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The Development of Methodological Techniques and an Algorithm for Diagnosing Modern Intake Systems for Internal Combustion Engines

Type Diagnosing and detecting malfunctions in internal combustion engines (ICE) is not an easy task due to their complex design. Timely and high-quality ICE monitoring allows performance to be maintained and prevents breakdowns. Vibration and acoustic analysis is a powerful and informative tool for detecting faults even at an early stage. This article considers a method for determining the main malfunctions of the valvetrain (VT) (tightness of the "valve-seat" interface, thermal gap in the valve drive, valve opening and closing phases) by measuring and analyzing vibroacoustic pulses caused by the operation of individual engine elements. The maximum amplitude and the moment of vibration impulses are used as signal parameters. For the reference signal of the piston, the top dead center (TDC) of the cylinder under study, a vibration pulse from the impact of the piston on an elastic tip placed in the combustion chamber is taken. This technique makes it possible to exclude the external influences and inaccuracies associated with a change in the geometry ICE elements.

Keywords: *clearance, rotation frequency, valvetrain, valves, vibration diagnostics.*

1. INTRODUCTION

In modern mechanical engineering, there has been a tendency to improve systems and assemblies for high-tech standards EURO-5 and 6 [1-5]. Various scientific, research and design organizations are improving the characteristics of fuels, oils, and working fluids [6, 7].

However, continuous monitoring of the correct functioning of vehicle systems is very important. On-board information systems, algorithms, methods, and means of diagnosing vehicle systems are being developed, including those based on convolutional neural networks [8-12].

Vibration data is converted into an angular domain, then used to generate training and test data. Training and test data are processed using wavelet-synchronous-compressed transform to generate time-frequency images. These images are used for deep learning of neural networks. The continuous wavelet transform method is also used among the common methods for diagnosing engine malfunctions. This method has a significant drawback - it requires a long computation time but has great potential in detecting defects [13, 14].

Shiyuan et al. in [15] propose a simple diagnostic method called partial sampling and feature averaging. This method selects and analyzes only a certain part of the vibration signal corresponding to a specific shock force in each working cycle. Then diagnostic signs are extracted from each part but averaged over many cycles. Detecting abnormal valve clearance requires only a partial sampling of the vibration signal extracted during the valve closing. Experimental results show that this technique is effective and easy to implement.

A signal processing technique is presented in [16]. A source separation algorithm is developed, separating the interference signal of adjacent cylinders from the controlled cylinder if the wave attenuation constant and the arrival time delay along the propagation path are known.

Yang and Yong [17] used vibration signals measured at the head of a diesel engine to study its combustion parameters. The vibration signals were processed using the Fourier Decomposition Method, which can be used to identify combustion parameters.

Ahmed et al. [18] used the smooth variable structure filter (for training artificial neural networks), which detects ICE faults with high accuracy compared to other methods, such as a defective lash adjuster, cam phaser, or chain tensioner. This diagnostic system can also be configured to detect other engine faults.

The development of diagnostic models that assess the technical condition of automatic gap compensators in piston valves of an ICE is presented in [19, 20].

Particular attention is paid to the adaptability of elements and systems for constantly changing operating and technical conditions. An example is the VT of modern cars, the design of which has undergone significant changes in recent years [21-25]. These changes are associated with hydraulic valve tappets, VT automatic hydraulic chain tensioners, and VT automatic phase adjustment. However, electronic systems for monitoring VT gaps and reliable methods for diagno–

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sing them are missing even with all these improvements. Several known collapsible and non-collapsible methods analyze VT [26-28].

The most notable are control methods: compression, air leaks from ICE cylinders, the compressor-vacuum method, the monitoring of thermal gaps using a probe, the endoscopic method, and the control of dynamic pressure in ICE combustion chambers, vibration, and noise [29-37]. However, the low reliability of these methods and their significant labor intensity requires the development of new methods or the improvement of existing methods for diagnosing VT.

Fig. 1 shows the statistics of failures of VT elements of modern cars [34].

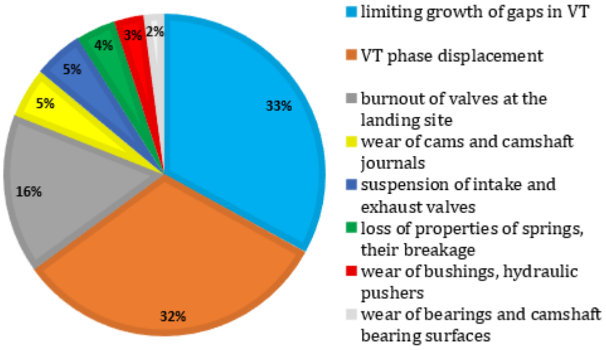


Figure 1. Percentage distribution of VT failures

Fig. 1 shows that most failures occur due to the limiting growth of VT and VT phase displacement gaps. The development of reliable methods for diagnosing VT and their subsequent application will eliminate many VT failures.

Currently, the technical status of VT is more often assessed by direct control methods, which require partial or complete engine disassembly. The accuracy of the results is high but not always complete since some properties of the parts are better manifested while interacting.

To determine the tightness of the valve–seat interface, the following instruments are most often used:

•a pneumatic tester, able to determine the tightness of the combustion chamber based on the values of the pressure drop of the compressed air supplied to the cylinder;

•a compression meter measures the pressure at the end of the compression stroke, which can also accurately determine the tightness of the above-piston space.

Stethoscope noise analysis provides important information for fault isolation and classification. When the expansion gap in the VT changes, there is a change in the interaction of the VT elements resulting in a typical change in the noise during operation. We can determine the VT status in a comprehensive, in-place manner based on analyzing the signal from a pressure sensor screwed into the cylinder and a depression sensor connected to the intake manifold.

To this end, we develop a comprehensive method for diagnosing the main VT malfunctions to improve diagnostic accuracy. The requirement for an in-place assessment of the technical status of the mechanism also brings to the fore the methods of vibroacoustic diagnostics as the most sensitive to deviations of the technical status from their normal values. Any such deviation leads to a change like the interaction of the parts and, consequently, a change in the vibroacoustic impulses accompanying this interaction. The wide frequency and dynamic range of oscillations and the low inertia and high speed of acoustic wave propagation through the structure determine the quick response of the vibroacoustic signal to any change in the technical status.

