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Acoustic Diagnostics Applications in the Study of Technical Condition of Combustion Engine

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The paper presents the possible applications of using acoustic diagnostics in inspecting the technical condition of an internal combustion engine with autoignition on the example of the Fiat drive unit with common rail system. As a result of measuring the sound pressure level for specific faults and comparing the noise generated by the motor running smoothly, the detailed maps of changes in the acoustic spectrum are possible to generate. These results may be helpful in the future diagnostics of internal combustion engines. In the paper, the results of scientific work in the area of research, design and operation of internal combustion engines, conducted at the Department of Automotive Engineering, in cooperation with the Laboratory of Hydraulic Drives & Vibroacoustics of Machines at the Wroclaw University of Technology are included.

Keywords: acoustic diagnostics; combustion engine.

1. Introduction

Diagnostics is an integral part of science dealing with the construction and operation of machines (Kirpluk, 2012; Luft, 2010; Collective work, 2005). For designers of internal combustion engines, one of the major problems is to design a reliable system of OBD (On-Board Diagnostics) which is the system of auto-diagnostic of a vehicle (Trzeciak, 1998). Unfortunately, such systems are a cause of increased size and overall production and operation costs of internal combustion engines. However, the OBD system is currently the only widely used non-invasive diagnostic system. Other diagnostic methods rely on visual assessment of the engine which forces an interference in its structure in order to disassemble the damaged and other components to gain the access to the damaged part (Osiński, Kollek, 2013; Serdecki, 2012). Obviously, the large amount of time and work is needed in order to ascertain often very minor faults. It seems that a reliable and non-invasive failure assessment system does not exist, however the development of acoustic diagnostics will undoubtedly solve this problem in the future. If the acoustic wave spectrum measurement systems, eliminating the impact of background noise and other noise sources, which do not affect operation of the engine, were developed, it would be possible for each user to carry out in-house acoustic diagnostics. The significant advantage of acoustic diagnostics is the simplicity and quickness of measurements and the advanced development of this method in the field of machines testing (Kirpluk, 2012), which by the kind of synergy may accelerate the development of its application in diagnostics of internal combustion engines. The test of engine operating parameters is important both in the manufacturing process and during its subsequent operation (Teodorczyk, Rychter, 2010). This allows to determine the optimal parameters of engine operation. By performing the measurements, it is possible to diagnose improper operation of engine and other parameters, which differ from desired values such as fuel consumption.

In recent years, the growing interest in the development of non-invasive diagnostic methods may be seen, particularly regarding internal combustion engines. Zhen *et al.* (2013) discuss the combustion process and engine dynamics by measuring signals of vibration, acoustic and pressure. The similar method of non-invasive measurements was proposed by Barelli *et al.* (2009). Carlucci *et al.* (2006) investigated the possibility of using engine block vibration as a mean to diagnose the combustion modifications. An interesting method for diagnosing common faults of the fuel injection system of maritime diesel engine was proposed by Ranachowski and Bejger (2005). The method concerns registration of the acoustic signal in frequency range of 1kHz to 10 kHz by acoustic sensor. The development of signal analysis algorithms may also be seen. Wu and Liu (Wu, Liu, 2009; Wu, Chen, 2006) described an expert system for fault diagnosis in internal combustion engines using wavelet packet transform and artificial network techniques.

This article focuses on the examination of the reliability of acoustic diagnostics methods of internal combustion engine and the preparation of accurate diagnostic maps for Fiat 1.3 JTD engine 70 horsepower model. Measurements consisted in comparing the sound pressure level of specific frequencies for motor operation with induced defects with the smooth operation of the engine. Diagnostic maps created on the basis of the measured acoustic spectrum will be helpful in the future in checking the technical condition of the engine under test. This will allow to create a new non-invasive diagnostic method that may soon become the leading method of engine diagnostics.

