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A NEW METHOD FOR TECHNICAL DIAGNOSTICS OF DIESEL ENGINE CYLINDER

NOVA METODA ZA ODREĐIVANJE TEHNIČKOG STANJA CILINDRA DIZEL MOTORA

U ovom radu dana je mogućnost primjenljivosti dijagnosticiranja cilindra na osnovu vibracija cilindra.

Definirana je nova metoda koja je pokazala prednosti u odnosu na druge poznate metode. Istražen je utjecaj promjene tlaka u cilindru i režim rada motora na određivanje istrošenja cilindra. Teorijske postavke i eksperimentalni rezultati potvrdili su da je to jedna nova mogućnost definiranja tehničkog stanja cilindra, bez rasklapanja, izrazito pogodna za primjeno u praksi.

1. INTRODUCTION

Increasingly complex engine design, severe conditions of exploitation and our present inability to simply and quickly determine the technical state of any means, have resulted in an increase of work and maintenance expenses. To reduce the amount of work and the expenses it is necessary to provide a quick and simple method for determining the technical state of the elements and assemblies.

Promising methods for engine diagnostics are methods that do not need disassembling, and among them the most powerful tool for determining the technical state of the engine is the vibration method. Vibrations of assembly elements as well as the engine cylinder contain numerous information about the assembly condition. To isolate the information parameters of the vibrations according to time and frequency, the existing spectral and correlation methods are complex regarded from the aspect of practical application for the cylinder diagnostics, because apart from the special processing procedure of the signal they need to be supplemented by detailed information about the pressure change in the cylinder [1].

The aim of this paper is to show a new possibility for determining the cylinder wear. As the diagnostic parameter, the moment when the piston strikes the cylinder is used, which is determined by the cylinder vibration signal. The theoretical assumptions of the new method have been verified by an experiment.

2. DEFINING THE IMPACT ANGLE AS THE DIAGNOSTIC PARAMETER

In the engine cylinder a process goes on in which the piston subjected to a set of forces shifts from one side of the cylinder liner to the other side. This shift is possible because of the clearance between the piston and the cylinder and it ends by the piston striking the cylinder. The most intensive impact occurs in the top dead center (TDC) in the expansion stroke when the lateral force of the piston is at the maximum. Time needed for the piston shift from the TDC to its impact into the cylinder, measured in degrees of the crankshaft, is called the impact angle. This angle is denoted as α_d.

The differential equation of the lateral shift of the piston in the cylinder is:

$$\frac{d^2 h_o}{dt^2} m_k = \lambda\omega\left(\frac{dF}{d\alpha}\sin\alpha + F\cdot\cos\alpha\right) t_p \tag{1}$$

$$\text{For } A = \frac{dF}{d\alpha}\sin\alpha + F\cos\alpha \tag{2}$$

the impact angle [2] is obtained from the formula:

$$\alpha_d = \left(\frac{6h_0 m_k}{\lambda\omega}\cdot A^{-1}\right)^{1/3} \tag{3}$$

where:

- h_o - clearance between the piston and the cylinder
- m_k - mass of the piston
- λ - relation R/L
- ω - angular speed
- F - total force acting on the piston
- α - crankshaft angle
- t_p - time of shift

The angle α_d depends, for a certain engine working cycle and a certain engine type, only on the clearance h_o, that is

$$\alpha_d = k(h_o)^{1/3} \tag{4}$$

Based on the formula for α_d it can be concluded that by increasing the clearance in the cylinder the impact angle increases as well.

3. CALCULATION OF THE IMPACT ANGLE

The piston shifts laterally under the lateral force F_n. The piston force impulse by the impact into the operating side of the cylinder is obtained from [2] formula:

$$In = k[(h_o^2 \cdot m_k \cdot \omega\lambda)A]^{1/3} \tag{5}$$

The angle α_d at which the piston strikes the cylinder wall and the magnitude of the impulse are significantly affected by the pressure of the gases in the cylinder, its lack of uniformity and variations during the successive cycles.