To reduce the cost and increase the diagnostic speed while increasing the maintenance and technical reliability requires universal diagnostic tools, which are relatively easy to manufacture and use and suitable for a wide variety of engine models.

We have developed a method for determining the main VT malfunctions (the tightness of the valve–seat interface, an expansion gap in the VT, and the valve opening and closure phases), which is the measurement and analysis of vibroacoustic impulses caused by the operation of individual engine parts. The amplitude maximum and moment are used as signal parameters.

2. THEORETICAL RESEARCH

We can determine the VT status comprehensively and in place based on the signal analysis from a pressure sensor screwed into the cylinder and a depression sensor connected to the intake manifold. Figure 2 shows an oscillogram of synchronously recorded signals from the pressure sensor (channel 1), the depression sensor (channel 2), and pulses from a standard crankshaft sensor for synchronization (channel 3) [38].

The signal from the pressure sensor displays the gas movement in the cylinder, which allows us to indirectly assess the parameters of the mechanical part of the VT and determine the phases with relative accuracy.

Piezoelectric sensors are most often used as pressure sensors. They ensure the high linearity requirements over a wide pressure range. The moment on the oscillogram when the pressure reaches its maximum is taken as the piston position at TDC. The pressure value at this point can vary significantly, depending on the degree of compression of the diagnosed cylinder, the engine speed, the engine load, and the amount of compressed air.

Using a sensor to measure the pressure of up to 6 Bars relative to the atmospheric pressure complicates finding the TDC. If this value is exceeded, the oscillogram is invalid. This is manifested in a cut pressure peak when the piston approaches the TDC. We can see from the oscillogram that the valve timings do not always have a clear point and are often described by sections. This leads to a deviation of the obtained values of the VT phases from the actual ones.

The depression sensor is based on a membrane with a piezoceramic plate interacting with the pressure in the measured area. The air pressure is determined by the throughput capability of the intake manifold (intake resistance) and its tightness, the state of the CPG, the capacity of the exhaust tract, the specified VT phases, and the tightness of the combustion chamber, the sensor connection, etc. The main depression wave and many reflections occur in the intake manifold.

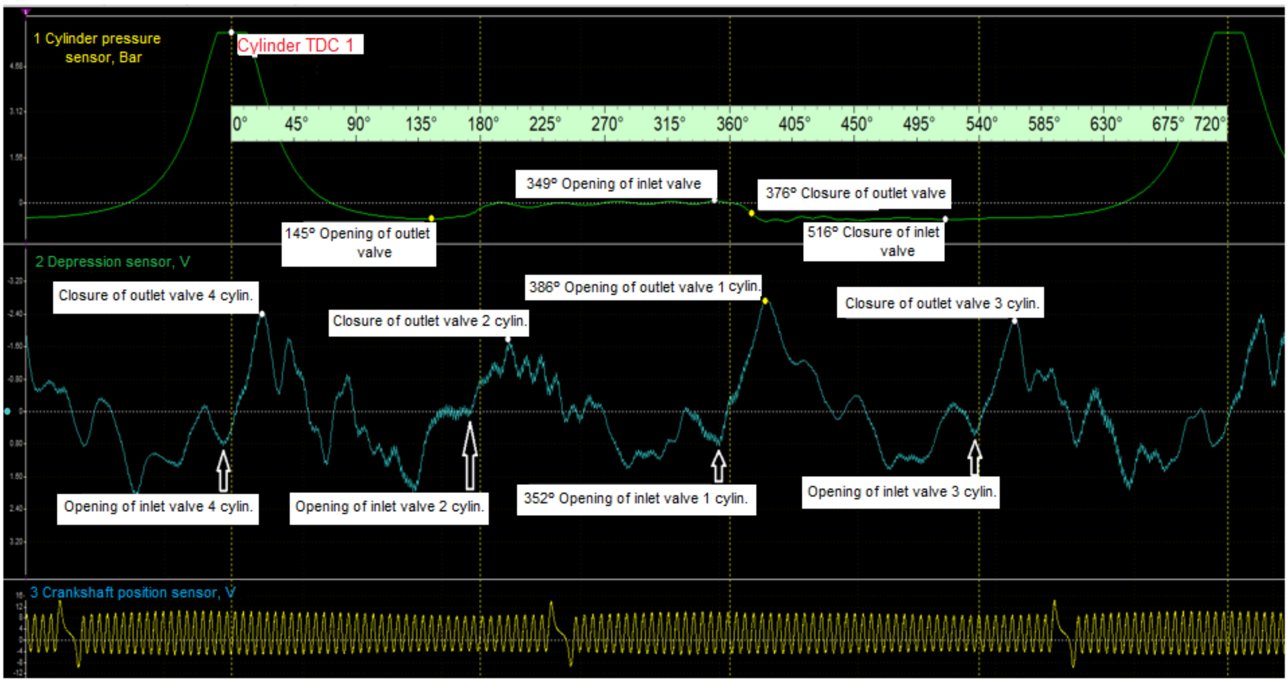


Figure 2. An oscillogram of the pressure sensor (channel 1), the depression sensor (channel 2), the crankshaft position sensor (channel 3)

In modern cars, the electronic control unit actively intervenes in the engine operation, correcting the fuel injection, air quantity, timing angle, and many other actuators. The signal received from the depression sensor constantly changes its format. This method is also characterized by the need for an additional synchronizing signal, which allows one to establish which typical pressure areas in the intake manifold belong to a specific cylinder.

The influence of many indicators on the signals from these two sensors leads to a deviation of the obtained phase values from the actual ones by over 10º by the crankshaft rotation angle. It is also difficult to determine the value of expansion gaps in such an error value.

A comparison of the signals from the crankshaft position sensor and the camshaft position sensor, which are parts of the electronic engine control system, relative to each other allows us to determine the relative position of the shafts.

To operate the sensors, we use encoders made in various driving disks, plates, magnetized tracks, a special shape of the shaft tail, etc.

Let us compare sensor signals on Toyota 2GR-FE (Fig. 3) and Nissan QG15 (Fig. 4).

