International Journal on Emerging Technologies **11**(3): 91-95(2020)

ISSN No. (Print): 0975-8364
ISSN No. (Online): 2249-3255

The Method of Controlling the Valve Mechanism of the Engine for Exhaust Pulsation Experimental Study

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(Received 28 January 2020, Revised 24 March 2020, Accepted 27 March 2020)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: The methodology of vibroacoustic control is usually defined by the gas distribution mechanism (GDM) of the internal combustion engine (ICE) based on the exhaust gas pulsations technical conditions' influence analysis. Theoretical and experimental studies were carried to determine the main defects and malfunctions of ICE by analyzing the parameters of the vibroacoustic signal. It was shown that development of highly sensitive vibration sensors and inexpensive USB oscillographs allowed to simplify vibroacoustic method and to expand possibilities for the processing of the diagnostic data. Nowadays burnout of valves, break of valves' tightness and phase displacement and growth of clearances in the ICE gas distribution mechanism occur quite rare. It was determined that the key factors that influence ICE technical conditions are untimely maintenance, the use of non-recommended oils and fuel, violation of thermal and load conditions, etc. In half of the cases, mentioned factors cause an increase in the clearance in the GDM valves. The experimental studies of the influence of the GDM technical condition on the pulsations of exhaust gases made it possible to create a vibrodiagnostic control mechanism: with a clearance tolerance value of 0.02-0.30 mm for the exhaust valve, the vibration pulse signal value was 180-200 mV. It is proved that even a slight excess of the amplitude of the vibration pulse signal above 200 mV requires adjustment of the clearances or replacement of the hydraulic pushers. It was mentioned that the method and the set of standard techniques will allow determining in the simplest way technical state of the engine systems for any intermediate conditions of diagnosed objects. Application of diagnostic equipment, technological techniques, and regulatory data provides modern motor transport methodology for development of the operation, repair, and maintenance of vehicles procedures and algorithms. Proposed methods provide possibility of simultaneous observation of the diagnosed GDM elements.

Keywords: amplitude, diagnosing, exhaust system, phase, vibration diagnostics

Abbreviations: GDM, gas distribution mechanism; ICE, internal combustion engine.

I. INTRODUCTION

Failures of ICE systems are among the first in the total number of failures of automotive engineering [1-4]. There is significant number of diagnostic methods and tools to be used to determine them [5-7]. So, in particular, the vibroacoustic method is known as a most effective method to solve the problem [8-10]. The fundamentals of its use on automotive engineering were developed as far back as 1970-1980 by GOSNITI, Leningrad Agricultural Institute, and other institutes [9-12]. Thus, for the diagnosis procedure an electronic stethoscope "Ekranas"(KI-13940-GOSNITI) was proposed. Nevertheless this method was not widespread due to the significant high cost of the equipmentto be used and technological complexity of implementation [9]. Nowadays, the practice of computer systems application is basic approach. They allow not only controlling ICE, but also provide the diagnosis by means of the vibroacoustic diagnostic method [11, 13-17]. At the same time, there are special conditions of the transmission and processing of information in the diagnosis of cars, tractors, and stationary installations with ICE. In order to test the developed measuring equipment, there were created measuring bench and improved information-measuring system. Thereby, the analysis of signals characterizing the operation of ICE mechanisms could be provided by applying to the gas distribution mechanism (GDM) valves, being based mostly on the experimental data. Since the vibration parameters of the GDM valves are random in nature, the deterministic diagnostic methods are not to be used. Under constant experimental conditions, mentioned parameter's oscillation clearly could be recorded by the vibrograms. Particularly noteworthy that oscillation of the GDM parameter value is affected by the vibration and noise of other components of the running engine.

Analyzing modern inexpensive diagnostic tools one could find relevant to the research and aimed at further improving of the vibroacoustic method of diagnosing the ICE valve mechanism for exhaust pulsation.