The pressure change in the cylinder is determined, apart from the way the combustion process is carried out, also by the choice of the working cycle. However, even when the engine operates at constant working cycles, there is a difference of successive cycles. The pressures vary throughout the combustion, and maximum variation occurs at peak values. These variations cause, regardless of the clearance magnitude, variations in the magnitude of the impact angle and impulse. On the other hand, the pressure varies, not only because of the difference in cycles, but probably also together with the greater cylinder wear.

While making the mathematical model for computing In and α_d, all the complex occurrences and other processes that take place in the engine cylinder during the shift of the piston could not be exactly described. Therefore, the cylinder pressure variations for different engine working cycles were determined experimentally for the diesel engine F4L 413 FR. In the calculation the pressure variations were used that are 50% higher than those obtained by the experiment.

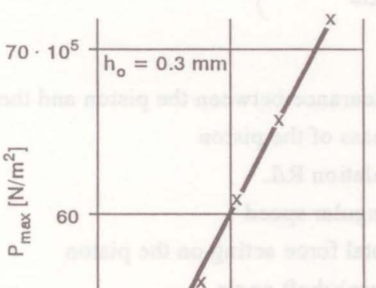

Figure 1 - **The impulse variation depending on the amount of pressure**

Figures 1 and 2 show the variations of impulse and impact angle, that have been calculated using the mathematical model at the constant working cycle, with pressure variation.

The pressure variation results in the variation of force F, F_n, and impulse, which also affects the cylinder vibrations. This means that with the drop of pressure, the impulse and the cylinder vibration intensity are also reduced, and it seems that the cylinder clearance is smaller than it actually is. If the wear of the cylinder is such that the pressure is significantly reduced, then it is not possible to assume the intensity of wear on the basis of vibrations. In order to be able to make a correct assumption about the wear, it is necessary to be acquainted with the rules regarding drop in pressure.

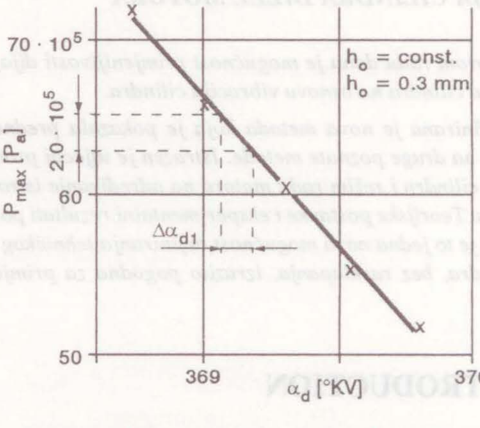

Figure 2 - **Impact angle variation depending on the amount of pressure**

Apart from the impulse variation, the impact angle varies as well with the pressure variation, as shown in Figure 2. It should be noticed that the variation of α_d with the drop in pressure has a different character than the impulse variation. With the drop in pressure the impact angle is increased. The same effect is achieved with the increase in wear. This means that if the drop in pres-

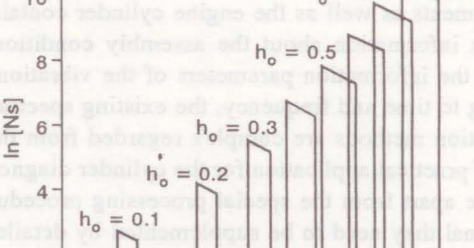

Figure 3 - **The variation range α_d and In for the pressure variation of $11 \cdot 10^5$ Pa**

sure was caused by the wear, the value of α_d would never lead us to the conclusion that the wear is less than it actually is.

Figure 3 shows different cases of variation in α_d and In for different cylinder wears. For the impact angle and the impulse ranges of values are given for specific cylinder wear, as a result of which the pressure variations for the constant engine working cycle have been taken into consideration.