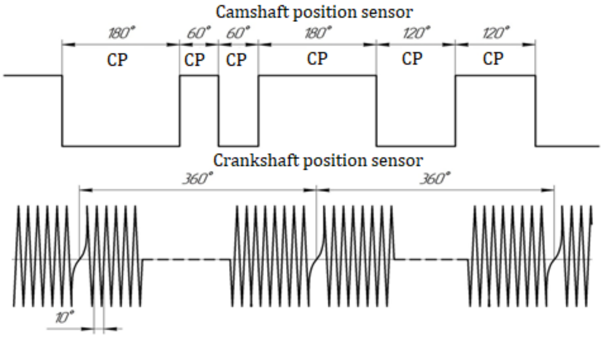


Figure 3. Crankshaft position sensor and camshaft position sensor signals on Toyota 2GR-FE (CP – crankshaft position)

An example of another variant of the crankshaft position sensor and camshaft position sensor signals is from a Nissan QG15 (Fig.4).

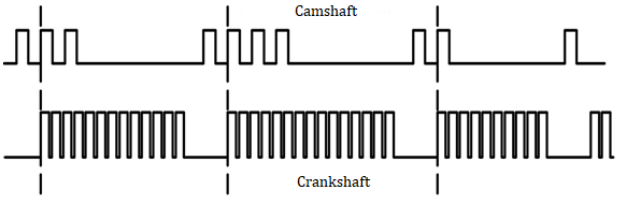


Figure 4. Signals of the crankshaft position sensor and camshaft position sensor on Nissan QG15

A cardinal difference, visible in Fig. 3 as compared to Fig. 4, is expressed in the difference in phase processes, complicating the use of the new phase control methods on various vehicles. Almost every car model has a new version of the phase relationship between the VT and the position of the ICE crankshaft, which, in turn, is its adapted algorithm for applying the diagnostic method. However, this method has unsatisfactory accuracy since it does not consider the presence of expansion gaps and the wear of individual parts of the VT drive.

Let us consider the theoretical features of applying the new method for diagnosing VT (Fig. 5).

Fig. 5 shows a diagram in which, instead of a plug, a bushing is screwed in with a rod at the end of which a tip is located. The tip rests against the piston, which is set TDC. A vibration sensor is screwed onto the end of the sleeve with a nut. With the help of the vibration sensor, a new method for determining the main VT malfunctions (tightness of the "valve-seat" interface, thermal clearance in the valve drive, valve opening and closing phases) is implemented, which consists of measuring and analyzing vibroacoustic pulses caused by the operation of individual engine elements. For the reference signal of the TDC of the piston of the cylinder under study, the vibration pulse from the impact of the piston on an elastic tip placed in the combustion chamber is taken. The maximum amplitude and the moment of vibration impulses are used as signal parameters.

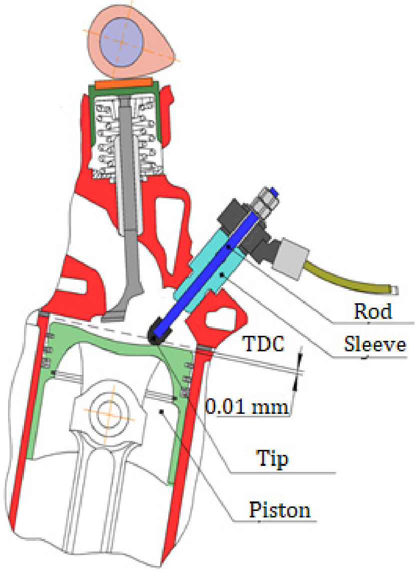


Figure 5. Diagram of the installation of elements when using a new method of diagnosing VT

We prepare for the diagnostics in two stages (Fig. 6).

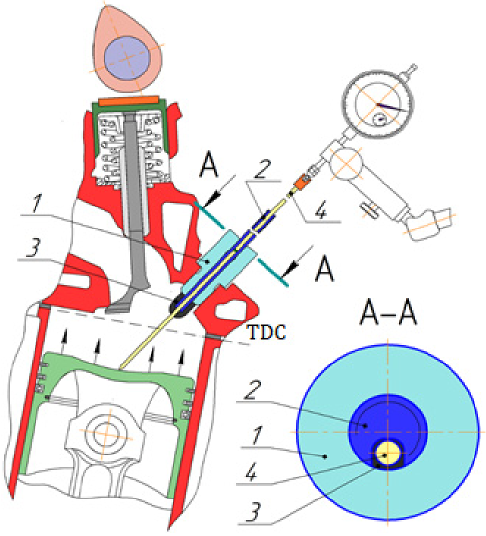


Figure 6. Preparation for measuring VT phases

1. Using a probe (pos. 4), we check the piston stroke of the cylinder for compliance with the standard value. This allows us to exclude possible distortions of the piston TDC caused by the consequences of hydraulic shocks, the discrepancy between the installed crank gear and the engine model, and changes in the combustion chamber volume due to updating the supporting surface of the cylinder head, etc. To this end, a sleeve (pos. 1) with a pin (pos. 2) and a tip (pos. 3) is screwed into the spark plug hole of the (tested) engine as far as it can go (torque ≈10–15Nm). In this case, the tip (pos. 3) with its flat face is pressed against the face (surface B) of the sleeve (pos. 1). The probe (pos. 4) is inserted into the groove on the pin (pos. 2), which can move freely inside the pin and the tip. The probe (pos. 4) has BDC, and TDC marks previously applied for this engine model. Scrolling the crankshaft conveniently, we alternately bring the piston to BDC and TDC. At the extreme positions of the piston, we check the coincidence of the corresponding mark on the probe (BDC, TDC) (pos. 4) with the face of the sleeve (pos. 1) (surface A). Using a dial indicator mounted on fixed support allows us to increase the accuracy of setting the extreme piston positions. After checking the compliance of the piston stroke with the standard value, the piston of the studied cylinder is set below TDC by ≤0.01 mm using the probe (pos. 4), which corresponds to 1–2° of the crankshaft rotation angle. Then the probe is removed from the sleeve bore. Note that we can use any other alternative method providing the specified accuracy to install the piston in a position of 0.01 mm below TDC.

2. Screwing in the pin (pos. 2), we bring the tip into contact with the piston crown. We install the vibration sensor (pos. 5) and press the nut to the sleeve (pos. 1) (8–10 Nm) through the washer (pos. 7), after which we fix it by unscrewing with the second nut. We install the circuit coupling (pos. 8) connecting the vibration sensor (pos. 5) with the oscillograph recorder (motor tester).

The vibration (knock) sensor is connected to the 1st channel of the motor tester tuned to the input range of ±2 V with a sampling rate of 30 kHz.

