VIBRATION BASED DIAGNOSIS OF INTERNAL COMBUSTION ENGINE VALVE FAULTS

Bogusław ŁAZARZ, Henryk MADEJ, Grzegorz PERUŃ, Zbigniew STANIK

Faculty of Transport, Silesian University of Technology
40-019 Katowice, ul. Krasińskiego 8, fax (+48) 32 603 41 08, email: boguslaw.lazarz@polsl.pl

Summary

Internal combustion (IC) engine is classical rotating machine that must be operated under various conditions. Sound and vibration signal of IC engine often give much dynamic information of mechanical system condition.

Vibration and angular velocity of crankshaft signal on Ford Fiesta engine 1,3 dm^3 were used for the tests. The tests were carried out in Bosch FLA 203 roller bench. The sampling frequency was 25 kHz and during data acquisition process, the rotating speed of the engine was kept at a constant rpm and at run up condition.

The energy state of the pistons and the connecting rods is determined by the mean angular speed and the angular positions of the crankshaft. Changes in the pressure in cylinder caused by compression faults or misfire will affect directly the instantaneous angular speed of the crankshaft and vibration energy. In this paper engine exhaust valve fault and its influence over the instantaneous angular speed waveform and vibration of engine head is presented.

Engine position sensor is one of part of the IC engine control system, thus an instantaneous angular speed based fault detection system does not require additional sensors.

It can be seen from example of the present paper, when the valve worked abnormally, the vibration energy is moved forward towards the high frequency region (larger than 8 kHz).

Keywords: IC engine, fault, diagnostics, valve.

DIAGNOZOWANIE USZKODZEŃ ZAWORÓW SILNIKA SPALINOWEGO NA PODSTAWIE ANALIZY DRGAŃ

Streszczenie

Silniki spalinowe są klasycznymi maszynami wirującymi pracującymi w zmiennych warunkach obciążenia i prędkości obrotowych. Drgania i hałas silnika spalinowego są nośnikiem informacji o stanie jego podzespołów mechanicznych.

Podczas prezentowanych badań, których obiektem był silnik samochodu osobowego Ford Fiesta o pojemności 1,3 dm^3, rejestrowano przyspieszenia drgań głowicy oraz prędkość obrotową wału korbowego. Badania przeprowadzono na hamowni podwoziowej FLA203 firmy Bosch. Częstotliwość próbkowania sygnałów drgań i prędkości obrotowej wynosiła 25 kHz. Badania przeprowadzono w warunkach ustalonej prędkości obrotowej oraz podczas rozbiegu.

Energia sygnału drganiowego generowanego w układzie tłokowo-korbowym zależy od średniej prędkości obrotowej oraz położenia kątowego wału korbowego. Uszkodzenia mechaniczne mające wpływ na ciśnienie sprężania oraz zjawisko wypadania zapłonów wywołują chwilowe zmiany prędkości obrotowej wału korbowego i chwilowej gęstości widmowej energii sygnału drgań. W artykule przedstawiono wyniki badań mających na celu określenie wpływu symulowanego lokalnego uszkodzenia zaworu wylotowego na zmianę chwilowej prędkości obrotowej i charakterystyk widmowych drgań głowicy.

Do pomiaru chwilowej prędkości obrotowej wału korbowego wykorzystano czujnik indukcyjny, stanowiący osprzęt silnika. Z przeprowadzonych badań wynika, że w przypadku pracy silnika z uszkodzonym zaworem wylotowym następuje widoczne przesunięcie energii drgań w kierunku wyższych częstotliwości (powyżej 8 kHz).

Słowa kluczowe: silniki spalinowe, uszkodzenia zaworów, diagnostyka drganiowa.