Based on the pressure variations, calculated according to Vibe [3] by the variation of combustion characteristic, the values for the impact angle and impulse have been calculated. If the calculated values obtained by a computer are shown as in Figure 3, it becomes evident that the start of the impact varies depending on the cylinder wear and the amount of pressure. The start of the impact or the piston's free motion can be expressed with α_d, so that

$$h_o = 0.1 \text{ mm}$$
$$\alpha_d = 6.07\text{-}6.46°KV$$

and for

$$h_o = 0.3 \text{ mm}$$
$$\alpha_d = 8.72\text{-}9.28°KV$$

The changes in pressure variation within the cylinder have a greater effect on the variation of the impact angle if the cylinder clearance is bigger. For $h_o = 0.1$ mm the angle change for the pressure variation of $11 \cdot 10^5$ Pa is 0.39°KV, and for the wear of $h_o = 0.8$ mm it is 0.79°KV. This means that greater cylinder wear is more sensitive to pressure variations.

As the impact angle varies with the change in pressure, thus also changes the impulse intensity. Figure 3 shows that even by the pressure variation of $11 \cdot 10^5$ Pa, it cannot be concluded that the wear is 0.2 mm if it is 0.1 mm, since the impact angle value for 0.1 mm will not take on values of the impact angle for the 0.2 mm wear. However, when the wear is greater than 0.5 mm it is possible to conclude incorrectly, regarding the impact angle, that the wear is greater or less than the actual. This becomes unimportant, since according to the instructions given by the producer of the engine F4L 413 FR (TAM from Maribor), when the wear exceeds 0.35 mm, the engine has to be disassembled and the cylinder ground.

All this shows that the impact angle is a very reliable source of information on the cylinder wear, provided that it is possible, with certain measuring equipment to obtain such a signal of the cylinder vibrations, which allows us to determine the moment of the impact of the piston into the cylinder.

4. RESULTS OF THE STUDY AND THEIR ANALYSIS

While making the mathematical model not all complex processes that take place in the engine cylinder during the shift of the piston, can be exactly described. A certain number of simplifications had to be done. However, each simplification brings the calculated values further from the actual values and the impact angle. This is the first reason why the impact angle has been determined by an experiment in this paper. The second reason is the wish to analyze the possibilities of such a vibration signal which would allow simple determination of the impact angle. Only in case of such a possibility can all the theoretically assumed advantages of this method be tested in practice.

All the readings in this paper were obtained on an engine F4L 413 FR - TAM vehicles. Studies were carried out for the cylinder wear of 0.83; 0.63; 0.42;- 0.25 mm and for a new cylinder not yet worn.

4.1. Influence of the working cycle, engine heat and pressure variation with the cylinder wear on the impact angle.

While measuring the cylinder acceleration, we succeeded after several attempts with the available equipment to obtain such a signal with which the moment of the impact of the piston into the cylinder could be determined. Thus the possibility of determining the impact angle was solved.

The impact angle was measured simultaneously at all four cylinders with different wears. In this way identical testing conditions were provided regarding the variation in the rotational speed, cylinder temperature, oil temperature, environmental pressure, and other. The results have shown that the impact angle varies with the change of load and engine rotation speed. The influence of the rotational speed and wear on α_d for a not loaded engine is shown in Figure 4.

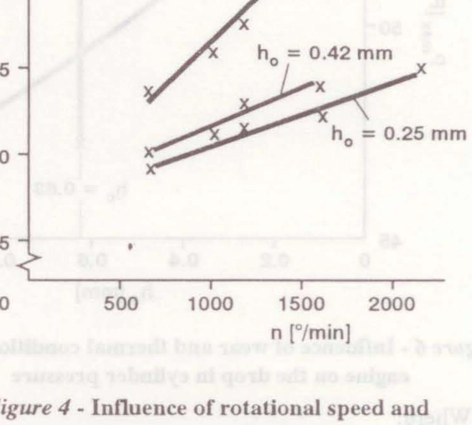

Figure 4 - **Influence of rotational speed and cylinder wear on the impact angle**

The impact angle variations are linear, and greater sensitivity to the variations in rotational speed have been found for greater wear.

Figure 5 shows the variations of the impact angle when the engine load changes. The variation of the impact angle is not linear any more. This is understandable since the cylinder pressure changes significantly with the change of inertia force.