In a number of literature sources, the most characteristic spectra of the SMD-14A and D-50 engines vibration pulses were experimentally determined. It has been established that for clearances in the piston-sleeve interface as the most characteristic spectrum of vibration pulses lies in the frequency range of 2-4 kHz, gas distribution mechanism – 7-10 kHz, piston rings – 10-16 kHz, connecting rod and main bearings – 0.5-2 kHz [5, 18]. Thereby, further we will focus mainly on the gas distribution mechanism.

SenX Technology was the first to identify problem cylinders by exhaust using its FirstLook sensor and an oscillograph (Fig. 1).

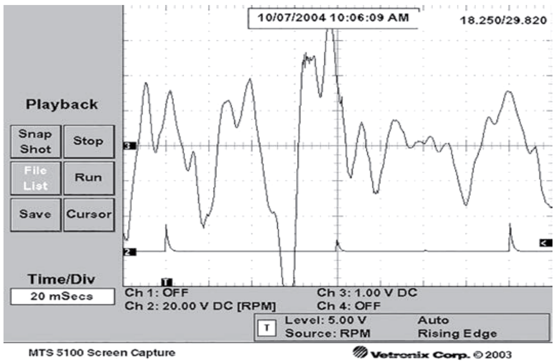

Fig. 1. Exhaust Gas Flow Pulsation Captured with FirstLook Sensor.

In order to analyze the pulsations of the exhaust gas flow, the FirstLook sensor pipe had to be inserted into the exhaust pipe and its output signal will be recorded together with the spark signal of cylinder No. 1. But this principle is not widely used due to the complexity of the obtained waveform. Determination of cylinder's ignition while during pulsations of undermined amplitude is not trivial problem.

We would like to single out the works devoted to the causes of valve knocking in the case of expansion clearances between the valve stems and rocker nose (pusher) increase which depends on the GDM design [5, 19, 20]. These distinct sonorous knocks are easily recorded for the warmed-up engine at the low frequency rotation of a crankshaft level [8]. Clearly audible knocking of the camshaft bearings could be detected at low idle of a warm engine.

In terms of vibroacoustic diagnostics, elastic vibrations due to collisions of associated parts should be mentioned as one of the most important subject to study. Variability of the load and the change in the direction of the acting forces of the mechanisms parts considering clearances between the associated parts leads to shocks, which causes vibration of the mechanisms parts and the entire engine [11, 12, 16, 17]. For example, one could mention the transfer of the piston from one side of the sleeve to the other ends with a collision and the formation of a pulsed vibration.

Impacts of the mechanisms associated parts usually cause deformation and elastic vibrations in the colliding parts with corresponding amplitudes and frequencies. The velocity at the beginning of the impact of the colliding parts is a function of several quantities [5]:

$$\upsilon_0 = f(s, F, m_1, m_2, t_B, t_M, \omega) \qquad (1)$$

where *s* is a clearance in parts mating, m; *F* is a value of the force under the influence of which a collision occurs, N; m_1, m_2 are masses of colliding parts, kg; ω is an angular rotation speed of the crankshaft, rad/s; t_B, t_M are water and oil temperatures, respectively, °C.

Each associated pair of mechanism parts generates pulsed vibrations upon impact which usually occurs with a corresponding pulse filling frequency (natural vibration frequency). Each conjugated pair of mechanism parts generates vibrations upon impact, which usually could be characterized by a pulsed nature with a corresponding pulse filling frequency (natural vibration frequency). The spectrum of shock accelerations is defined as a function of maximum accelerations depending on the natural frequencies of the colliding parts. Knowing the frequency of the engine or machine mechanisms parts shift, it is possible to establish the moments of the pulses formation, the energy of which is proportional to the shock pulse *R*, and therefore, the clearance *s*. The larger the clearance in the associated parts, the farther the vibrational pulse moves to the reference point; moreover, up to the increase in the clearance *s*, the energy and intensity of the vibration caused by the collision of the checked joint increase.