1. INTRODUCTION

The timing gear system is one of the principal, and precise in their operation, components of the combustion engine. Operational and breakdown wear of such components as the camshaft, pushers, valve springs and levers, as well as valves themselves, has a significant influence on the work of the engine, its performance and reliability. The timing gear system component subject to the highest load, both mechanical and thermal, is the exhaust valve. The valve head temperature reaches locally the value of 700÷800°C, and in engines subject to the highest thermal load, it reaches 900°C. This happens as a result of the action of combustion gases, the temperature of which amounts to 900÷1000°C, and their speed reaches a value of 600 m/s in the initial phase of opening the valve. The high temperature of the valve head results also from the lack of possibility of its cooling, which only takes place at the moment of contacting the valve-seat. The higher the rotational speed, the less heat will be taken by the head which has a direct contact with the coolant. The seat face of the valve and of the valve head wears out mostly as a result of exposure to streams of combustion gases. The wear of the exhaust valve is a consequence of joint action of repeated strokes during the valve closing, erosive influence of combustion gases with products of incomplete combustion and corrosive effect of flames [4].

A particularly important issue in case of valves is to maintain, for as long as possible, their satisfactory tightness during periods of closure, for insufficient tightness of inlet valves causes a reduction of engine power and an increase of specific fuel consumption. Leakage of exhaust valves affects the engine power to a lesser degree, while the main problem here is a rapid increase of their wear intensity as a result of combustion gas blow-by, which very often leads to a complete damage of valve heads, caused by their burn-out.

Damage of this type results in a reduction of effectiveness of action and durability of the catalyst, or its complete destruction. The symptoms of valve burn-out in its first stage can be effectively camouflaged by adaptive systems of control of the combustion engine operation [1, 3]. The modern control systems allow taking into account the differences which result from the scatter of parameters connected with tolerances in workmanship of a given engine, and with changes of characteristics caused by wear, which considerably hinders diagnosing of the engine. Detection of valve faults is also quite difficult in case of 6- and 8-cylinder engines. For this reason, it is justified to search for effective methods of processing vibroacoustic signals, which will allow detecting those faults in valves which cause leakage of a combustion chamber already in their initial stage.

2. RESEARCH OBJECT AND TESTING PROCEDURE

The object of tests was a 1.3 dm^3 engine of a Ford Fiesta personal car. During tests, carried out on a Bosch FLA203 chassis test bench, acceleration of the head vibration and rotational speed of crankshaft were recorded. The frequency of sampling of vibration signals and rotational speed was 25 kHz. The tests were performed in conditions of a steady rotational speed and during starting. An inductive sensor, being part of engine tooling, was used to measure the instantaneous rotational speed of the crankshaft.

The main purpose of the study was to determine the effect of the simulated local fatigue crack of an exhaust valve of the first cylinder on the changing instantaneous rotational speed and spectrum characteristics of head vibration.

In Figure 1, an engine head with a damaged exhaust valve is presented.

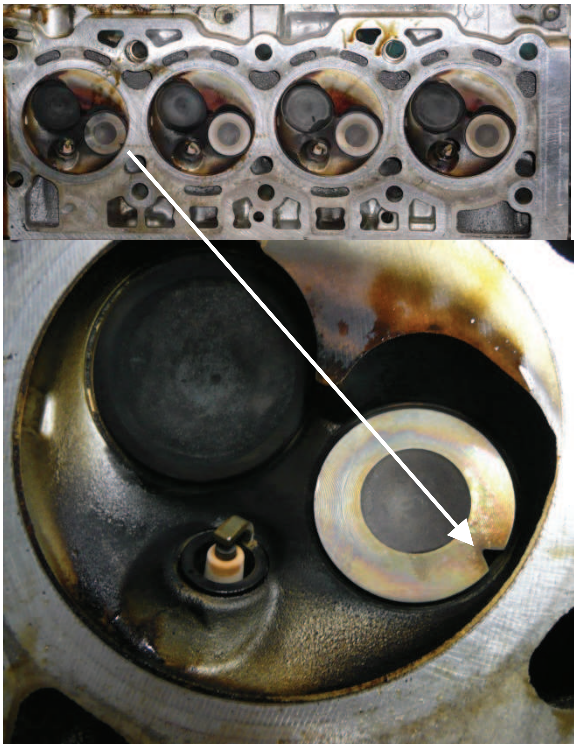


Fig. 1. Simulated damage of exhaust valve

Measurement of compression pressure has shown that the simulated damage caused its decrease by ca. 20%. The tests made on a chassis test bench have shown an insignificant power reduction caused by the introduced damage of the valve (Fig. 2).

