence of the responses of all elements of the drive system.

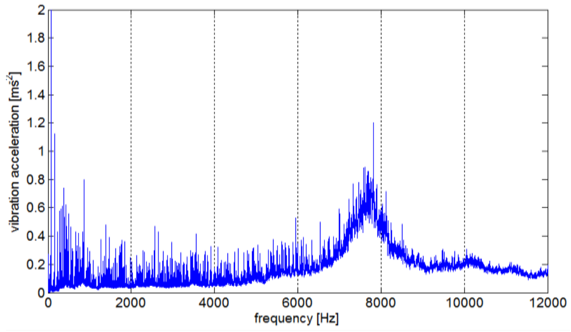
2. The concept of the signal base model

During the life time of the engine its vibration characteristics are changing, spectrum becomes smeared, new components are added, etc. The scale of differences is clearly seen when analysing vibration spectra of engines: Ford of a mileage of 2000 km, Renault of a mileage of 30 000 km and Fiat of 400 000 km with efficient drive systems (Fig. 1).

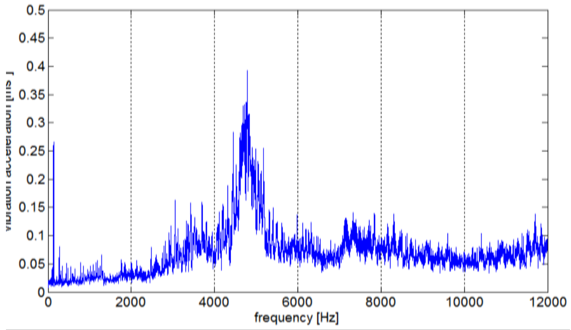
The spectrum characteristics of acceleration of the vibrations of automobiles presented in Fig. 1 are very different. Amplitudes of vibration components depend on the engine brand, its life time as well as on the place of fixing the vibration sensor. For the new Ford and for Renault engines the frequency of resonance vibrations is clearly seen. For the Fiat engine vibrations are characterized by a broad resonance zone and are overlapping on components generated by different kinds of clearances caused by wearing out, etc.

Time waveforms of the vibration signal differ also with each other (especially their amplitudes) since sequences of vibration impulse responses caused by valves operations, ignition etc. are analogous. Transient processes, being responses for valves closing, are dominating in the vibration signal recorded during the work cycle (Fig. 2).

Therefore the grounds for diagnostics of engine defects is the time waveform of the vibration accelerations signal. For the identification of time events the technical data concerning the engine – in this case: angles of valves opening and closing (at constant valve timing) - are needed. Synchronising signals, which can be the signals controlling injection, ignition etc. from the injection-ignition controller or voltage signals from the ignition coil of the injector as well as the basic synchronising signal from the sensor of the crankshaft location or valve timing are also necessary.



a



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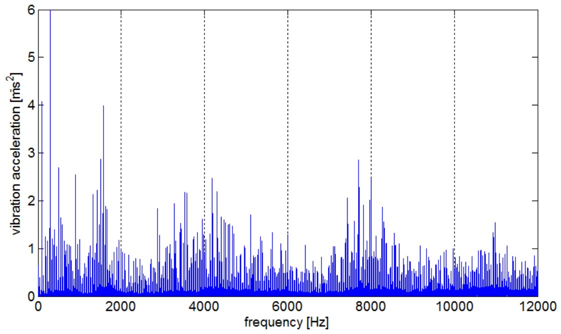

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Fig. 1 Average spectrum of acceleration of the engine head vibrations, in the horizontal direction at the engine rotational speed of 3000 rpm for the efficient drive system: a) Ford of a mileage of 2000 km, b) Renault of a mileage of 30 000 km, c) Fiat of a mileage of 400 000 km

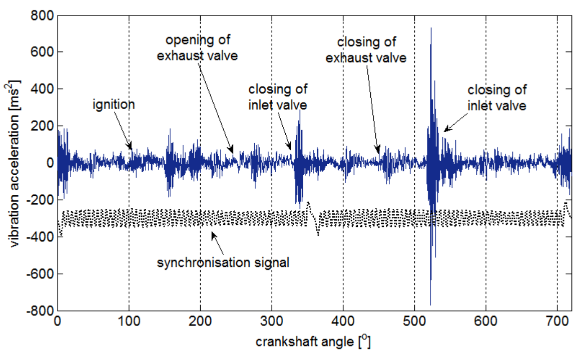

Fig. 2 Signal of the acceleration of engine vibrations in one work cycle, together with the synchronising signal

The procedure of processing the engine vibrations signal and diagnostics its defects on the grounds of the base model is as follows [3], [10]. The signals of the engine head vibrations and the synchronising signal are recorded during driving the automobile at a constant speed. The vibration signal is pre-processed, it means it is high-pass filtered, synchronized and converted from the time domain into the crankshaft angle domain. The amplitude spectrum is determined, and its envelope constitutes the reference for the control measurements during the further engine maintenance.

