New analytical method for engine diagnostics based on pressure indication of cylinder clearance

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Abstract: Engine indication is a measuring method applied primarily in the field of engine development. The development of sensors have made it possible to apply it - without dismantling - for diagnostic methods.

We have elaborated its methods within the frame of a research project. We are to introduce the results of this work in the forthcoming study.

Keywords: indicated pressure, mean indicated pressure, indicating spark-plug,

1. Introduction

With the traditional analytical methods only the engine performance on the crankshaft could be measured (P_e, namely effective performance). The pressure change of the process which is taking place in the cylinder can be determined by measuring the pressure of the cylinder clearance or as it is defined by the technical literature with indication.

In internal combustion engines the chemical energy of the fuel taken in within the given cycle transforms into thermal energy, then - due to the change of pressure and volume - into power. In the meantime the volume of work space periodically changes. **During the work procedure the pressure of the working media constantly changes and this pressure change can be shown in the form of an indication diagram.**

The indication diagram displayed according to the piston shift of the four–stroke engine can be seen in Figure 1., while the diagram according to the angular displacement can be seen in Figure 2. In view of the features of crank mechanism, one of the diagrams contributes to the design of the other.

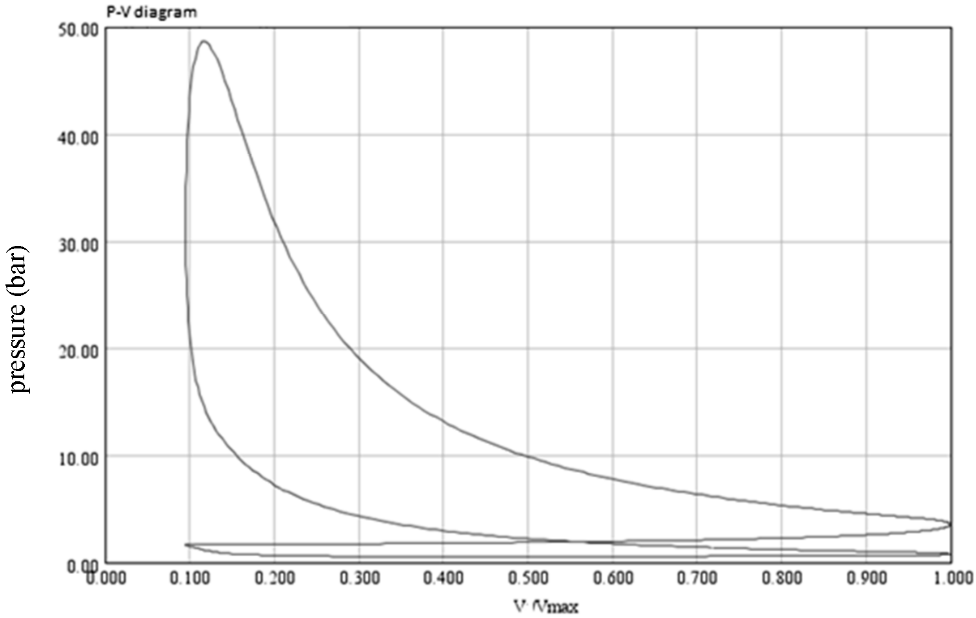

Figure 1. indication diagram displayed according to the piston shift

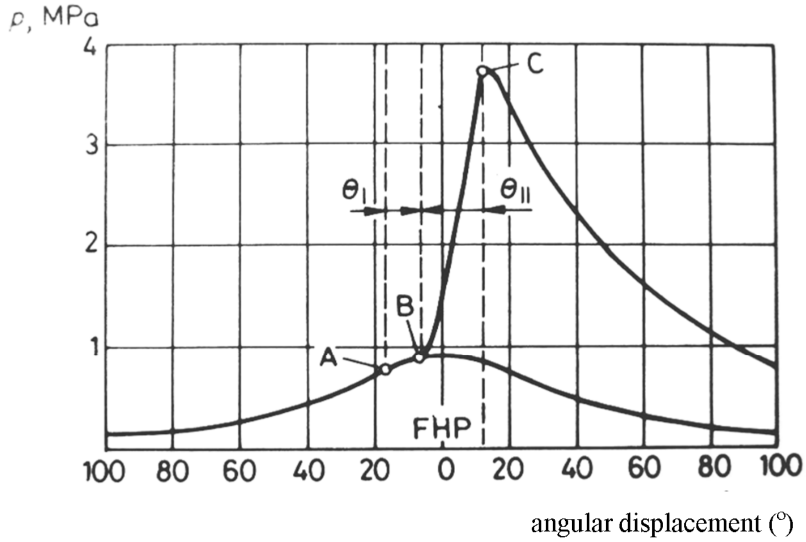

Figure 2. indication diagram displayed according to angular displacement (A – ignition, B – the beginning of the combustion, C – maximum pressure, Θ_I – ignition delay, Θ_{II} – pressure increase section)

2. Indicated features

The mean indicated pressure is the mean height of the efficient space of p-V indicator diagram. **The efficient space of p-V indicator diagram defines the value of the indicated work for a cycle**. If we divide the indicated work with the cylinder displacement we get the mean indicated pressure:

$$p_i = \frac{w_i}{V_H} \qquad \left[J/m^3 \qquad vagy \qquad N/m^2 \right]$$

(The mean indicated pressure is expressed in kPa or MPa.) It is obvious from the measuring units that the mean indicated pressure can be defined as well as the indicated work derived from unit cylinder displacement.

In view of the indication diagram the indicated work can be defined with clearance measurement. The clearance of the charge change process of uncharged two- or four- stroke engines has negative sign.

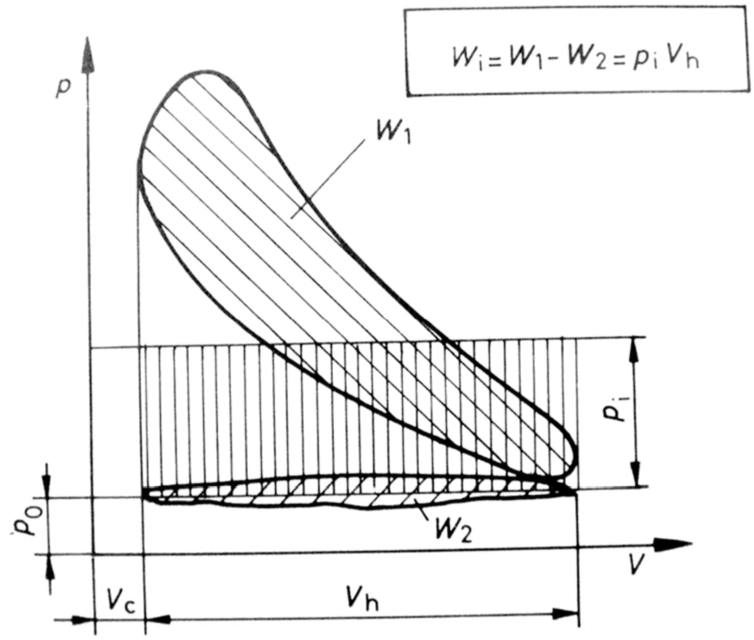

Figure 3. Indicated features

The indicated mean pressure changes along with the load of the engine, it reaches its lowest value in the idling position of the engine, here the indicated work only meet the energy needs of friction and auxiliary equipment (p_i=p_m).

Indicated work calculated from the indication diagram of one cylinder of the engine during one work cycle

$$W_i = p_i \cdot V_H \qquad [Nm]$$

Where:

- p_i the mean indicated pressure
- V_H the cylinder displacement.