After the preparatory work, we scroll the crankshaft with the starter for 2–4 seconds.

Figure 7 shows an oscillogram of the signal of the vibration sensor installed in a VAZ 21083 engine.

To visualize the binding of vibration bursts to the crankshaft rotation angle (processes in the ICE), we installed a pressure sensor in the 4th cylinder of the engine with a display of a special ruler. The signal from the sensors was recorded in parallel.

Over a full cycle (four strokes, 720° of crankshaft rotation, 360° of camshaft rotation), the piston at the top dead center twice touches the tip wound on a steel pin used to transmit vibrations to the sensitive element of the vibration sensor. At the same time, the close (valve seating) and open timing (the cam of the camshaft runs into the pusher) of the intake and exhaust valves are also accompanied by the impact action. On the time-based sweep of the oscillogram, we can see bursts standing out from the general noise level in amplitude, while the shape and level of the amplitude are repeated cyclically. The burst starts when the signal reaches 25% of the peak value for the first time and ends when the amplitude falls below this level. This time section of the oscillation onset and decay is a significant part of the signal.

The time dependence of this vibration burst provides information on the valve timings relative to the top dead center of the piston of the studied cylinder.

For the energy assessment of the vibration impulse, we chose the peak value of the amplitude, which is the maximum value of mechanical vibrations, taken into account for the quantitative assessment of short-term mechanical impacts.

During the research, we obtained the vibration impulse's dependence on the piston's impact on the tip (pos. 3) and the crankshaft speed (Fig. 8). In case, during the diagnostics, the amplitude deviates from the reference (graph) by more than 15%, we should check the setting accuracy of the tip and the presence of soot deposits on the piston crown.

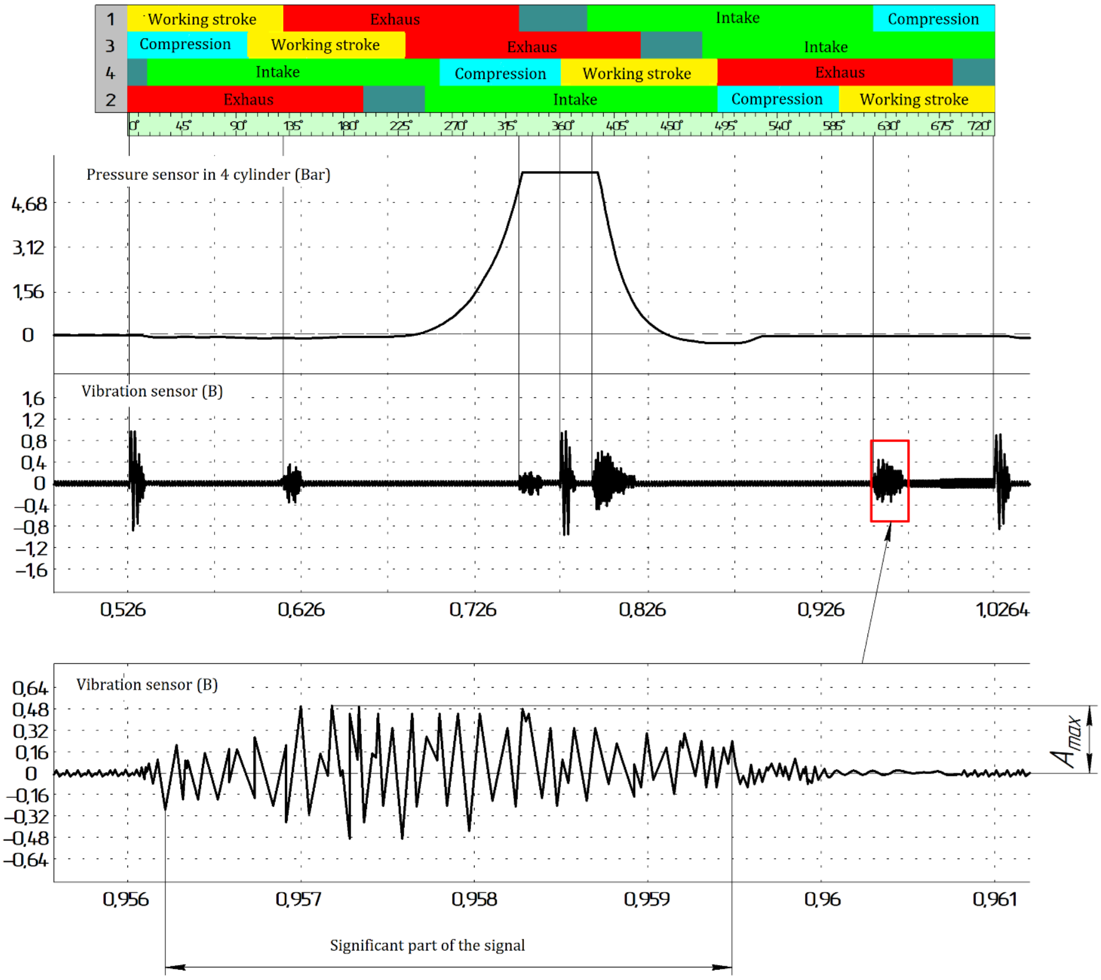


Figure 7. An oscillogram of the vibration sensor in a VAZ 21083 engine

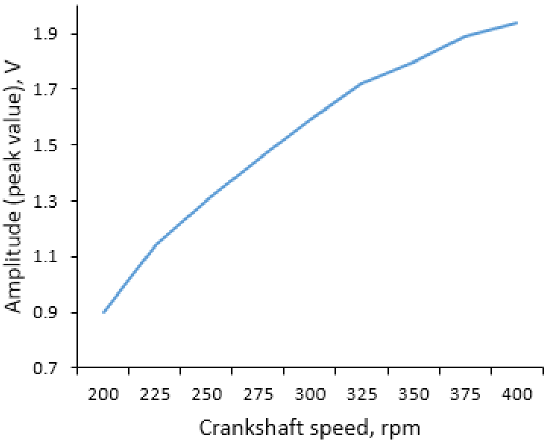


Figure 8. The dependence of the vibration impulse on the impact of the piston on the tip (set 0.01 mm before TDC) and the crankshaft speed for a VAZ 21083 engine

Soot deposits on the piston surface affect the spatial height of the piston and can range from 0.01 to 1 mm or even more. Using the spatial registration of the piston position at the BDC and then at the TDC relative to the base parts of the ICE unit, we can fix their position on the reference ICE before operation and by the angular position relative to the crankshaft position sensor and the VT phase sensor.