The spectrum envelopes and time waveforms as well as mathematical models of the processed signal – constituting the base models – are retained in the diagnostics system memory. On the grounds of the base models the basic measures characteristic for the needs of the defects diagnostics are determined.

The data concerning the engine allow to determine the angle-time ranged of the vibration response to impulse forces (generated by opening and closing of valves, by ignitions or by injections). The response starts at the determined crankshaft angle and ends after the determined time (which means that for various rotational speeds it lasts during the different angle intervals). For intervals, in which the vibration responses occur, root-mean square values are calculated.

The idea of diagnostics relies on comparing the vibration signal recorded in the determined time or distance intervals with the base model.

To be the universal model it has to be able to adapt itself for various drive systems being in various states of wear. First of all, the base models remembered for the new system must exist. Such model should automatically update itself after each repair or change of parts. Finally it must be determined for the selected engine rotational speeds since the vibration characteristic are strongly dependent on this parameter.

In described method the most important is good identification of the base model. It can be done using for example parametric identification [11] or wavelet reconstruction [10], [12].

The wavelet transform enables the linear signal decomposition by means of the arbitrary base function characterised by the finished and short interval in which assumes non-zero values. If $\psi(t)$ is the mother wavelet then the daughter wavelet has a form [13]

$$\psi_{a,b}(t) = \frac{\psi(t-b)}{a} \tag{1}$$

where a is a scale coefficient and b is a shifting.

By changing parameters a and b the wavelet family can be formed.

The continuous wavelet transform is easy for interpretation, however in practical applications it is better to use the discrete wavelet transform. As the result of the quantization of parameters a and b, the following equation equivalent is obtained

$$\psi_{mn}(t) = 2^{-m/2}\psi\left(2^{-m}\left(t - 2^{m} n\right)\right) \tag{2}$$

where m is a discrete scale coefficient and n discrete shifting.

The inverse discrete wavelet transform allows for the signal reconstruction and is described by equation [14]:

$$f(t) = \sum_{m,n} \left(f, \psi_{m,n} \right) \psi_{m,n} = \sum_{m} \sum_{n} d_m[n] \psi_{m,n} \qquad (3)$$

where $d_m[n] = \left(f, \psi_{m,n} \right)$ denotes wavelet coefficients and $\psi_{m,n}$ wavelets of the frequency scale coefficients m and displacement in time n.

On the grounds of wavelet coefficients as a scale coefficient and displacement in time (or a shaft rotation angle) function the signal reconstruction can be performed. Thus, the model identification can be reduced to the detection of coefficients $d_m[n]$.

Since in case of random signals can be many wavelet coefficients, their compression can be performed taking into account only the most energetic.

The example of identification of the base model for the engine vibration response signal on closing the exhaust valve is shown in Fig. 3.

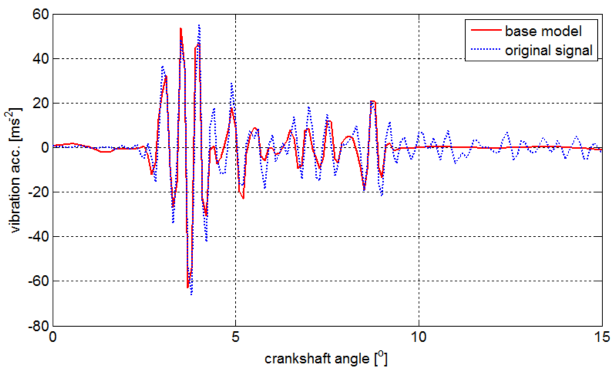

Fig. 3 Model identification using wavelet reconstruction of the engine vibration response signal on closing the exhaust valve

3. Verification of the diagnostic method

The methodology of proceedings can be presented on the basis of the exhaust valve defect in the Fiat engine (Fig. 4).

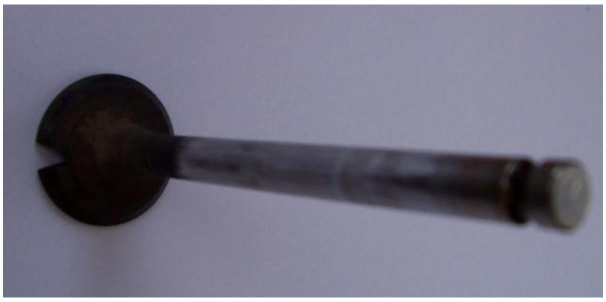

Fig. 4 Defective exhaust valve

The envelope of the averaged spectrum of the vibrations of the head engine with the defective valve was compared with the base spectrum of the engine in good technical condition (Fig. 5).