The number of work cycles per seconds $\frac{2n}{i}$, where **n** is the revolution number of the crankshaft in 1/s; **2n** is the number of piston stroke per seconds, **i** is the number of strokes during one work cycle. On the basis of this the indicated performance of the engine with **z** number of cylinders:

$$p_i = \frac{2}{i} \cdot p_i \cdot z \cdot V_H \cdot n \qquad [W]$$

Where:

- in case of four-stroke engine: i=4,
- in case of two-stroke engine: i= 2.

The performance is generally expressed in kW. The indicated power efficiency and the indicated specific fuel consumption are the economic efficiency indices of the indicated features of the engine.

The unit used for specific fuel consumption in practise is **g/kWh**. In case of natural gas vehicles the specific fuel consumption is defined according to volume unit, **m^3/kWh**, or **MJ/kWh** specific thermal energy consumption is applied to describe the efficiency of the engine.

The measured performance on the crankshaft of the engine, the effective performance, is lower than the indicated performance calculated on the basis of the indication diagram. A definite proportion of the indicated performance is consumed to move the components of the engine shifting on each other and to sustain the continuity of the operation of the engine. By signing this necessary loss with P_m the effective performance of the engine can be expressed in the following way:

$$p_e = p_i - p_m$$

The notion of mean effective pressure (p_e) and the mean pressure (p_m) featuring the mechanical losses can be defined by the mechanical performance loss and the work of effective performance for a work unit- as in case of indicated work- according to a unit displacement. With the help of them the adequate performances can be expressed like in case of the indicated features.

The mechanical losses can be expressed even with the help of the mechanical power efficiency:

$$\eta_m = \frac{P_i - P_m}{P_i} = 1 - \frac{P_m}{P_i} = \frac{P_e}{P_i}$$

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One part of the mechanical losses of the engine is caused by friction (firstly between pistons and cylinders, secondly bearing frictions) which is signed by P_s. We mean by the performance needs (P_b) of the auxiliary equipment the needs of the oil pump, the water pump, the ignition or injection device, the fuel pump and depending on the standards about recording the measuring conditions the performance need of the cooling fan. In addition the performance need of the compressor (P_k) in case of two-stroke engines without crank chamber compression (and mechanically charged four-stroke engines). Thus the relation between effective and indicated performance is the following:

$$P_e = \eta_m P_i$$

3. DIAGNOSTIC METHOD BASED ON ENGINE INDICATION

3.1. Analysed vehicle and engine

The vehicle selected for the analysis was a VW Jetta (Figure 4.).

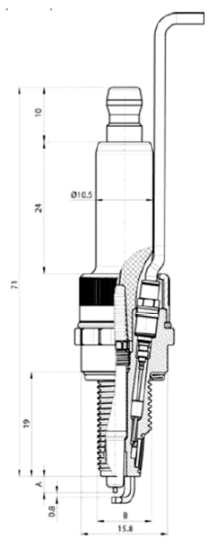
Figure 4.: The analysed vehicle

3.2. The compiled measurement system

Engine indication is a fundamental method for engine experiments. In the project we took up the challenge to elaborate a new diagnostic method (analysis without or with partial disassembly).

For measuring we chose the following type of pressure gauge spark-plug (according to the dimension and the heat range of the spark-plug prescribed for the engine):

GG1452 INDICATING SET GH13Z-24/ ZF43 F7L PRT



Other dimensions

A=The position of the electrode

Figure 5: Indicator spark-plug

AVL DPM-800 spark-plug for checking cylinder clearance completely contains the pressure gauge integrated into the spark-plug.

The newly developed indicator spark-plug is suitable for very precise pressure measurement without disturbing or influencing the combustion procedures anyhow. Available with M10, M12 bore diameters, different length and 3, 5 and 7 heat range.

Built-in detecting piezocrystall, namely GaPO4 (gallium-phosphate) unit sensitivity 12 pC/bar. The new device can provide aid not only in engine development, in chip-tuning, but in the field of engine diagnostics of repair industry.