We can also fix the position of the camshaft cam when the TDC is reached. Subsequent checking is accompanied by an assessment of the technical status of the VT during the gradual formation of soot. There is also an angular displacement of the piston position and its contact with the elastic tip relative to the angle measured by the crankshaft position sensor and the VT phase sensor. This is recorded by the proposed indicator with an accuracy up to thousandths of a millimeter. However, soot can have a damping effect on the elastic tip. Still, this effect is minor since it is integral to the mass of the piston and is deposited on the inertial parameters of the piston. In our case, a small contact is needed to identify the TDC moment. Fixing the relative piston position on a new ICE allows us to consider this soot formation error and its influence on the assessment of vibration para–meters relative to the angular parameters of the crankshaft position.

We similarly constructed the dependences of the vibration impulse energy on the valve timing, the value of the expansion gap, and the crankshaft speed (Fig. 9).

After comparing the reference values (for this engine model) of the vibration impulse energy with the actual am–plitudes of the received signal, we can conclude that the expansion gap in the valve drive is the main factor affecting the dynamics of the interaction of the VT elements.

We propose analyzing the tightness of the valve–seat interface as follows. The piston rapidly moves up during the compression stroke while the valves are closed. The above-piston space is connected to the atmosphere through the hole in the tip (pos. 3). Twenty degrees before TDC, the speed of the outgoing airflow increases significantly, mainly affecting the sleeve (pos. 1), thereby causing oscillations in the sensitive element of the vibration sensor. A section with a significant increase in the maximum amplitude appears on the oscillogram (Fig. 10).

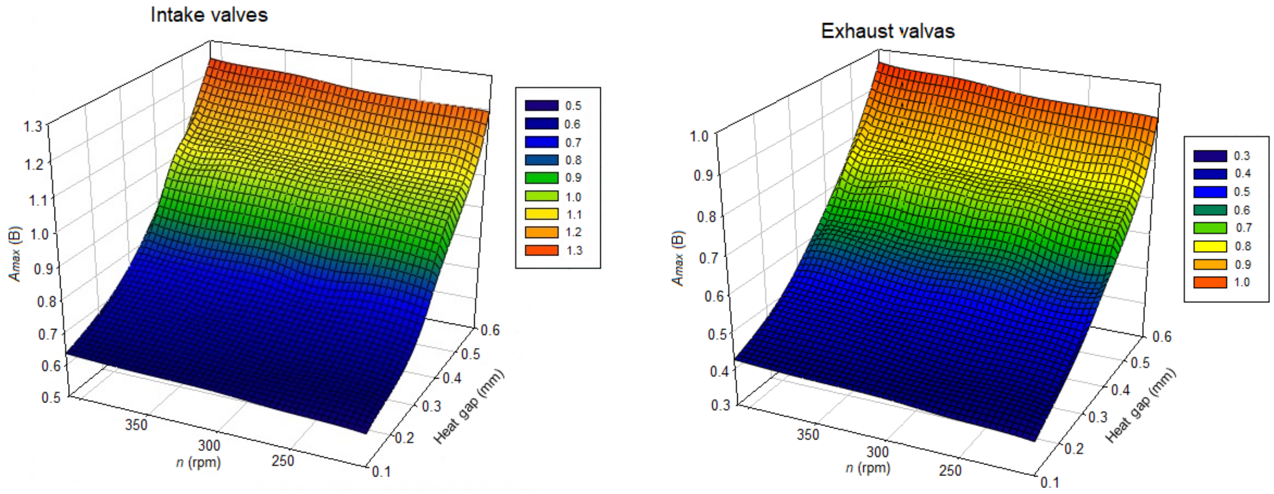


Figure 9. The dependence of the vibration impulse on the impact of the valve on the seat (valve timing), the value of the expansion gap, and the crankshaft speed for a VAZ 21083 engine

