UTILISING THE RESONANCE FREQUENCY OF THE ENGINE VIBRATION SENSOR IN DIAGNOSTICS OF THE EXHAUST VALVE LEAKAGE

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Abstract

A vibroacoustic signal of an internal combustion engine contains several diagnostic information, which are - for the most part - not utilised since they require complex processing methods in order to separate useful data and to eliminate disturbances. The way of analysis of such complex signal depends on the diagnostic aim. It is a rich source of information not only concerning the combustion process, but also various mechanical defects occurring in the driving system (valves, clutch, gearbox). Wear of elements as well as small mechanical defects cause the adaptation of the control system to new parameters. Thus, in many cases these adaptive systems can be masking mechanical defects. Burning out of exhaust valves or an improper valve clearance are examples of such defects. The method of diagnostics of leakages in a system: exhaust valve – cylinder, on the basis of measuring the vibration signal of the engine head is proposed in the paper. The results of the analysis of the engine vibration signal under conditions of a defected exhaust valve and an increased valve clearance are presented. The active diagnostic experiment was performed on the engine of Fiat Punto 1.2. During road tests the vibrations acceleration signal was recorded as well as certain auxiliary signals used for a synchronisation and identification of engine timing. The natural acceleration of vibrations in the resonance frequency range of the piezoelectric sensor was utilized. The vibration signal was pre-processed i.e. filtered, synchronously averaged and windowed. Satisfying diagnostic results of the valve defect or the improper valve clearance were obtained on the basis of the analysis of the engine vibration acceleration signal envelope. The signal measures explicitly indicating the valve condition were determined. The method, after certain modifications, can be applied for the on-line valve diagnostics.

Keywords: *combustion engine, valve defect, engine vibration, vibroacoustic model*

1. Introduction

A vibration engine signal is a result of superposition of periodical components related to rotations of a crankshaft, gearbox operation etc. as well as damped vibrations being impulse responses to such operations as: valve opening and closing, ignition, piston stroke etc., occurring in a relevant succession and in an appropriate time sequence. Attempts to model this signal are described in [7, 8]. It contains several diagnostic information, for the most part not used, since it requires the complex processing in order to separate useful components and to eliminate interferences. Whereas a continuous development of signal processing methods, and availability of microcontrollers and signal processors enable an accurate signal analysis and separation of frequency components, in real time. However, only the formation of multi symptom system utilising additional information from the OBD system sensors has a chance to use the vibroacoustic signal fully.

A wear of elements and small mechanical defects cause the system adaptation to new parameters. Thus, in many cases the adaptive systems of engine controlling can be masking mechanical defects [3]. Examples of such defects are burning-out of exhaust valves or a not proper valve clearance.

Investigations aimed at utilising vibration signals for diagnostics of exhaust valves leakage are undertaken in the country. The monograph [10] presents broadly such investigation results.

Diagnostics methods of this defect by means of spectrum and wavelet analysis are presented in works of the Silesian University of Technology [9, 11]. The work of the Warsaw University of Technology uses Rice's frequency in valve diagnostics [4].

The method based on the analysis of the time signal envelope of engine vibrations is presented in the hereby paper. A natural amplification of vibrations in the range of the resonance frequency of the piezoelectric sensor was utilised (app. 55 kHz). An analogical method is also used for the detection of knock combustions [5].

2. Description of examinations

Examinations were performed during road tests on the four-cylinder engine of spark ignition of Fiat Punto 1.4 of 400 000 km. mileage. Series of engine vibration measurements for various rotational speeds and loads were performed.

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 +250oC, fastened by means of 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 from the engine vibrations 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 working cycles, injection moments, ignition and timing of gear phases.

Signals of 1-minute duration were recorded during driving with a constant speed. 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. A load influence is not so important [6].

The signal of the acceleration of engine block vibrations for the single working cycle with the marked moments of ignition, opening and closing of the exhaust valve is presented in Fig. 1, as an example.