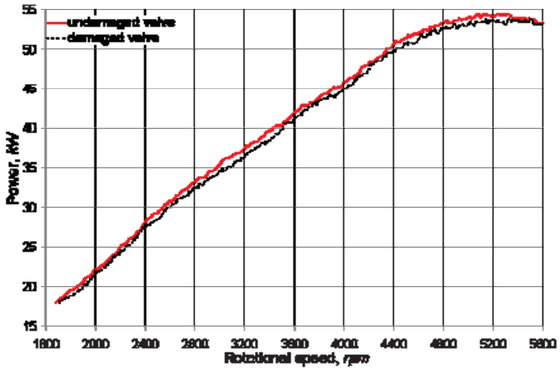


Fig. 2. Engine power as a function of rotational speed for two states of the exhaust valve

3. RESEARCH RESULTS

It appears from the previous research that mechanical damage which affects compression pressure induces instantaneous changes of rotational speed of the crankshaft and of instantaneous spectral concentration of the vibration signal energy [2, 5].

The signal obtained from an inductive sensor, the latter being usually placed over the toothed rim of a wheel rigidly connected with a crankshaft, is one of basic diagnostic signals used by the EOBD system during detection of misfiring. This signal enables determining the rotational speed and instantaneous changes in angular velocity and angular position of the crankshaft.

To identify instantaneous changes of rotational speed as a function of the crankshaft rotation angle, the signal from the inductive sensor, sampled at a frequency of 25 kHz, was appropriately processed by means of a procedure specially developed to this end. Damage of the valve caused increased non-uniformity of rotational speed, clearly visible during both, idle running (Fig. 3) and under load at different rotational speeds (Fig. 4).

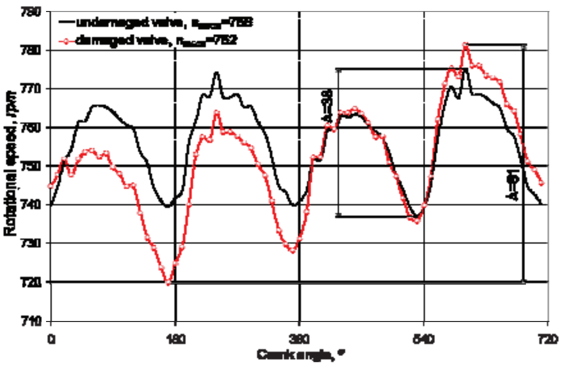


Fig. 3. Course of instantaneous rotational speed (idle run)

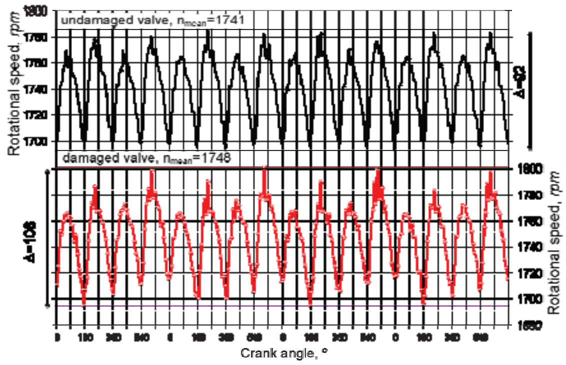


Fig. 4. Course of instantaneous rotational speed for four working cycles (13.2 kW – good valve, 11.6 kW – damaged valve, full load)

Vibration acceleration of the tested engine head in a vertical direction was recorded by means of a piezoelectric sensor. Simultaneous recording of the head acceleration and the crankshaft position signal enabled an analysis of further working cycles of the engine. For the purpose of separating the predominating low-frequency components, preliminary high-pass filtration of the signal was carried out, based on wavelet transform. In this way, a residual signal containing high-frequency components, induced, inter alia by pulse excitation, was obtained. Figure 5 presents an example of a signal of head vibration acceleration during a full working cycle before and after filtration.