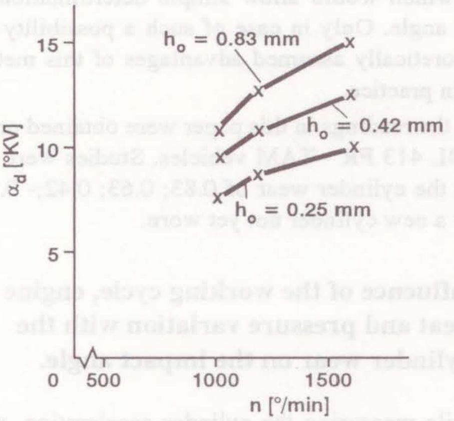

Figure 5 - **Influence of the rotational speed and wear on the impact angle**

(for the maximum injected amount of fuel)

A common characteristic of all the testing is that the dependencies between the impact angle and wear are clearly marked, and that in all the engine working cycles.

While testing the impact angle the change in cylinder pressure has also been registered. Results are shown in the form of a diagram in Figure 6.

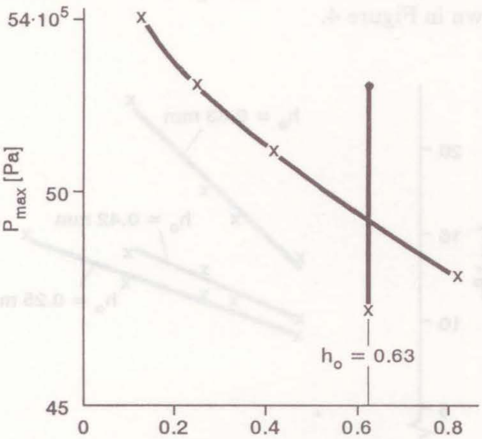

Figure 6 - **Influence of wear and thermal condition of the engine on the drop in cylinder pressure**

Where:

x - value of pressure, for idle speed of the engine, with the cylinder head temperature t = 62-67°C, and rotational speed varying in the range of 845-854°/min,

o - value of pressure for an overheated engine with the cylinder head temperature t = 93°C (n = 882°/min), and

o - value of pressure for a cold engine with the cylinder head temperature t = 32°C (n = 810°/min).

It should be pointed out that the difference in pressure for the wear of h_o = 0.63 mm for a cold and an overheated engine, of $47.2\text{-}52.5 \cdot 10^5$ Pa renders a change in impact angle of 12.9-11.9°KV. This means that the 10% change in pressure causes a change in impact angle for only 2.4%. It is obvious that the change in pressure is not accompanied by an adequate change in impact angle. The reason for this is that when there is a rise in engine temperature, there is also an increase in the rotational speed. As the rotational speed increases, the impact angle increases, and with the rise in pressure, it decreases.

Along with the increase in rotational speed and engine load disturbances occurred in the acceleration recording. Disturbances are the result of more intensive vibrations of engine elements and assemblies due to the increase of inertia forces and pressure in the cylinder. Therefore, it was difficult, at 1700°/min to read the impact angle, and at 2300°/min it was impossible to determine it. The best signal is obtained at the engine idling speed. For greater rotational speeds and loads signals should be processed by spectral or correlation method.

4.2. Defining of the engine working cycle

Output signal parameters vary depending also on the disturbance magnitudes (pressure variations, changes in rotational speed, temperature fluctuations etc.). The most suitable signal is if the influence of disturbance factors is reduced to a minimum, or if such working cycles are chosen which emphasize some of the output signal parameters which best describe the cylinder wear. Studies have shown that for the tested engine the least cycle variations occur at n = 1350°/min when the maximum value for the engine moment is reached. All this requires the engine to be tested in a diagnostic center. Some authors [4], [5] and [6] have based their testing and diagnostics of the cylinder on these assumptions. Naturally, such a selection of the engine working cycles that required engine testing at a diagnostic center, on the brakes, has its justification and logic.