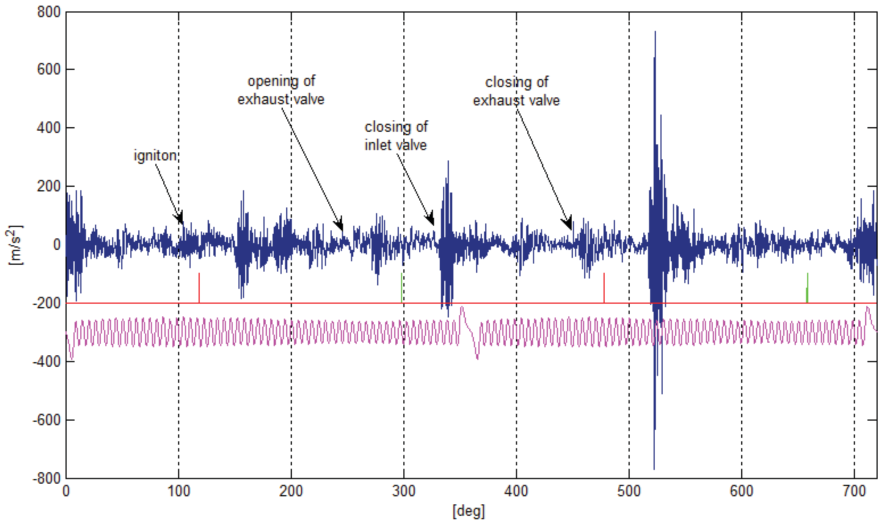


Fig. 1. Signal of vibration acceleration during one cycle of engine operation with timing for 1. cylinder

Examinations were performed for various conditions of the exhaust valve:

- Valve in a good working order, optimal clearance (0.25 mm),
- Valve in a good working order, increased clearance +0.06 mm,
- Valve out of order I (small defect), optimal clearance,

- Valve out of order II (large defect), optimal clearance,
- Valve out of order, increased clearance.

Valve defect I constituted the valve head cut 3 mm long (Fig. 2), while defect II had this cut increased to 6 mm.

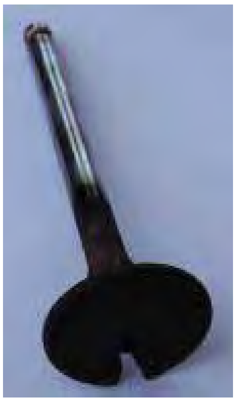


Fig. 2. Exhaust valve out of order

Instantaneous time progresses of the acceleration of vibrations for the increased valve clearance and defected exhaust valve, with the marked moments of opening and closing of the exhaust valve, are presented in Fig. 3 as an example.

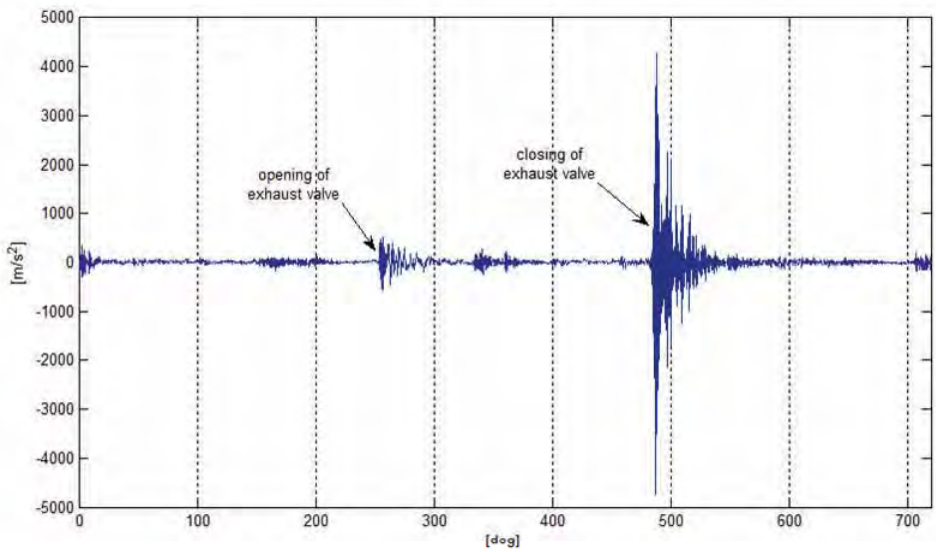


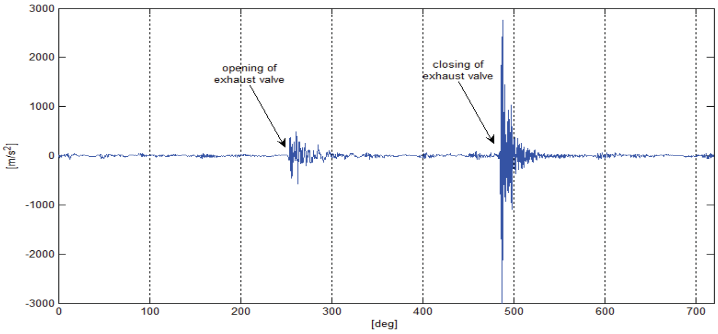
Fig. 3. Instantaneous time progress of the acceleration of engine vibrations in the horizontal direction – for one cycle of engine operation and 3000 rpm

It was observed, in all mentioned types of leakage in the system: exhaust valve – cylinder, that in the time progress of vibration the signal responses for the valve opening and closing are dominating.