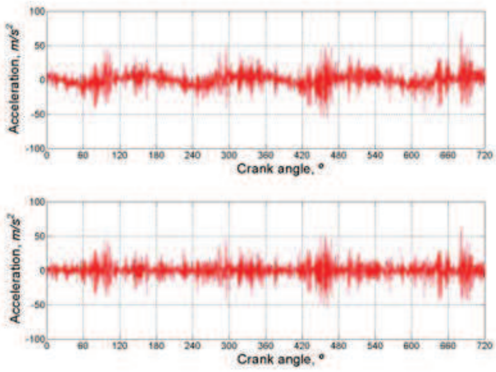


Fig. 5. Signal of head vibration accelerations before and after filtering with use of Daubechies 4 wavelet

An initial spectrum analysis of the head vibration acceleration has shown that in the case of an engine working with a damaged exhaust valve, a visible shift of vibration energy took place in the direction of higher frequencies (above 8 kHz). For the purpose of identifying resonance frequencies of the investigated engine, tests were conducted under conditions of unsteady work. Transitory or unsteady conditions are the conditions of start-up or coasting. Tests in such conditions enable observation of the system's response to various, often non-stationary, forcing. In the process of determining resonance frequencies of the engine during start-up or coasting, there are forcing functions which affect its structure. In a modal analysis (classical or experimental), modal parameters of the identified object are determined on the basis of frequency characteristics obtained in the process of controlled forcing of vibration and measurement of response. In comparison to modal analysis, in this experiment, resonance frequencies can be determined in a much wider range.

Figure 6 shows the courses of changes of rotational speeds with an indicated interval used for determining the start-up characteristics.

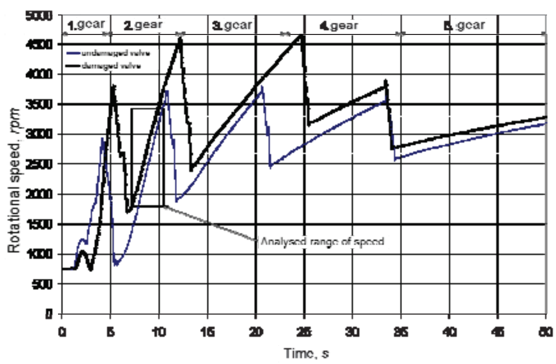


Fig. 6. Course of rotational speed of the engine during coasting performed on a chassis test bench

Spectral concentrations of power, determined based on residual signals of the head vibration accelerations for an engine working with a fully operational valve and with a damaged valve, as a function of rotational speed, reflect the changes of signal energy induced by valve damage (Fig. 7 and 8).

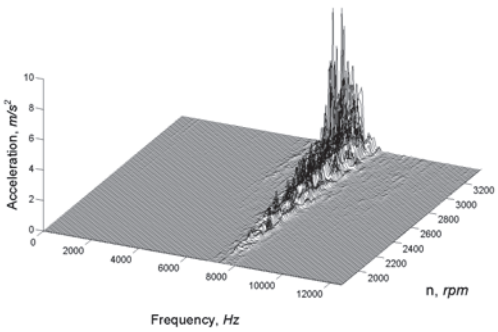


Fig. 7. Time and frequency distribution of the head vibration acceleration; undamaged valve

As can be seen in the above figures, the damage of the valve which caused leakage of the combustion chamber, stimulated the head to vibration in the range of higher frequencies. In order to accurately identify those frequencies, average values were determined of instantaneous amplitudes in the investigated range of changes in rotational speeds (Fig. 9).