The primary objective of the development of the pressure gauge of the spark-plug was to achieve an adequately long lifespan during test circumstances. The platinum-electrode is such a component of the spark-plug which has adequate solidity and bears thermal strains for long period. The body electrode is also platinum-tipped. During the 30.000 km long test cycle no failure was experienced by the developers in the combustion and pressure gauge function of the spark-plug. Due to the transparent modular structure even the end user can replace the components of the units.

The construction of the measuring system:

The new measuring system was designed by using the following components:

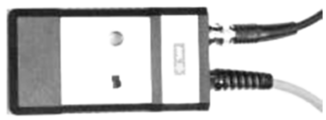
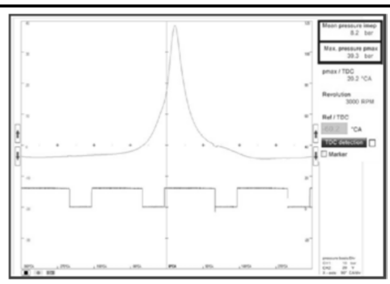
AVL piezo spark-plug	
AVL amplifier unit	
AVL DiScope 802 dual channel oscilloscope	
AVL DiX modular measurement software	

Table 1.: components of the new diagnostic system for measuring pressure

The installation of the indicator spark-plug had to be conducted with due foresight.

3.3. Analysing working points

The load feature range of combustion engines consists infinite number of working points.

For the purpose of our analysis we have selected some of these points located on the characteristic curve. The working points of the characteristic curve are stationary working points, which mean that the characteristic features of the engine (revolution number and load) defining the working point are kept at a constant level. The regulated operation of today's engines affects the cycle stationarity within the working points. This fact will be analysed later.

To serve the purpose of the analysis we have chosen two types of characteristic curves (Figure 6.):

- the rolling resistance characteristic curve (Fv ~ v2)
  1. load characteristic curve,
- the external (complete load) moment characteristic curve
  2. load characteristic curve.

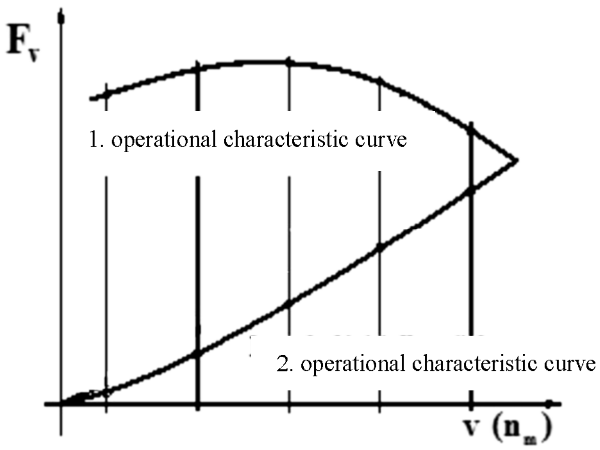


Figure 6.: analysed operational characteristic curves

In the following part of the study we summarize the values of indicator diagrams at the given measurement points of the characteristic curve. The values in the rows of the diagrams are the data of the indicator diagram characterising the work cycle of the examined cylinder of the engine. The deviation of the values derives from the fact that variable work cycles are added to the average (constant) level of the performance achieved through the wheels due to the operation of the engine. This variable value is strengthened by the control cycles located on the engine, such as the regulation of lambda or combustion knock. Their operation cause slight continuous changes on operating parameters.

The working point values are in every case the average of the cycle values. Some photos are shown below to illustrate the measurements.