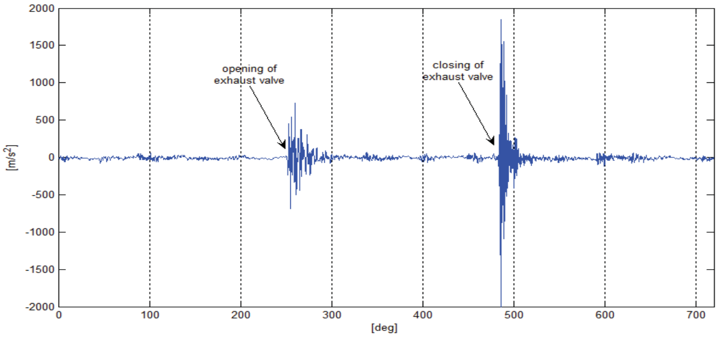
3. Analysis of the obtained results

The vibration signal was resampled in order to equalise the number of samples analysed in each cycle of engine operations. This procedure enabled changing the domain from the time into the angle of rotation of the crankshaft, during the analysis. This, in turn, allowed performing the synchronous averaging of the vibration signal. The synchronously averaged signal of 30 engine operation cycles for various types of the exhaust leakage is presented in Fig. 3.

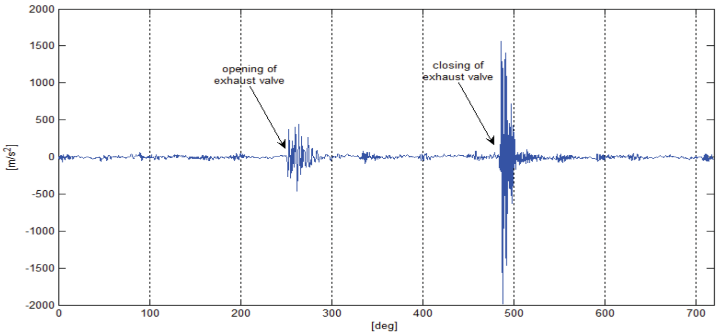
a)



b)



c)



d)

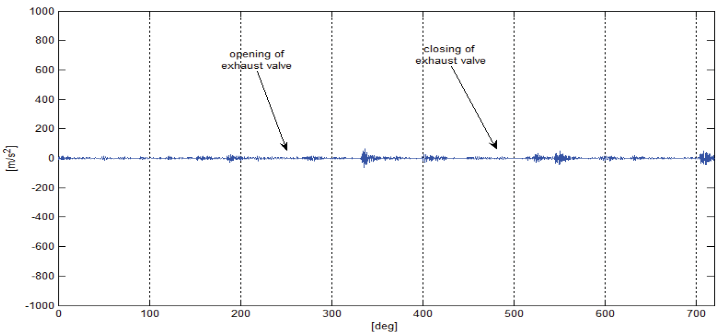


Fig. 4. Synchronously averaged signal value of the acceleration of engine vibrations in the horizontal direction, 3000 rpm for the following conditions: a) increased valve clearance, b) valve defect I, c) valve defect II, d) valve in a good working order, optimal clearance

The result of this operation confirms repeatability of the process of the vibration response to the valve opening and closing as well as eliminates the possibility of occurrence of a random error of diagnostics. In the moment of the valve opening and closing the components of vibrations of frequencies super positioning on the sensor natural frequency are generated, which causes natural amplification of the measuring element vibrations. This explains the impossibility of differentiating the wear degree of valve defect. The simultaneous clearance increase and the valve defect do not cause noticeable signal changes.

The next step in the analysis constituted windowing of the vibration signal, which means leaving only the vibration response related to the operations of the exhaust valve of cylinder No. 1. The final signal, being the result of multiplication of the window function by the acceleration signal was processed into its envelope a_{env} in accordance with [1]:

$$a_{env}(t) = \sqrt{x^2(t) + \hat{x}^2(t)}, \tag{1}$$

where $\hat{x}(t)$ is the Hilbert transform of the vibration signal $x(t)$ defined as:

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

The idea of signal windowing is presented in Fig. 5, while envelopes of signals for the investigated cases of leakage are compared in Fig. 6.