2. Measurements

The measurements were made on a Fiat diesel engine with common-rail system. The tested model was Fiat 1.3 JTD, series designation – 188A9000. In total, 13 measurements of the acoustic wave spectrum for different cases of induced engine faults were conducted. To determine the average L_{av} [dB], the maximum $L_{A\,\text{max}}$ [dB] and the minimum sound level $L_{A\,\text{min}}$ [dB], a modular sound pressure level meter with the record time history and analysis of the frequency (sound level meter, accuracy class I) from B&K type 2250 serial No. 2506429 with preamplifier type ZC 0032 serial No. 4112 and microphone type 4189 serial No. 2519832 were used. The sound level meter meets the requirements set out in Regulation of Polish Tripartite Commission for Social and Economic Affairs from 28 May 2007 (Journal of Laws from, No. 105, item 717) and is confirmed by the current calibration certificate of the Regional Office of Weights and Measures in Wroclaw No. W5/401-156/2/12 from 18 July 2012.

Before and after measurements, the test rig was subjected to calibration. For this purpose the reference sound pressure source with a specific level $L_p =$ 93.98 dB was used. Acoustic calibrator B&K type 4231 series No. 2415888 meets the metrological requirements for instruments of accuracy class 1, set in the PN-EN 60942 standard from April 2005. The requirements of valid calibration are confirmed by the certificate of the Regional Office of Weights and Measures in Wroclaw No. W5/401-156/1/12 from 17th July 2012. Calibration correction before starting the measurements was – 0.02 dB and after the measurements was 0.00 dB. Assumed reference pressure level for acoustic measurement results from the limit sound pressure level $p_0 = 20\ \mu\text{Pa} = 2 \cdot 10^{-5}$ Pa (0 dB) (Kirpluk, 2012).

The test rig consists of eddy-current brake comprising a cooling system, the coil, the magnetic plate mounted on a shaft which is connected to the crankshaft of the engine. At the exit of the cooling channels two temperature sensors are provided. The rotational speed is measured by the rotation sensor and the torque is determined by the strain gauge force transducer attached to the arm of a known length to the brake housing, which is located on the bearings to obtain free rotation in the axis of the torque.

The sound level meter was placed at a distance d equal to 1 m from the cuboid surrounding the motor housing with accordance to the standard (Fig. 1).

Fig. 1. Test rig for acoustic measurements.

The first study was to measure the background noise on the test bench, which is mainly caused by the flow of the coolant system of eddy current brake. Another 12 measurements were carried out for 6 different cases of the engine diagnostic condition during the load of 80 Nm for two engine speeds – 1,000 rpm and 2,000 rpm. The time of each measurement was $t = 10$ s. These included the following cases:

- engine in a perfect diagnostic condition, not warmed-up,
- engine in a perfect diagnostic condition after reaching the proper operating temperature,
- disconnected boost pressure sensor,
- disconnected the camshaft position sensor,
- disconnected injector No. 2,
- disconnected fuel pressure sensor.

3. Results of the measurements

The results are presented in the form of spectral characteristics of acoustic pressure. The sound pressure level difference compared to the reference sound pressure level is depicted in the bar charts (Fig. 2, Fig. 3). An important parameter is the actual difference in sound pressure level which specifies the real difference in the energy of the acoustic wave (Fig. 4, Fig. 5). Differences in sound pressure level relative to

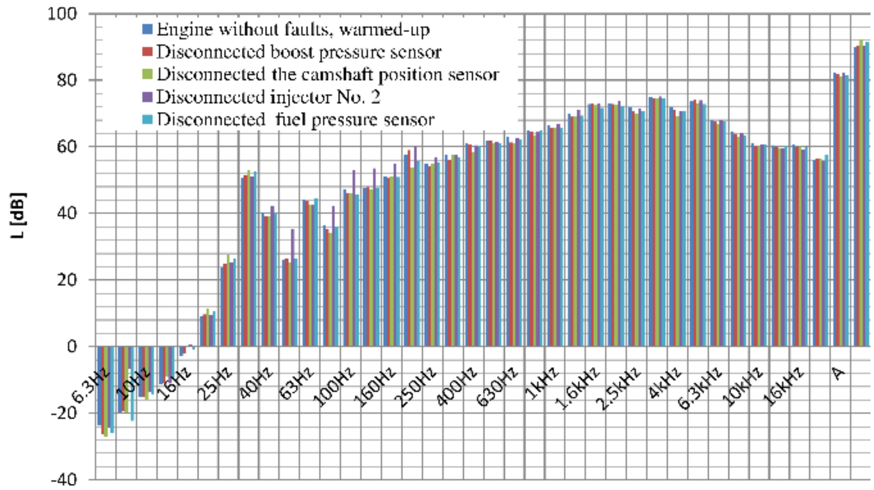

Fig. 2. Graph of the average sound pressure level L_{mA} for the speed of 1,000 rpm.