Figure 7.: installation of the indicator spark-plug

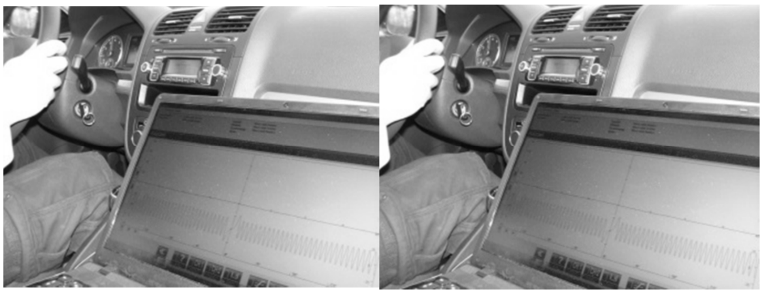


Figure 8.: Measurement on the motorway

The majority of the measurements due to reproductivity were accomplished in the Vehicle Diagnostic Laboratory of the Department of Automotive and Railway Engineering on free rollers.

The measurements were accomplished even in flawless conditions and with simulated failures.

Velocity 60 km/h; load 100%						
	Mean indicated Pressure		Maximum combustion pressure		pmax/FHP	Revolution number
	bar	N/mm^2	bar	N/mm2	degree	Rev/min
1.	4,3	43	14,9	149	112	2280
2.	4,5	45	16,3	163	110,7	2270
3.	4,5	45	17,1	171	111,3	2270
4.	..	..	..	..	..	..
19.	4,7	47	16,4	164	110,7	2230
20.	4,5	45	22,5	225	109,9	2230
Max	4,7	47	22,5	225	114,8	2280
Min	3,7	37	12,1	121	109,8	2220
Average	4,29	42,85	15,33	153,25	112,02	2244,50
Difference	1	10	10,4	104	5	60
Variation	0,22	2,23	2,11	21,13	1,50	20,38

Table 2.: cycle features of square load characteristics (v=60 km/h)

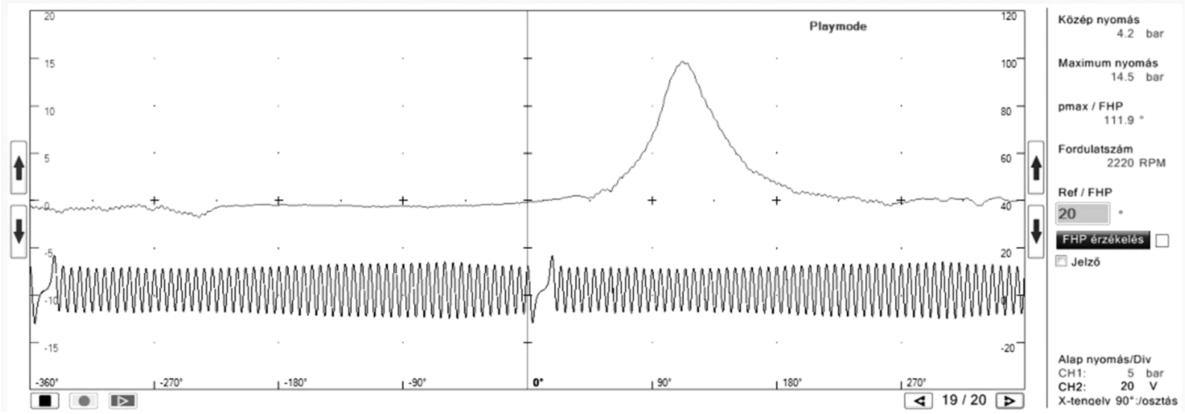


Figure 9.: indicator diagram (Working point: square load characteristics, v=60 km/h)

After the flawless conditions let's have a look at some simulated failures, or more precisely their consequences on diagrams and measured registers:

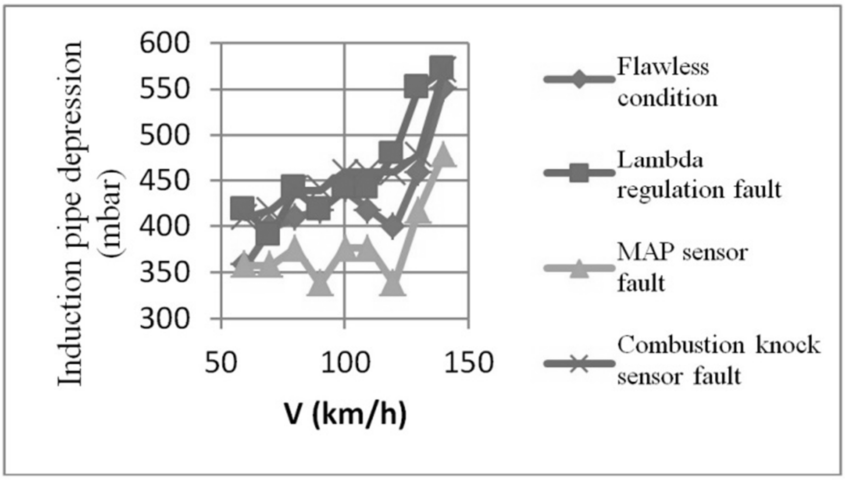


Figure 10.: failures measured along with square load characteristics compared in the view of induction pipe depression

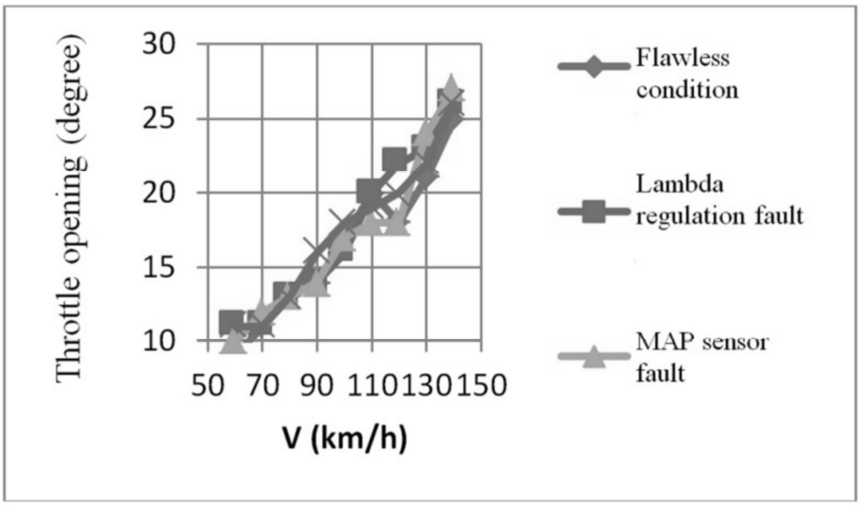


Figure 11.: comparison of failures measured along with square load characteristics in the view of opening angle of the throttle

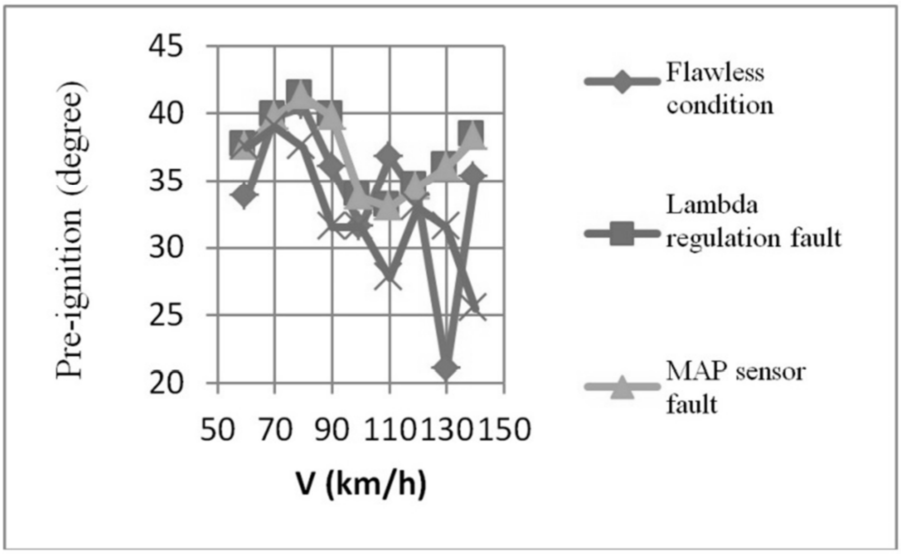


Figure 12.: comparison of failures measured along with square load characteristics in the view of opening angle of the pre-ignition