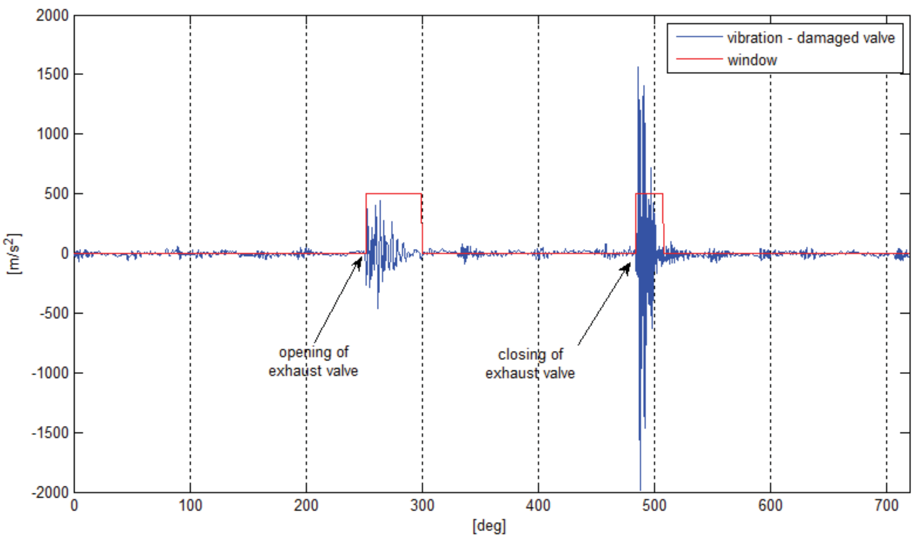


Fig. 5. Vibration signal windowing on the example of the time history for the defected exhaust valve

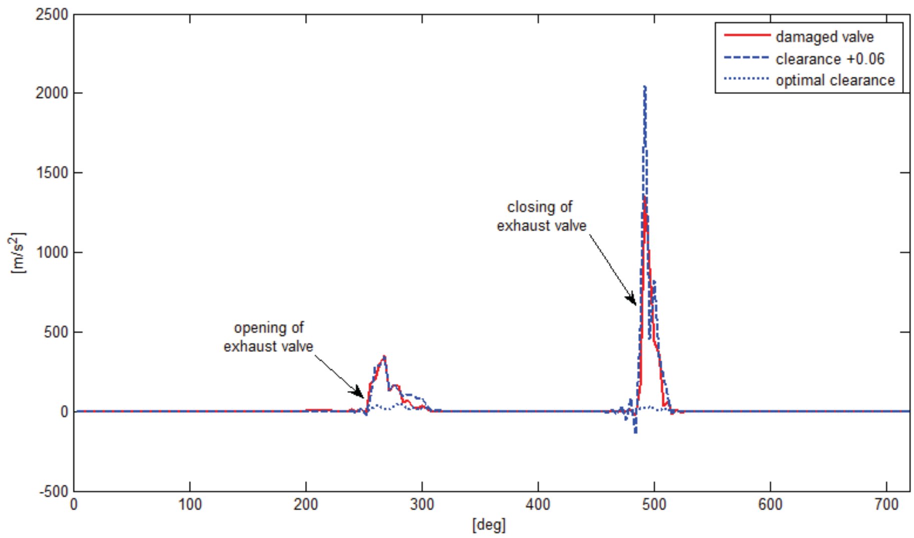


Fig. 6. Envelope of the synchronically averaged windowed signal

On the basis of the signal of the signal envelope a_{env} the cycle measures separately for opening and for closing of the exhaust valve were calculated.

$$a_{op} = \frac{1}{T_{op}} \int_{t_1}^{t_2} a_{env}(t)dt,$$
$$a_{cl} = \frac{1}{T_{cl}} \int_{t_3}^{t_4} a_{env}(t)dt, \tag{3}$$

where:

a_{op}, a_{cl} - cycle measured for the exhaust valve opening and closing – respectively,

T_{op}, T_{cl} - duration time of the vibration response for the valve opening and closing - respectively,

t_1, t_3 - moments of the valve opening and closing determined by the signal from the crankshaft position sensor - respectively,

t_2, t_4 - moments of extinguishing of vibration responses for the valve opening and closing (established at the assumption of resonance vibrations) – respectively.