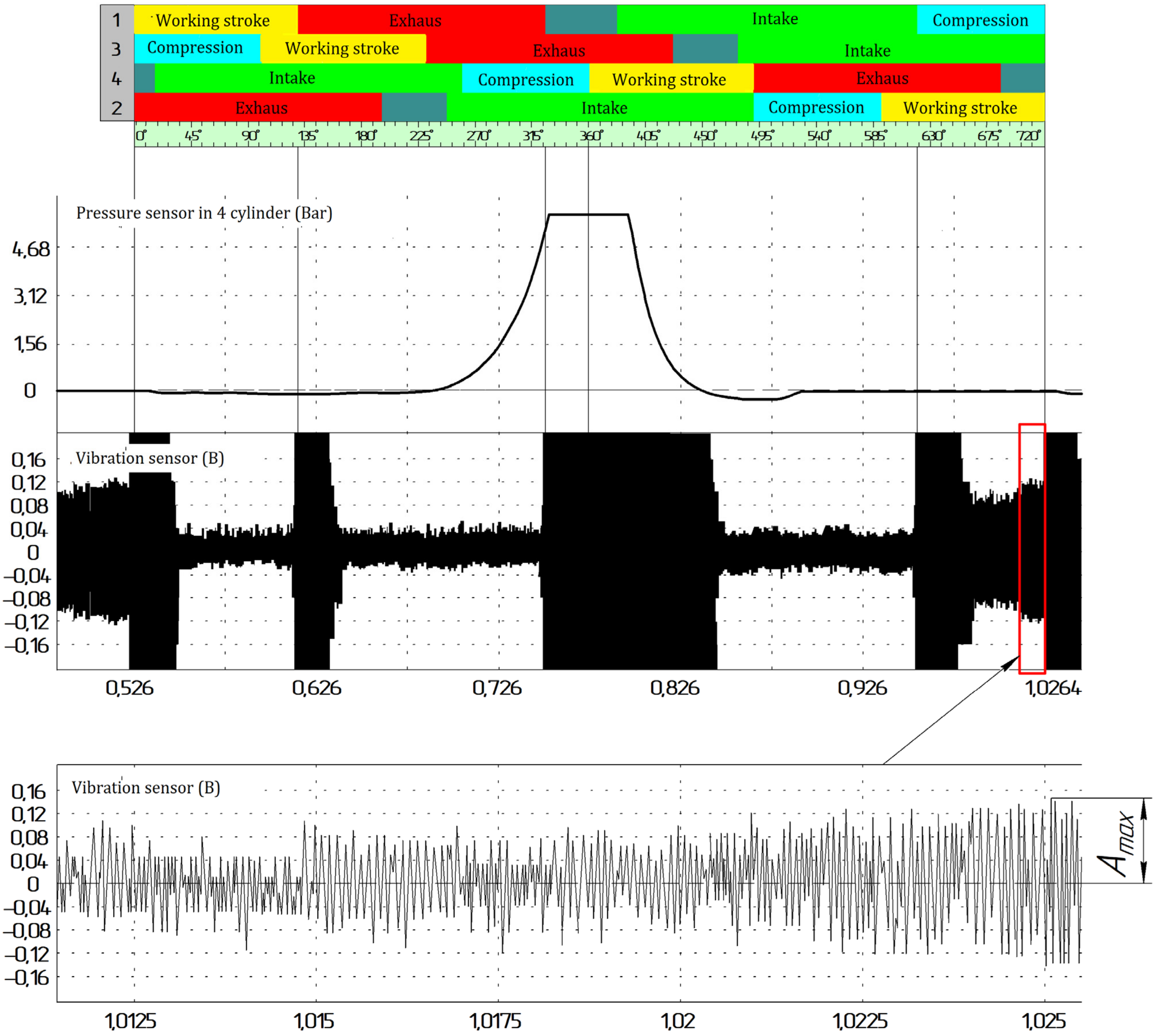


Figure 10. An oscillogram of the vibration sensor during the compression stroke for a VAZ 21083 engine

After predetermining the leakage of the above-piston space with a pneumatic tester, we determined the dependence of the maximum vibration amplitude during the compression stroke on the crankshaft speed (Fig. 11).

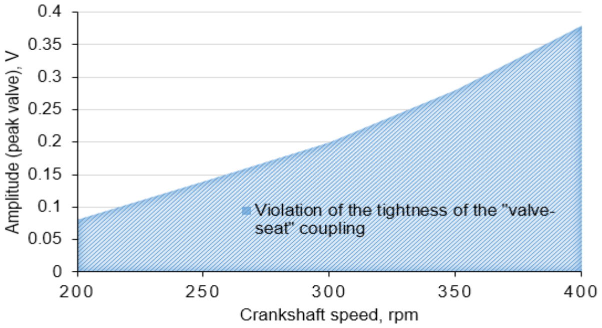


Figure 11. The dependence of vibration during the compression stroke on the crankshaft speed for a VAZ 21083 engine

Our results establish that if there is a free area for the gases to pass near the valve equal to 0.2 mm^2, the maximum vibration amplitude during the compression stroke is reduced by 30% of the indicator at complete tightness of the valve–seat interface.

3. THEORETICAL CALCULATIONS

With the further development of the new method, the need arose for calculations to ensure a trouble-free diagnostic. The software used was Solid Works Simulation with the Finite Element Method (FEM) built into it. The FEM method solves a system of equations that consider each element's behavior in connection with other elements. These equations relate the model used to known material properties, constraints, and loads. Next, the program arranges the equations into a large system of joint algebraic equations and finds the unknowns. The program finds the displacements at each node to calculate the stresses and then calculates the strains and final stress.

The studies were carried out based on nonlinear dynamic analysis since the BFlex material from which the tip is made has a nonlinear relationship between stress and deformation. The loads, in some cases, change during the deformation of the model.

Before reaching TDC 0.01 mm (which corresponds to less than 2 degrees of crankshaft rotation), the piston strikes against the elastic tip rigidly fixed to a steel rod. According to the kinematic calculation, the piston moves at a set speed with the total reduced mass equal to 0.665 kg.

It is common to use a 2-D simplification of the in-plane stress type since the forces acting normal to the selected section plane are negligible (Fig. 12).

Each element has been assigned a material from which it is made, with the related physical properties.

Due to the very small change in speed when the piston moves, let us set the dependence of the displacement on the rate linearly at two points corresponding to the moment of impact and TDC of the piston. Figure 13 shows the dependence of the piston speed on the size of the gap. The gap size was chosen as 0.01 mm, taking into account the properties of the material used for the tip.

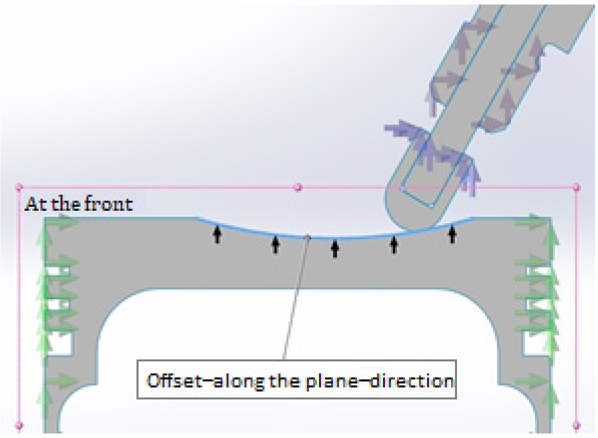


Figure 12. Limitations (fixed geometry)

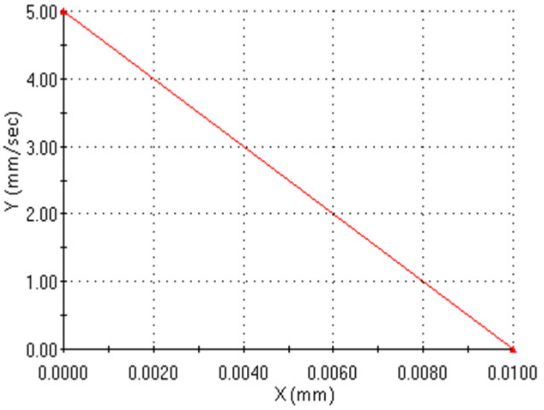


Figure 13. The dependence of the piston speed on the clearance

Let us choose two contacting edges with the condition – "no penetration" and a friction coefficient of 0.5.

Fig. 14 shows the contact conditions of the elements when implementing the new diagnostic method.