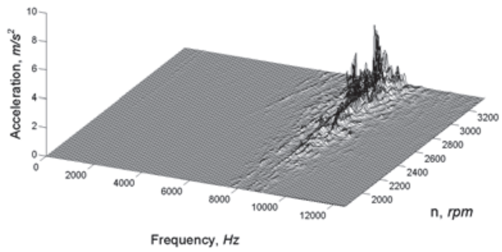


Fig. 8. Time and frequency distribution of the head vibration acceleration; damaged valve

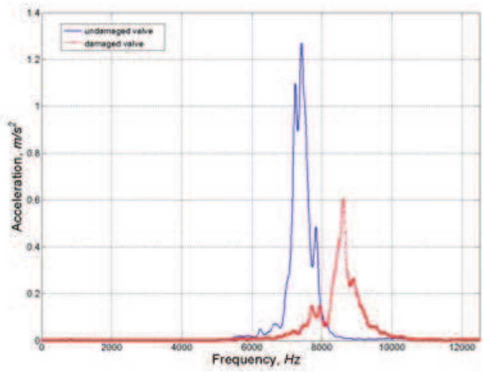


Fig. 9. Average values of instantaneous amplitudes of the head vibration acceleration

In the case of the undamaged valve, the highest energy of the vibration acceleration signal is contained in the range of 6.5 ÷ 8 kHz. Damage to the valve causes a shift of the energy maximum to a range of above 8 kHz.

Taking advantage of the phenomenon described here, dimensionless coefficients of valve damage were proposed: S_1, S_2 and S_3, described by the dependencies:

$$S_1 = \frac{\sum_{i=A}^{B} p_i}{\sum_{i=1}^{N} p_i} \qquad (1)$$

$$S_2 = \frac{\sum_{i=B}^{N} p_i}{\sum_{i=1}^{N} p_i} \qquad (2)$$

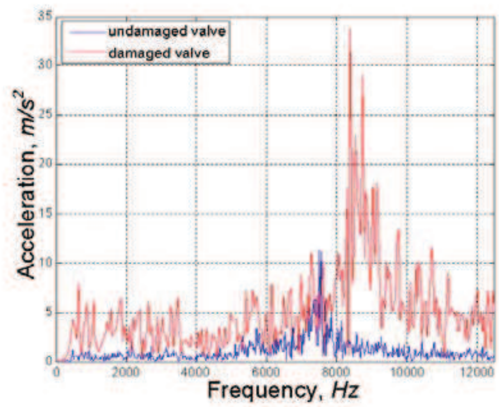
$$S_3 = \frac{S_2}{S_1} \qquad (3)$$

where:

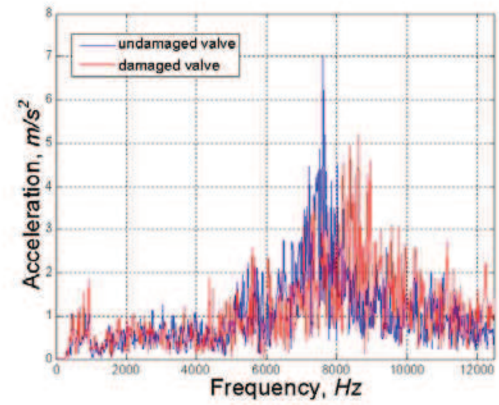
A and B mean the number of the first and last component, p_i, of spectrum in the range of 6.5 ÷ 8 kHz, and N corresponds to the upper limit of the spectral analysis made (12.5 kHz).

Fig. 10 presents the vibration acceleration spectra for the head of an engine working at different rotational speeds and under different loads.

a)



b)



c)

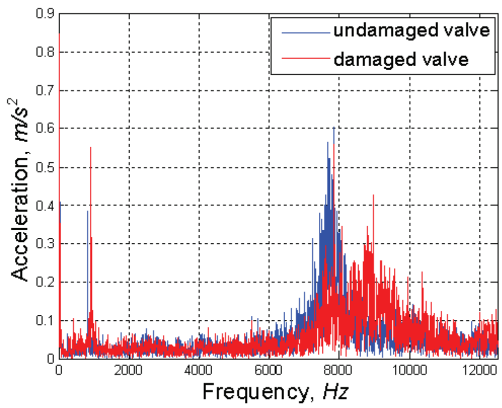


Fig. 10. Spectra of head vibration accelerations a) n=2945 r.p.m., N_{und}=25,7 kW, N_{dam}=25,9 kW, b) n=2905 r.p.m. N_{und}=23,7 kW, N_{dam}=21,8 kW, c) n=754 r.p.m., idle run

The effect of damage and working conditions on the proposed measures, S_1, S_2 and S_3, is presented in Figs 11 ÷ 13.