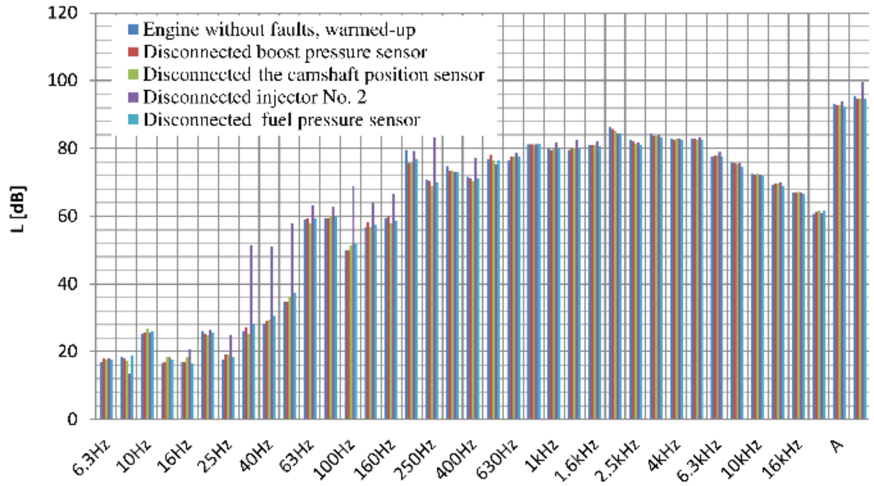

Fig. 3. Graph of the average sound pressure level L_{mA} for the speed of 2,000 rpm.

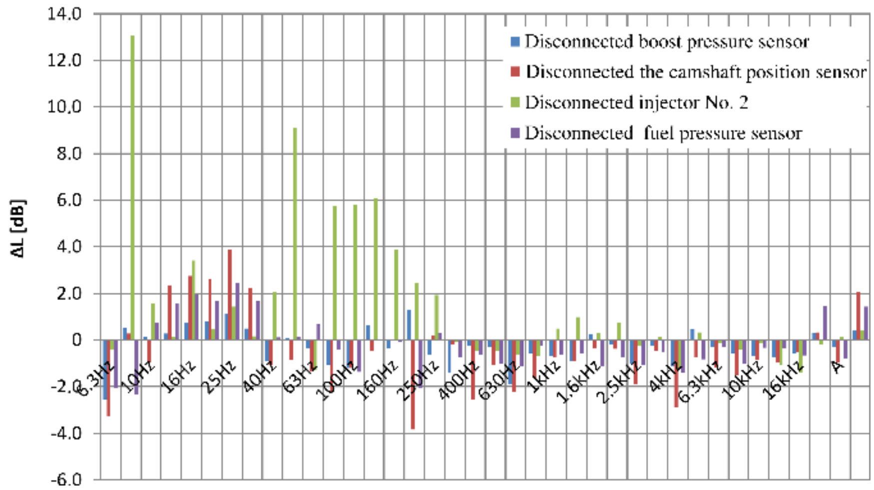

Fig. 4. Graph of differences in sound pressure level ΔL at the speed of 1,000 rpm.