The frequency of action (Hz) of the disturbing force is determined by the formula:

$$f = \frac{i \cdot k \cdot g \cdot n}{60}, \qquad (2)$$

where *i* is total transmission ratio; *k* is multiplication factor of the disturbing force action; *g* is order of harmonic components; *n* is crankshaft rotation speed, rpm.

Knowing the frequency of disturbing force action of the kinematic pair, it is possible to determine the sources of vibration pulses of the vibration temporary realization.

In order to decipher the oscillograms and spectrograms of the engine mechanism vibration, it is necessary to know the frequency characteristics of the elastic vibrations of the colliding and basic parts of the studied mechanisms. In general terms, the natural frequency of the part oscillation will be, Hz:

$$f = \sqrt{\frac{d^2y}{dt^2}} / \sqrt{y}, \qquad (3)$$

where $\frac{d^2y}{dt^2}$ is acceleration of colliding objects, rad/s; *y* is deflection at a given acceleration, rad.

The equation shows that in order to determine the frequency of elastic vibrations, it is necessary to know the acceleration $\frac{d^2y}{dt^2}$ that can be determined for any part element for the given deflection *y*, or any other deflection for a given acceleration.

Therefore, there is reason to believe that there is insufficient certainty in the methodology for obtaining and processing the vibration signal of the exhaust gas pulsation and assessing their influence on the technical condition of the ICE gas distribution mechanism, which necessitates further study.

The purpose of the work is the method of controlling the valve mechanism of the engine for exhaust pulsation experimental study.

To achieve the purpose, the following objectives were set:

– justify the use of the method of acoustic vibration diagnostics to monitor the technical condition of the valve mechanism of an Internal Combustion Engine (ICE).

– develop an information measuring system for determining the technical condition of the valve mechanism in real time.
– identify the dependence of the moments of closing and opening of valves on acoustic vibration.

II. MATERIALS AND METHODS

In order to measure of the amplitude and phase parameters of the exhaust pulsation (vibration pulses) and to record the oscillograms USB DISco2 (USB-oscillograph) with the USB DiSco 3.24 program (Motor-Master) has been used.
Further research included a method based on the analysis of malfunctions of the pulsation of exhaust gases has been applied.
In preliminary experiments, the method has been improved by changing the design of the piezoelectric sensor (Fig. 2) and by determining the location (Fig. 3) and the distance of the highest vibration intensity mainly from the signal amplitude.

Fig. 2. Piezoelectric Sensor for Measuring Exhaust Gas Pulsations.

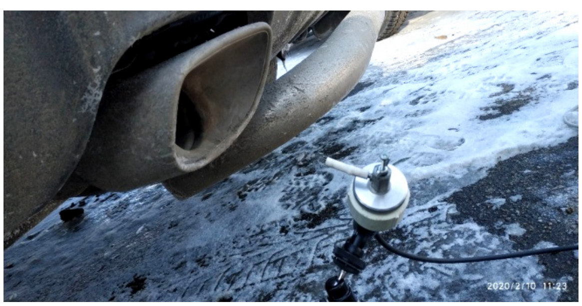

Fig. 3. Location of the Piezoelectric Sensor for Measuring Pulsation.

The design of the sensor has been changed by turning on the adjustment screw, which allows working with engines with any number and working volume of cylinders and exhaust pressure.
It should be noted that the amplitude and phase of the vibration signal have been evaluated at least three times during measurements procedure. The waveform sweep was recorded continuously and brought enough quantity of data for the analysis. Moreover, a continuous comparisons of the vibration pulses measurement data and direct control of the clearances for the GDM valves with the help of a probe was carried out.
During measurements by means of USB DISco2, an oscillogram of the amplitude and phase parameters of the Sens vehicle with misaligned valves vibration pulses was obtained.