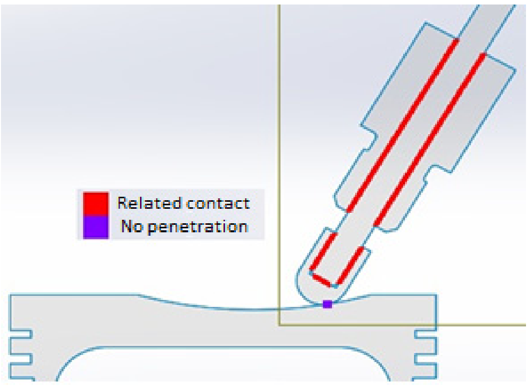


Figure 14. Contact conditions

We will apply a mesh of parabolic tetrahedral solid elements in the next stage, as shown in Fig. 15.

For the calculations, a high-quality mesh was created in parabolic tetrahedral solids (Fig. 15) since they more accurately represent curved boundaries and produce better mathematical approximations than linear tetrahedral solids. Based on the volume and surface area of the model, a 0.9-mm global mesh element was selected, while in the contact and transition zone, the mesh has a denser structure to increase the convergence of the results.

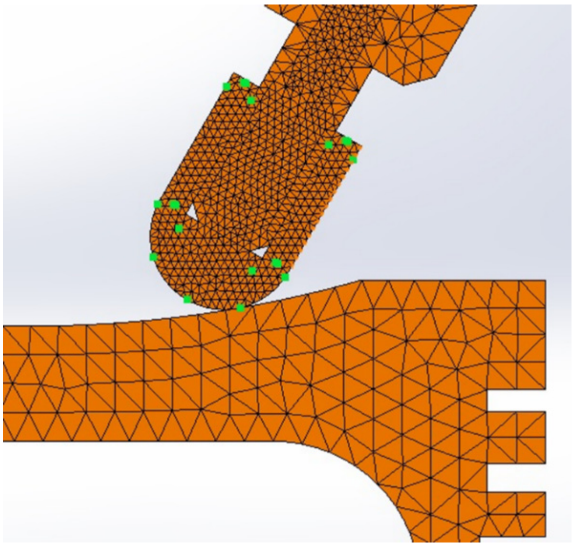
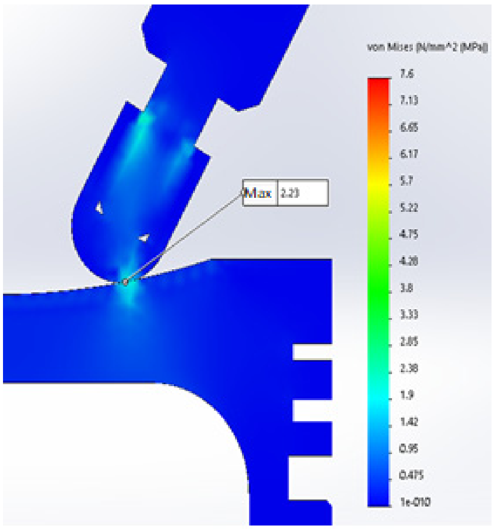


Figure 15. Mesh of parabolic tetrahedral solid elements

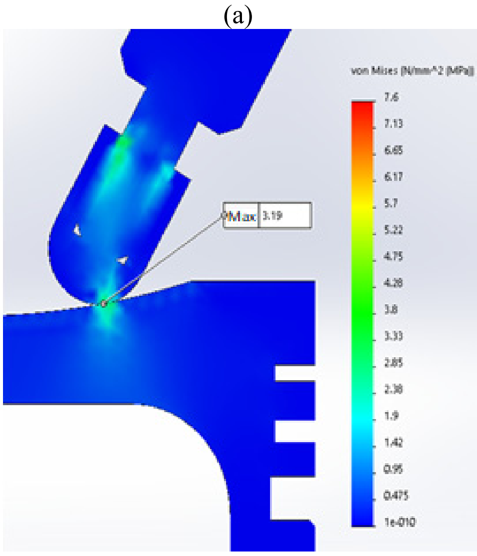
The calculation results in the Solid Works Simu–lation application are shown in Fig. 16.

Fig. 16 shows the stresses realized when the tip contacts the piston surface at different speeds of the piston movement.

In Fig. 16 (e) and (f), the limiting stresses have formed, which indicate a limitation of the applied load.



(a)



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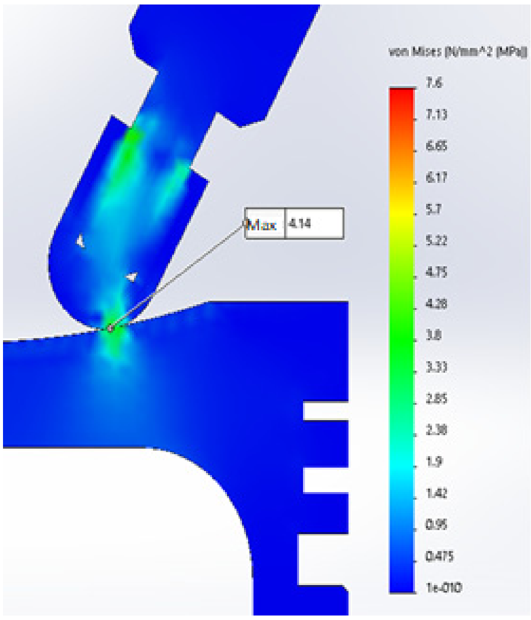
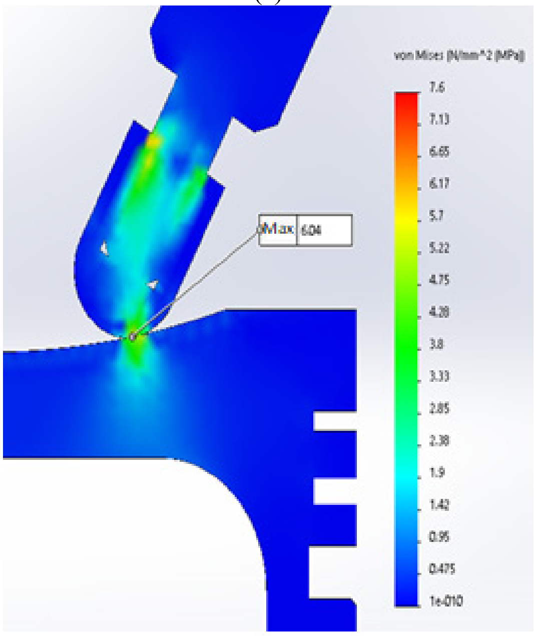