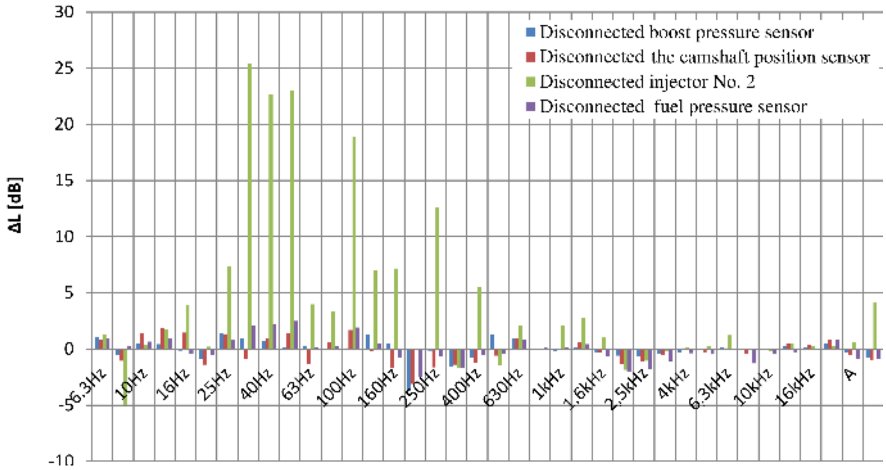

Fig. 5. Graph of differences in sound pressure level ΔL at the speed of 2,000 rpm.

the reference sound pressure level are calculated according to the Eq. (1):

$$\Delta L = 10 \log \left(\left| 10^{0.1 L_n} - 10^{0.1 L_0} \right| \right) \text{ [dB]}, \qquad (1)$$

where ΔL – a change in the sound pressure level [dB], L_0 – reference sound pressure level (engine without defects) [dB], L_n – sound pressure value for n sample [dB].

4. Results analysis

On the basis of Figs. 2, 3, 4 and 5 failures occurring in the test engine can be clearly identified without the need of OBD system application. As the comparison of the sound level at all frequencies for each fault is time-consuming it is worth paying attention only for the characteristic changes in the acoustic spectrum for specific faults that are described below.

Boost pressure sensor disconnected – the main changes concern the frequency of 315 Hz and 2.5 kHz, because there occurs a clear decline in the sound pressure level at the both speed of 1,000 rpm and 2,000 rpm. These differences are about -1.5 dB for 315 Hz for both speeds, -1.01 dB for 1,000 rpm and -0.66 dB for 2,000 rpm for a wave frequency of 2.5 kHz. In addition, the acoustic wave spectrum for this type of defect is characterized by a reduced sound pressure level in the frequency band of the range of 200 Hz – 20 kHz.

Disconnected the camshaft position sensor – the best picture of the spectrum changes is produced during the test at a rotational speed of 1,000 rpm. For higher speed, there were no significant differences. The clear increase in the sound pressure levels recorded for frequencies in the range from 12.5 Hz to 31.5 Hz, and attenuation in the range 40 Hz – 20 kHz may be seen.

Disconnected injector No. 2 – the only type of fault, which can be determined by using the unaided ear. The strong increase in the noise level at low and medium frequency. It is worth pointing out here a correlation of enhancement for 1,000 rpm and 2,000 rpm, where increase of the pressure level of the first speed occurs at the doubled frequency values of higher speed. This is most likely due to the cyclical nature of the operation of the piston, with which the operation of the injector is closely related.

Disconnected fuel pressure sensor – a situation similar to the one with disconnected camshaft position sensor, however both strengthened and damped waves are smaller. It is worth mentioning here that the sound pressure level in the frequency of 20 kHz at the speed of 2,000 rpm is increased by about 1.46 dB.

5. Method of decision trees

The method of decision trees has been proposed in order to increase the efficiency of making a diagnosis of engine damage. This method identifies the damage on the basis of the sound emission spectral characteristics and is sufficient for recognition of injuries taking into account not large number of measurements. In the literature many studies regarding other methods of failure identification may be found (Adaileh, 2013; Elamin *et al.*, 2010; Ettefagh *et al.*, 2008; Glowacz, Kozik, 2013; Glowacz, 2014; Wu, Kuo, 2009).

It is possible to use heuristic search methods in order to create the method of decision trees (Divina, Marchiori, 2005). Actions undertaken while the problem is being solved can be classified as searching of objects of the specified characteristics. Rules of procedure by the generate-and-test method focused on testing of a given property of an acoustic signal have been used in the identification of the type of engine damage.

Game graphs have been used as a generate-and-test (search) tool (Deptuła, 2015). Game graphs have been used in the optimization of hydraulic properties of machine systems (Deptuła, Partyka, 2011; 2014; Deptuła, 2014; Osiński *et al.*, 2013).