The inlet valve opening for the examined engine occurs at 43° before BDC (Bottom Dead Centre), while closing starts at 5o after TDC (Top Dead Centre). These moments can be precisely determined on the basis of the signal from the crankshaft sensor during the off-line analysis. At the on-line analysis the accuracy is slightly worse and depends on the complexity of the algorithm of the crankshaft rotation angle determination.

The results of the measure calculations (3) are listed in Fig. 7.

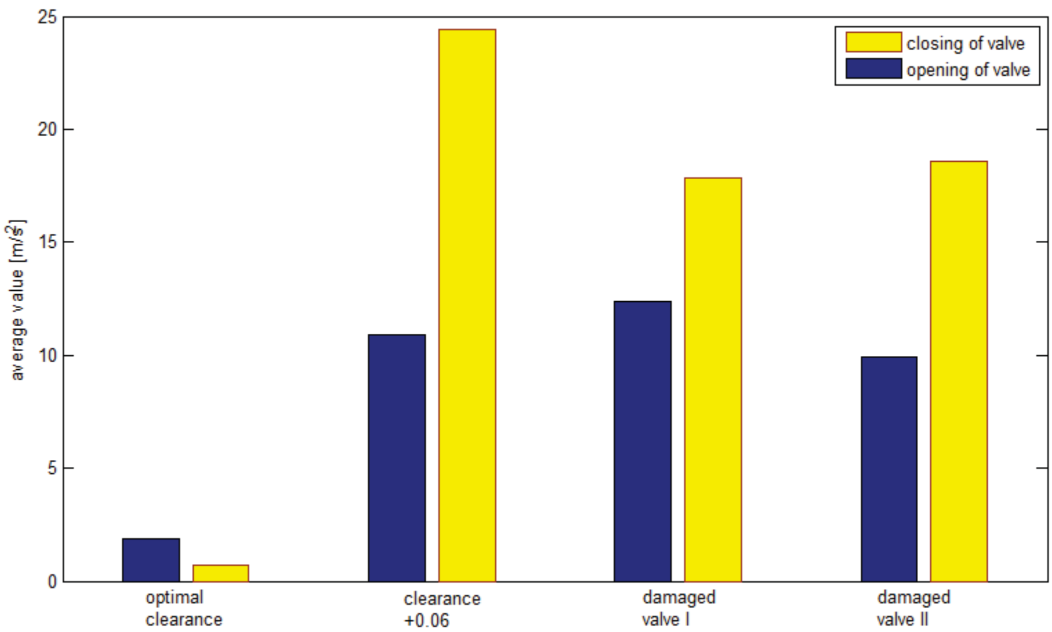


Fig. 7. Average value calculated on the basis of the signal envelope of acceleration vibrations in the horizontal direction for engine speed 3000 rpm

It results from the calculations that the defect of the exhaust valve, e.g. its burn-out or too large clearance cause the following increases of the measure defined by equations (3):

- more than 5 times increase for the valve opening,
- more than 20 times increase for the valve closing.

Due to an occurrence of the resonance the valve defect severity has no influence on the measure.

Diagnostics can be realised in the real time. Thus, in systems with stable phases of the timing gear the processor calculates moments of the exhaust valve opening and closing on the basis of the signal from the sensor of the crankshaft position (inductive, Hall-unit, optical or other). However, in engines with variable phases of the timing gear the processor obtains signal of the valve opening and closing from the engine controller or from the separate controller of gear phases.

The condition of performing the synchronous averaging, during the on-line analysis, is mounting – on the crankshaft – the transmitter of angle of rotation generating at least 1800 impulses for a rotation.

4. Conclusions

The diagnostic method of the leakage between the exhaust valve and cylinder, on the basis of measuring the signal of the engine head vibration, was proposed in the paper. The satisfactory results were obtained for the tested engine. The method is non-invasive. The recorded signal undergoes not very sophisticated analysis of filtering, windowing and averaging.

The synchronous averaging eliminates random diagnostic errors. The method is based on the analysis of the vibration response envelopes for the valve opening and closing. Since the leakage causes generating of high frequency vibrations, the sensor natural frequency was used to amplify the vibration response of the engine. However, this method does not allow differentiating the defect degree, it only states: in a good working order - out of order.

Diagnostics can be performed on-board. The limitation constitutes the engine angular velocity, which should be relatively constant due to the dependence of the vibration signal amplitude on this velocity.

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