In choosing the engine working cycle for cylinder diagnostics, it was not possible to start from these concepts. The idea was, first of all, to be able to obtain a reliable conclusion about the cylinder wear, using fast diagnostics, little effort, time and without having to disassemble the engine. If the engine working cycle is selected where the testing can be done on the vehicle, far from the diagnostic center, provided that necessary information are obtained, then it can be concluded that the vibration method is practical. In other words, the structure of the information vibration signal does not determine the engine working cycle, but the simplicity and suitability of application, while determining and finding the method which will give reliable and in practice feasible conclusions from such an obtained signal. One of such working cycles is idle speed operation. At idle speed operation the reading of the impact angle is simple if the suitable measuring technique is applied. Figure 7 shows the time recording from which α_d can be directly read.

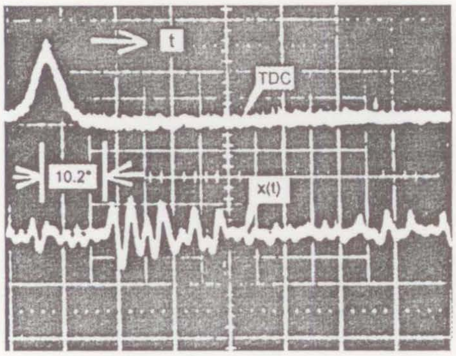

Figure 7 - **Impact angle at cylinder wear h_o = 0.42 mm**

Figure 8 shows the values for α_d obtained by experiment for various cylinder wears. Experimentally tested correlation coefficients for specific conditions are determined in the mathematical model. Therefore, there are slight departures of the experimentally obtained values from the calculated impact angle values for different engine wear.

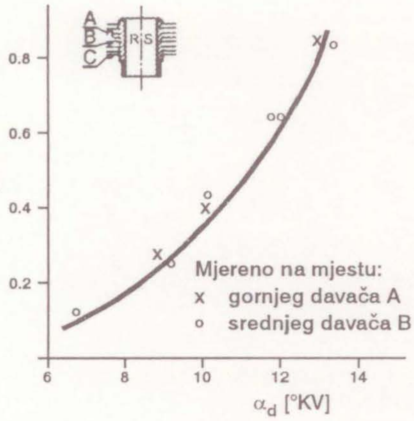

Figure 8 - **Influence of wear on the impact angle**

Finally, it can be concluded that the assumed dependence between the impact angle and the wear is confirmed by experiment as well.

5. CONCLUSION

1. The impact angle is defined as the time the piston needs to shift from the top dead center (in the expansion stroke) to the moment it strikes the cylinder. Theoretical analyses and experiment have proven the possibility to apply this indicator as a diagnostic parameter.
2. Characteristics and advantages of the impact angle as a diagnostic parameter are the following:
   - Impact angle increases with the drop in pressure in the cylinder. The same effect is achieved with the increase in wear. This means, if the drop in pressure is caused by the wear, the impact angle will not lead us to the conclusion that the wear is less than it actually is.
   - The cycle variations are not accompanied by the adequate change of impact angle. For ten successive cycles of the constant engine working cycle there were no changes in the impact angle.
   - Impact angle is not sensitive to piston and cylinder temperature variations.
   - Diagnostics of cylinder wear by the impact angle is quick and simple. Signals do not have to be specially processed, there is no need for a computer, analyzer or other equipment.
3. In selecting the engine working cycle in order to analyze the cylinder wear, the only suitable one was found to be the idle speed. Other working cycles require that the engine be tested in the diagnostics center, so that these are not acceptable from the practical point of view. In the idle speed working cycle the cycle variations are the greatest, and the impact angle has shown exceptionally low sensitivity to them.

SUMMARY

In this paper the possibility of application of the cylinder diagnostics on vibration basis is given. A new method is defined. It shows advantages in comparison to the other known methods. The influence of various pressures in the cylinder and the influence of engine working cycle on determining of the cylinder wear are analyzed. The theoretical assumptions and experimental results have proved that this method is a new possibility for defining the technical state of the cylinder without being disassembled, especially suitable for the practical application.

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