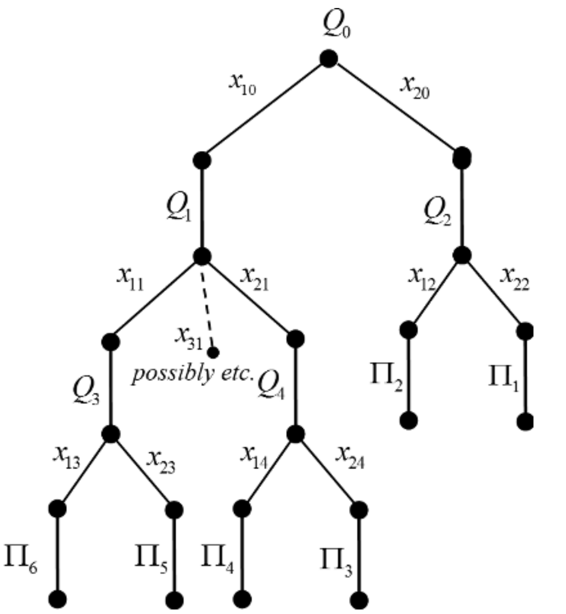

Fig. 6. A game tree structure with the start vertex q_1.

Four terms are defined in order to create a decision support system: elements of the system, relations, properties of elements and the objective function.

It can be assumed that elements of the system form the set Q, relations – the set Π_s, properties of elements – the set Γ, the objective function – F.

It can be assumed that states of the engine are elements of the set (Eq. (2)):

$$Q = \{X_0, X_1, X_2, ..., X_i, ..., X_m\}, \tag{2}$$

where X_i – i-th engine damage if Q is a finite set.

It is necessary to define the relation of the measured values of sound pressure levels values of given damages X_i in order to differentiate damages. The set Π_s composed of the ordered pairs (X_i, X_j) can be called the relation on the set Q. The set Π_s is a subset of the Cartesian product $Q \times Q$ and has the following form (Eq. (3)):

$$\Pi_S = \{(X_{i1}, X_{j1}), (X_{i2}, X_{j2}), ..., (X_{is}, X_{js})\}, \tag{3}$$

where i_s, j_s are specific values of sound pressure of a given damage.

Relations of different kinds can occur among sound pressure values, e.g. arithmetic (signs +,−), causal, logical, reciprocal and this is why the set of possible relation types in the decision system [Q] among damages X_i is taken into consideration and it has the following form (Eq. (4)):

$$\Pi_S = \{\Pi_1, \Pi_2, ..., \Pi_S, ..., \Pi_r\}, \tag{4}$$

where $\Pi_s \in \Pi$ is a set from the expression (3).

When searching the game graph, it will be possible to determine the kind of damage X_i in relation to the relations of Π_s type by means of defining highlighted values.

A game graph taking into account the search algorithm finds features, characteristic points or values (individual for each damage) by means of which it is possible to characterize to which damage the analysed sound pressure distribution belongs. The damage detection will be based on the identification whether there is a negative difference of sound pressure in relation to the difference in pressure of the operating engine for a specific frequency at the rotational speed equal to 1000 rpm and 2000 rpm or whether there are alternate signs of sound pressure. If features such as signs do not characterise the belonging to given damages, values or deviations occurring in the sound pressure level measurement can be taken into consideration in the algorithm.

A more detailed description of the method of decision trees based on game graphs used to diagnose damages of the tested engine will be included in the next paper.

6. Conclusions

Above results indicate the usefulness of the noise emission in the problems of diagnosing internal combustion engines. Measurements of examined cases of engine failure provided information on the acoustic wave spectrum changes generated by the engine. Thanks to them the complete graphs showing enhancement or attenuation of the specific frequencies at certain faults were created. Charts were made for the average sound pressure level L_{mA}. This parameter was selected because of the stationary nature of the registered signal (the difference between the maximum level $L_{A\,\max}$ and the minimum level $L_{A\,\min}$ was less than 5 dB). The proposed decision method of identifying engine failure based on sound emission spectral characteristics, will allow the quick identification of specific damage. It should be noted that the method based on game graphs is sufficient in the indicated case, with a small number of measurements. The method may be successfully used for subsequent measurements on the same engine and engines of the same kind. In the case, where the greater number of measurements is made, it might be considered to use a better system of classification based on the tools with reversed correlation matrix, e.g. by means of neural networks.

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