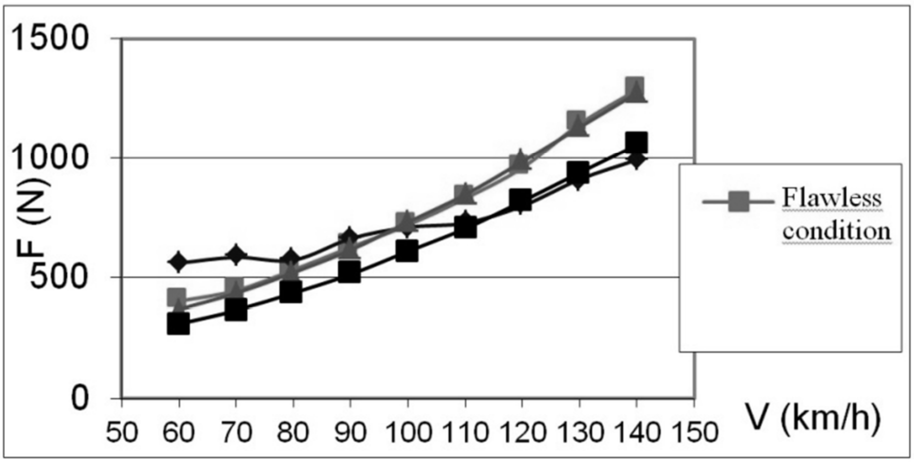


Figure 13.: comparison of failures measured along with square load characteristics in the view of tractive force

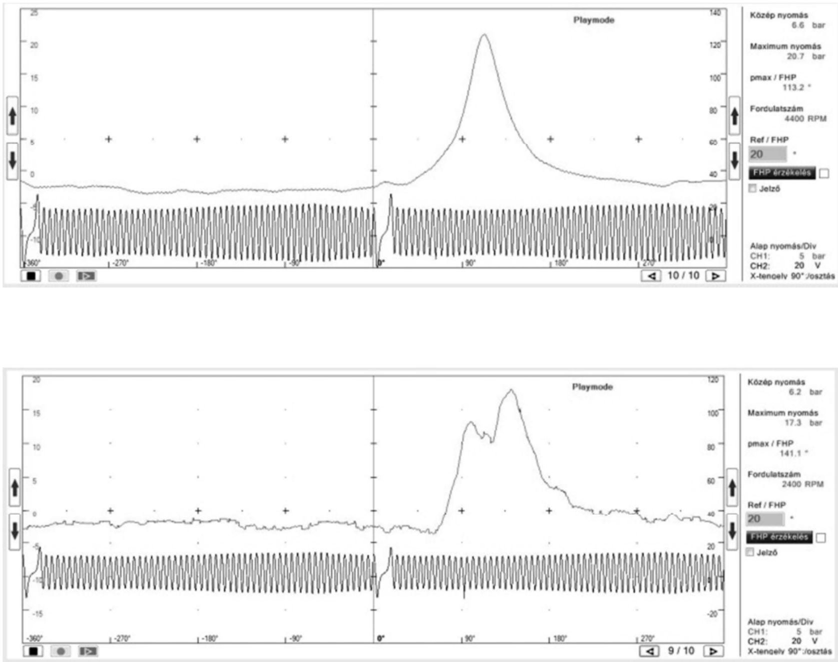


Figure 14.: Combustion knock sensor fault (maximum load): the picture above is flawless, the one below is faulty

4. CONCLUSIONS, ASSESSMENT

In case of Otto engines the variation of work cycles is typical on given working points. The reasons derive from the values differ in time and space of combustion velocity. This is caused by the fact that at different points of the combustion chamber the mixture formulation is not homogeneous. With the improvement of the quality of the mixture formulation the range of cycle variation can be reduced.