(c)



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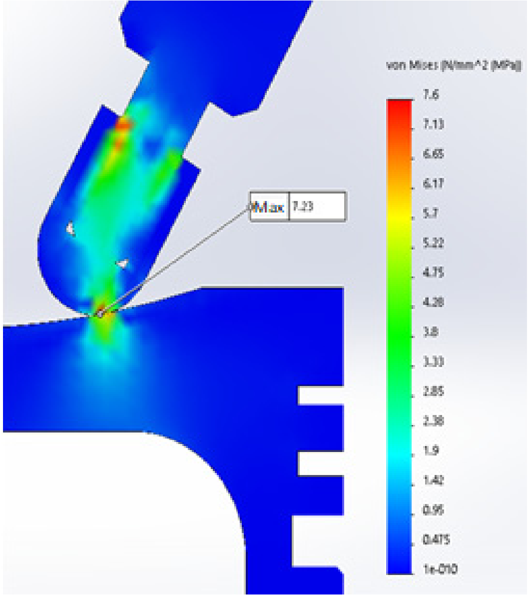
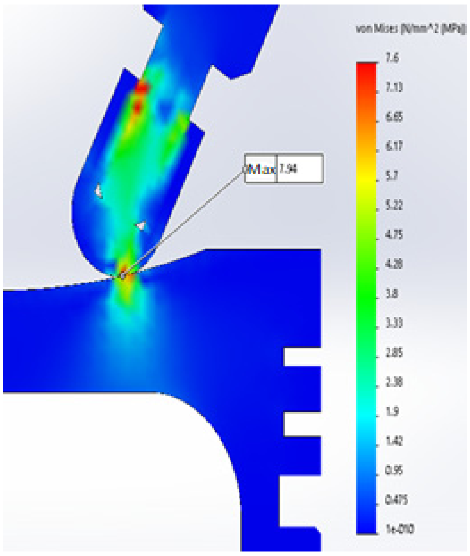


(e)



(f)

Figure 16. Calculation results in the Solid Works Simulation application: (a) 250 rpm, (b) 300 rpm, (c) 350 rpm, (d) 500 rpm, (e) 600 rpm, (f) 700 rpm.

Based on the strength calculation results, the stress values' dependence on the crankshaft rotation frequency was plotted for various depths of the tip depth towards the piston (Fig. 17).

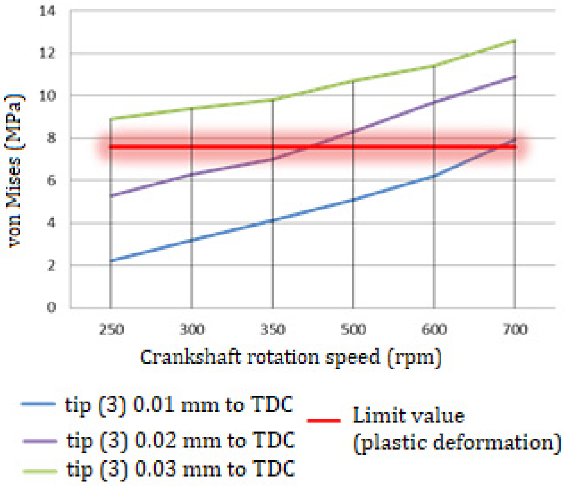


Figure 17. Dependence of the stress values on the crank–shaft speed at different depths of the tip towards the piston

The red line denotes the limiting stress value at which deformations flow from elastic to plastic. From Fig. 17, we can conclude that when the tip is deepened, according to the diagnostic method, it is 0.01 mm lower than the TDC, at a speed of up to 600 rpm (which is more than the crankshaft speed when cranking with a starter), the tip does not experience plastic deformation and reused.

4. CONCLUSION

This article demonstrates a new method for diagnosing VT, based on monitoring the vibrations of its elements.

The main advantages of this method are:

•the high versatility in relation to components and systems of vehicles,

•the controllability of the relative change in the parameters of the vibration process over time, taking into account the spatial displacement of the phases,

•the simultaneous usability of signals recorded from sensors and ICE actuators,

•the ability to filter the signal and separate useful frequencies from the content,

•the easy use of oscilloscope monitoring tools and the ability to record and analyze the diagnostic information,

•the usability of ready-made program scripts for information analysis,

•the high sensitivity to minor changes in the vibration parameter,

•the precise determination of the angular position of the piston and individual valves when an elastic tip is used,

•the ability to determine the error, taking into account the effect of soot deposits on the piston, the timing belt's stretching, and the camshaft cam's wear.

The main elements of the VT control device have been designed and calculated. The installation gap between the tip and the piston should not exceed 0.01 mm. The use of the diagnostic motor tester Diamag 2 in conjunction with a vibration sensor increases the reliability of VT diagnostics up to 0.96.

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РАЗВОЈ МЕТОДОЛОШКИХ ТЕХНИКА И АЛГОРИТМА ЗА ДИЈАГНОСТИКОВАЊЕ САВРЕМЕНИХ УСИСНИХ СИСТЕМА ЗА МОТОРЕ СА УНУТРАШЊИМ САГОРЕВАЊЕМ

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Тип Дијагностиковање и откривање кварова у мото–рима са унутрашњим сагоревањем (ИЦЕ) није лак задатак због њиховог сложеног дизајна. Право–времени и висококвалитетни ИЦЕ надзор омогућава одржавање перформанси и спречава кварове. Ана–лиза вибрација и звука је моћан и информативан алат за откривање кварова чак и у раној фази.

У овом чланку се разматра метода за одређивање главних кварова вентилског механизма (ВТ) (заптивеност интерфејса „седиште вентила“, термални јаз у погону вентила, фазе отварања и затварања вен–тила) мерењем и анализом виброакустичких им–пулса изазваних радом. појединих елемената мотора. Као параметри сигнала користе се мак–симална ампли–туда и момент вибрационих импулса. За референтни сигнал клипа, горње мртве тачке (ТДЦ) цилиндра који се проучава, узима се вибрацијски импулс од удара клипа на еластични врх постављен у комору за сагоревање. Ова техника омогућава искључивање спољашњих утицаја и нетачности повезаних са променом геометрије ИЦЕ елемената.