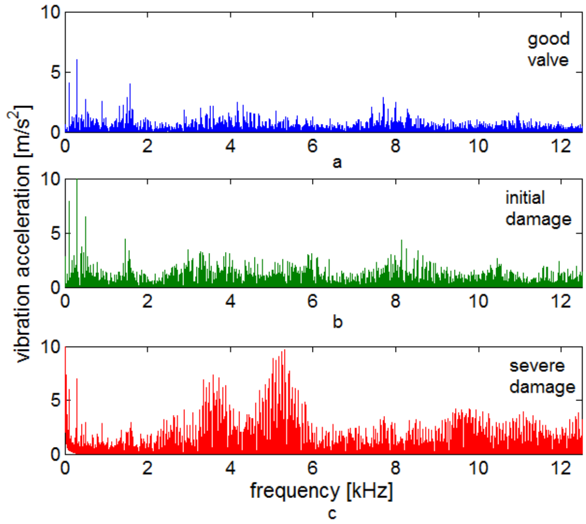

Fig. 5 Comparison of averaged spectra of the head engine vibrations acceleration for the good valve a), for initial defect of the exhaust valve b) and for the damaged valve c)

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, broadband and that the further vibration signal analysis as a function of the crankshaft angle of rotation should be performed.

Based on the difference between the envelopes of the current spectrum and the basic one, it can be only stated that it is a large, broad-band and that the further analysis of the vibration signal as a function of the crankshaft angle should be carried out.

Instantaneous vibration waveforms during 10 work cycles of the engine in good technical condition and with the defective exhaust valve are shown in Fig. 6.

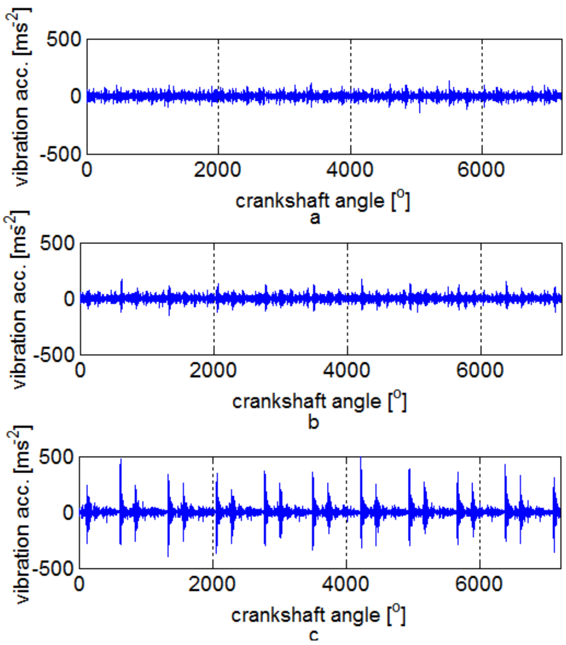

Fig. 6 Time histories of head engine vibration: a) base model for a good valve, b) with initial defect of a valve and c) with a defective valve, in 10 operating cycles of engine

Since the sequence of events is very important in analysing the engine vibration signal, the time waveform should be subjected to the time windowing (time selection process). Fig. 7 presents the concept of the signal time windowing procedure. Limits of the time window must be precisely determined for each cylinder and each event (opening and closing of valves and injectors, ignition, etc.).

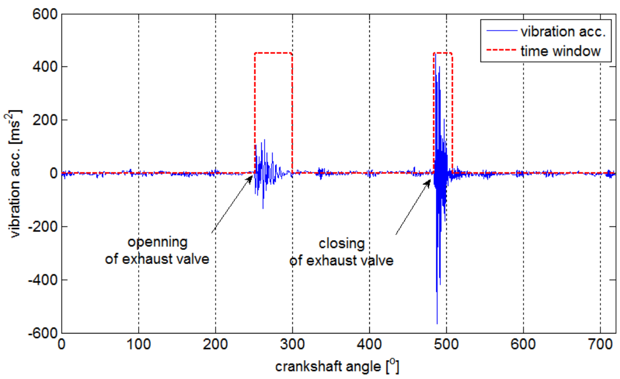

Fig. 7 Time windowing of the signal of the vibration acceleration based on the example of the time waveform for the defective exhaust valve

The envelopes of the waveforms are estimated [15]. There are a few conceptual ideas on the function envelope determination. One of them is based on the analytical signal described by the following function [16]

$$x_A(t) = x(t) + j\hat{x}(t) \tag{4}$$

where $x(t)$ is the Hilbert transform of the vibration signal $x(t)$ defined as

$$\hat{x}(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty} x(\tau)\frac{1}{t-\tau}d\tau \tag{5}$$

where τ denotes the time delay.