The average of the cycle features differing form each other is typical to the given working points. Due to this in the tables recorded at the working points with measurements we have shown the values of the average and the deviation.

The variation of the cycles is influenced by the controlled systems of the engine, too, as at the given working points they affect the setting features of the engine. Thus, if the controlled systems are excluded (e.g.: lambda- and combustion knock control) the rate of cycle variation is reduced. Concerning this, several measurements have been accomplished in the previous chapter.

The biggest recognizable difference triggered with the exclusion of combustion knock sensor, in both of the cases of maximum and square load. In this case the maximum load condition is more characteristic since the risk of combustion knock is the highest here.

The newly designed measurement system and method make it possible to apply engine indication, which was only used formerly for research and development, for diagnostic purposes.

Its significance is that the introduced procedures make it possible to conduct measures even on the highways due to the flexibility of the formulation of the measurement system.

For measures we have to possess reference pictures and data about the analysed type which can be obtained by measuring reference vehicles with flawless technical conditions. We should assign the reference data to the measured operation identification features.

During the further diagnostic analyses, we measure at the same working points as of the reference state, and the measured pictures, data are to be compared with the features of the given type recorded at its flawless state.

We should take into account the cycle variations and always take the average picture as a basis from the cycle pictures of measured time intervals (e.g. 20s).

The advantages of the laborscope integrated into the measuring instrument can be utilized at the examination to accomplish the oscilloscope analysis of sensors and interferers besides pressure analysis. For this, reference pictures are stored for the measuring notebook, moreover there is availability to store more data on it.

The prototype of the developed new measurement method and measurement system within the scope of the research is such a practically applicable digital measuring unit or measurement system which is not only adequate for indicating the cylinder clearance of the engine (measuring pressure) but with the help of the integrated digital oscilloscope the signals and characteristic features of electronic transmitters can be displayed and compared with reference pictures or with one another.

During the research work we tested the tool for weeks, gathered information and measurement results.

On the basis of this according to its usage the measurement system can be divided into 2 main types:

Direct measurement: when one of the signs of the transmitter of the vehicle is displayed on the screen, and by considering the value and shape of this electrical sign we can deduce to the failure. In case of e.g.: generator, ignition system, transmitters, etc.

Indirect measurement: We record reference values with the instrument and we compare them with the later measured values or signs (E.g.: pressure analysis of the cylinder clearance or even the analysis of transmitters, interferers can be accomplished).

The process of indirect measurement:

Recording reference signal or value

The reference signal is actually the comparative parameter of the original state (Those service-stations which have availability to the original parameters of the vehicles serviced by them do not have to take reference data, just obtain these original data)

The database of reference signal can be voluntarily extended:

The recording of the reference signal can take place on straight, level road while the vehicle is moving (level road rolling resistance load or rolling road).

According to our experiences the speed at 100 km/h is suitable for that. It is advisable to look for a relatively long straight flat section of a motorway. Be careful, as a hill- or slope running or load of the vehicle may significantly affect the measurement. The instrument can record altogether 100 pictures during a measurement. It is suggested to be utilized by the users namely the length of recording signs should last at least 1 minute.

Recording signs of diagnosed/faulty vehicle

The process of recording signs of faulty vehicle takes place exactly in the same way as it was described at the reference signs. The process of evaluation is also equivalent.

Revealing the fault

The fault is revealed by comparing the reference and the faulty sign. Here we have to pay attention to the values and the shape of the sign.

With the help of the comparison of the two figures it can be unambiguously stated that there is a significant variance both between the sign shape and the values of maximum and mean pressure.

The practise of everyday application will provide the routine of decision making in diagnostic measurement for which the storage of more faulty and reference pictures in the database is needed.

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