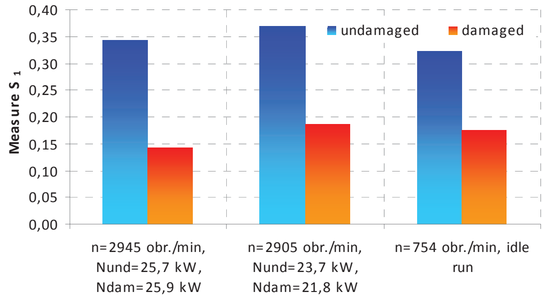


Fig. 11. Values of measure S_1 for an engine working at different rotational speeds and loads

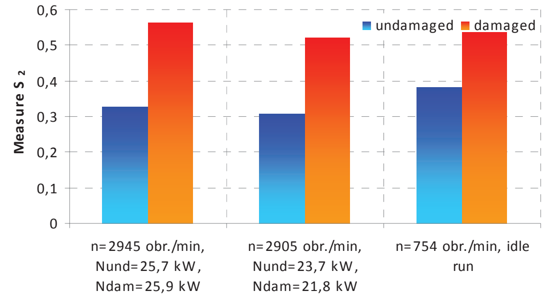


Fig. 12. Values of measure S_2 for an engine working at different rotational speeds and loads

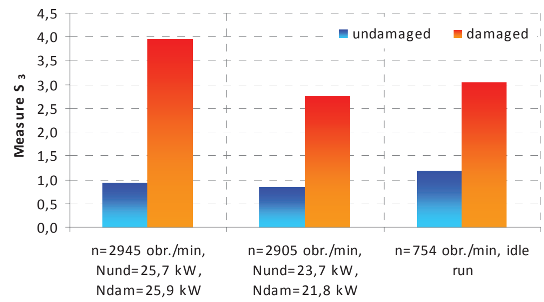


Fig. 13. Values of measure S_3 for an engine working at different rotational speeds and loads

4. CONCLUSIONS

Due to the phenomenon of vibration energy relocation towards higher frequencies during the work of an engine with a damaged exhaust valve, changes in values of the proposed measures detect well a local damage to the exhaust valve, irrespective of the engine operation conditions.

The measure S_3, which takes account of changes in vibration energy in the bands of 6.5 ÷ 8 kHz and 8 ÷ 12.5 kHz simultaneously, has turned out to be particularly sensitive to faults.

The values of measure S_3 for an engine with undamaged valves were contained in the range of 0.83 ÷ 1.35, while in the case with a damaged exhaust valve, they were contained in the range of 2.34 ÷ 3.95.

The proposed measure can be useful in diagnosing faults of valves.

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Bogusław ŁAZARZ Ph. D., D.Sc. Eng. professor of The Silesian University of Technology. Scientific interest: modelling of dynamic processes, diagnostics of tooth gear, machine design and vibroacoustic signal processing. Member of Machines Construction Committee and Polish Society of Technical Diagnostics.

Henryk MADEJ, Ph. D., D. Sc. Eng. work as a professor in the Department of Automotive Vehicle Construction Silesian University of Technology in Katowice. He deals with IC engines and powertrains diagnostics with the application of vibroacustical signal analysis, also with minimization of machine vibroactivity. Member of Polish Society of Technical Diagnostics.

Grzegorz PERUŃ is Ph. D. student in the Department of Automotive Vehicle Construction Silesian University of Technology in Katowice.
Scientific interest: modelling of power transmission systems, machine design and vibroacoustic signal processing.

Zbigniew STANIK is Ph. D. in the Department of Automotive Vehicle Service Silesian University of Technology in Katowice.
His interests are connected with analysis of exploitation and emergency attrition of frictional coupe elements. His doctoral thesis about excessive wear of camshaft eams and followers was published in year 2002.

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