Then the signal envelope $x_{env}(t)$ is calculated according to the following equation

$$x_{env}(t) = \sqrt{x^2(t) + \hat{x}^2(t)} \tag{6}$$

It can be stated that they significantly differ in the maximum amplitudes and that the signal is the cyclostationary one. The next step is synchronous averaging of signal envelopes (Fig. 8).

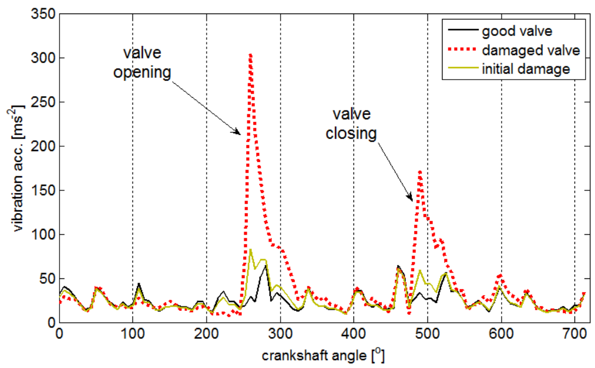

Fig. 8 Synchronously averaged the vibration envelope signals: the base one, for the engine with initial defect of exhaust valve and with the damaged valve

In this case the averaging of envelopes is more justified than averaging of the signal since each, even the smallest, time shifting of the instantaneous signal can cause an error. On the basis of the signal of the signal envelope the cycle measures separately for opening and for closing of the exhaust valve were calculated.

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

a) average value of the discrete signal envelope x_{ENV}

$$\bar{x} = \frac{1}{N}\sum_n x_{ENV}(n) \tag{7}$$

where N is the number of samples;

b) RMS value of the discrete signal envelope x_{ENV}

$$x_{RMS} = \sqrt{\frac{1}{N}\sum_n x_{ENV}^2(n)} \tag{8}$$

c) max amplitude

$$x_{MAX} = max(x_{ENV}) \tag{9}$$

The indicators are calculated for the vibration signal envelope of opening and closing of the exhaust valve and placed in the Table 1.

Table 1

Point parameters calculated for envelope of the base model and defective valve

Name of indicator	Valve opening Base model/ Initial defect/ Heavy defect	Valve closing Base model/ Initial defect/ Heavy defect
Average value, ms^{-2}	27.7 / 35.2 / 100.0	26.1 / 33.7 / 97.6
RMS value, ms^{-2}	31.1 / 42.5 / 127.8	26.5 / 38.8 / 108.9
Max value, ms^{-2}	64.2 / 82.8 / 302.7	34.0 / 59.6 / 170.4

4. Conclusion

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 damage increased four times. But the initial defect of the valve can be undetected because of engine noise and signal averaging. The model is adaptive, which means that the diagnostic program obtains the base model after each change of the drive system element. Later on, the program compares the recorded and properly processed signal with this model. The envelope signal must be examined in the time ranges characteristic for the successive vibration responses of the engine for the operations of valves, ignitions, injections etc.

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I. Komorska

VARIKLIO VIBRACIJŲ SIGNALŲ ADAPTYVUSIS MODELIS MECHANINIAMS DEFEKTAMS DIAGNOZUOTI

R e z i u m ė

Variklio vibracijų ir triukšmo signalų analizė, pritaikyta variklio darbui įvertinti, taip pat suteikia informacijos apie vožtuvų tarpelius, galvutės tarpiklio pažeidimus ir variklio judamųjų dalių išsidėvėjimą. Kai variklio rida didėja, didėja ir judamųjų elementų išsidėvėjimas, o dėl to kinta vibracijų ir triukšmo lygis. Defektų diagnostika gali būti atliekama palyginant su modelio vibroakustiniais signalais. Tačiau modelis turi būti adaptuojamas po kiekvieno judamųjų elementų pokyčio ir po kiekvieno variklio kapitalinio remonto. Dėl to tai turi būti lengvai ir automatiškai identifikuojama. Pasiūlyti bazinio modelio sudarymo ir jo identifikavimo metodai. Modeliavimu pagrįstas pasiūlytasis diagnostikos metodas darbe buvo panaudotas variklio išmetimo vožtuvo diagnostikai.

I. Komorska

ADAPTIVE MODEL OF ENGINE VIBRATION SIGNAL FOR DIAGNOSTICS OF MECHANICAL DEFECTS

S u m m a r y

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 drive 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 subassemblies 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. Methods of generating the base model and its identification were proposed. The model based diagnostic method was verified – in the paper - on the example of the engine exhaust valve defect.

Keywords: defective exhaust valve, diagnostic model, engine vibrations, model identification.

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