During implementation of measuring vibration from the collision of GDM valves, the engine warmed up to operating temperature. The measurements have been carried out at ICE rotation speed corresponding to idling value of 860 rpm. Comparison of the vibration measurement results has been carried out with the results of direct control of the clearances in the GDM valves. The Sens was selected with a slight knock during ICE operation.

III. RESULTS

Before conducting experimental studies of the vibration signals measurement, the clearances in the GDM valves have been checked using a feeler gauge. On a warmed-up engine, the clearances according to technical requirements should stand 0.15 mm for intake valves and 0.30 mm for exhaust valves. The clearance tolerance is +/- 0.02 mm.
Before the main part of the experiment, a piezoelectric sensor has been calibrated (Fig. 2). For this purpose, on a “cold” engine, after removing the GDM cover, the valve clearances were checked with a feeler gauge. After that, the nominal values of the clearances have been established and an oscillogram of vibration pulses was recorded at the operating temperature regime. On the oscillogram is presented the amplitude corresponding to each GDM valve. It invoked increments growth from 0.02 mm to 0.38 mm. Thereby, adjusting washers have been installed and vibration pulses have been fixed for the installed clearances. After that obtained measurements results have been summarized and represented at the graph (Fig. 4).

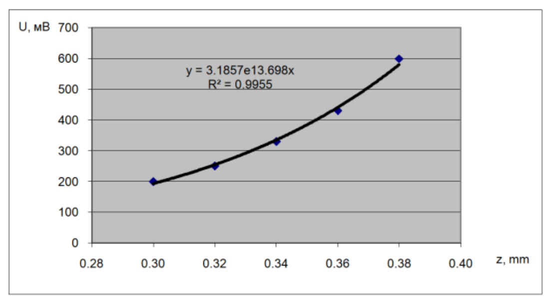

Fig. 4. Piezoelectric Sensor Calibration Results: Dependence of the Output Signal U, mV, on the Clearance Size z, mm, in the GDM Valve.

It’s shown that the shape of the calibration curve (Fig. 4) has a nonlinear appearance, which could be explained by the proportionality between the clearance and the squared value of the vibration pulse formation velocity. The curve obtained during calibration with a confidence of 0.9955 has been approximated by an exponential line. The equation in unencrypted form will look like:

$$y = 3{,}1857 e^{13{,}698 \cdot x} \tag{4}$$

where y is the value of the vibration pulse amplitude, mV and X is clearance value in the GDM valve mechanism, mm.
In order to measure the amplitudes of vibration pulses and the corresponding clearances in the GDM valves, one can use the trend line (Fig. 4) and the equation presented ibid. Multiple repetitions of the vibration pulses phase parameters amplitudes measurements

have shown a deviations of a maximum values at the range of 1-3% which shows sufficient accuracy value that can be used for the vibration process analysis.

The main part of the experimental studies included the control of vibration pulses from the collision of GDM elements on 3 Sens cars with a 1.3-liter engine. Before conducting the “cold” experiment, we have measured the clearances with a feeler gauge. After that we monitored the amplitude and phase parameters of the heated ICE vibration pulses. The measurement data are shown in Table 1.

Table 1: GDM Vibration Pulse Impact Monitoring Results.

Indicators	1 cylinder, mV	2 cylinder, mV	3 cylinder, mV	4 cylinder, mV
Sens ICE (mileage 120,000km)	250	200	185	190
Sens ICE (mileage 180,000km)	220	230	190	195
Sens ICE (mileage 150,000km)	180	190	210	220

The clearance control on 3 ICE Sens with a volume of 1.3 liters, different mileage and the feeler gauge established a significant dominance of the increased clearances in the exhaust valves. Subsequent diagnostics by means of piezoelectric sensor with measuring equipment confirmed the results of direct control with the feeler gauge. So it was shown that for the exhaust valve clearance tolerance of 0.30 ± 0.05mm, the value of the vibration pulse signal will be 200 mV. Therefore, any excess of this parameter above this value requires adjustment of the clearances and specifically for the cars with hydraulic pushers of valves it will cause replacement of hydraulic pushers. Table 1 demonstrates that the values of the vibration pulse are greatly exceeded for some cylinders, and thereby 5 out of 20 cylinders require clearance adjustment. Moreover, significant deviations of the exhaust process for these valves have been observed (exhaust phases, phase overlap, time of flow around the valve facets with exhaust gases).

IV. DISCUSSION

The widespread use of alternative fuels, in particular gas fuels in Ukraine, as well as a number of operational factors lead to the failure of the engine gas distribution mechanism elements. Mentioned problem causes severe malfunctions of the engine, such as burnout of valves, violation of their tightness, phase displacement, and growth of clearances. A significant number of methods to detect GDM malfunctions have been developed, but most of them have low sensitivity. In our opinion, the vibroacoustic method is characterized by highest sensitivity to the malfunctions of GDM elements. Problematic issue of its widespread use and related technological methods to date are significant cost of diagnostic systems, calibration complexity of the sensors to be used, and complexity of processing and analysis of diagnostic information. However, the development and application of USB oscillographs and highly sensitive piezoelectric sensors have solved this problem. Despite a fairly systematic study of the GDM elements failure indicators, the use of the vibroacoustic diagnostic method and the tools that implement it, the application of vibration diagnostics technology for other engine systems should be investigated in subsequent works, which will be aimed at studying the limiting values of diagnostic parameters, justification of tolerances, and measures for their restoration.

In our opinion, a promising direction for the development of this method is implementation of integrated (standard) method for recognizing changes in clearances in the interfaces of engine systems. This direction has been developing recently due to the cheaper cost of piezoelectric sensors, accelerometers, and devices for analyzing and displaying information, as well as its subsequent processing. It could be compared with detonation pickup and its use for correcting the ignition timing. The results presented in the paper can serve as the fundamentals for developing an integrated diagnostic system based on the results of exhaust gas pulsation with subsequent adaptive adjustment of engine system elements in accordance with a change in technical condition.

The proposed in the paper method can be extended to any modern cars, as well as to promising new models. Modern engines with hydraulic pushers are very sensitive to the quality of the oil and therefore the control of clearance in operation is very important for the purpose of examination and recognition of intensive increase signs of vibration pulses of individual GDM valves.

V. CONCLUSIONS

The conducted experimental studies made it possible to determine wide possibilities for the use of vibration equipment in diagnosing clearances in GDM valves. For the exhaust valve clearance tolerance of 0.30 ± 0.05 mm, the magnitude of the vibration pulse signal was 180-200 mV. Any excess of the amplitude of the vibration pulse signal requires adjustment of the clearances or replacement of the hydraulic pushers. The developed technological methods and, in particular, the vibroacoustic diagnostic method have significant advantages in comparison with other modern approaches (by compression, pressure pulsations, intake manifold, changes in cylinder pressure and cylinder blowing with air parameters). First of all, this is a significant sensitivity of the vibration signal to a change in the clearance, while the other methods generally do not allow detecting a change in the expansion clearance. Proposed methodology provides possibility of simultaneous (relative) observation of the diagnosed GDM elements, while other methods require measurements in a separate engine cylinder and electronic amplifiers. Finally, it should be mentioned that we propose two-fold decrease in the complexity of the diagnostic process with high reliability of control. Furthermore, a significant advantage of the method is versatility with respect to other colliding, rubbing, and rotating units and engine systems. In case of crankshaft and camshaft position sensors, one can get a synchronous picture of the operation of any unit at a given point in time or at the required angular position of the crankshaft and camshafts of the engine.

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How to cite this article: Chepurnyi, Y. V. and Leonenko, O. M. (2020). The Method of Controlling the Valve Mechanism of the Engine for Exhaust Pulsation Experimental Study. *International Journal on Emerging Technologies*, *11*(3): 91–95.