# Monitoring of the Pressure Inside the Cylinder for an Internal-Combustion Engine

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*Abstract:* - This work presents the achievement of a monitoring, recording, processing and interpretation concept, at laboratory scale, of the pressure inside the combustion chamber for a spark-ignition engine, based on electronic equipment, which measures the values of 17 parameters that describe the operation of an internal-combustion engine. The measured pressure depends on the crankshaft's position. Is used a pressure transducer with strain-gauge socket, and measurement of the crankshaft's position with a speed transducer with variable reluctance. From experimental data, on one hand, can be analyzed the pressure modification in the combustion chamber depending on the crankshaft's position, and on the other hand, the maximum pressure modification in the cylinder depending on the speed.

*Key-Words:* - Internal-combustion engine, Sensors, Cylinder, Pressure, Speed

## 1 Introduction

The daily presence of the road vehicles, be them motor vehicles, public transport vehicles, utility vehicles, road trains or special motor vehicles, is a very usual and indispensable one. As we all know, their propelling is done nowadays with the help of the internal combustion motor in an overwhelming percentage.

Along time, utilization of the internal-combustion engine was accompanied by the permanent improvement of its performances, reliability and efficiency by increasing the power, decreasing the fuel consumption, decreasing the waste noxes, diminishing the utilization of shortage materials and, lately, the utilization at larger scale of unconventional fuels. Achievement of these desiderates is based on laborious theoretical and experimental researches which involve an immense work volume, alongside suitable financial resources.

The experimental research represents today “the truth criterion” for numerous results obtained on a theoretical basis, and also an important source of useful information on which extraordinary technical achievements are based. It can be said that experiments are almost irreplaceable if they are correctly processed and economically efficient. In order to run highly difficult laboratory research the first experiments that have to be understood are the ones that concern fundamental phenomena.

The optimal operation of an internal-combustion engine, translated by its capacity to supply the prescribed power and torque, in conditions of a fuel consumption as reduced as possible and, implicitly, of a waste noxes level within the limits of the norms in force, is strongly connected to its functional parameters' values. Knowing of these values is, therefore, indispensable for the correct management of the processes that take place inside the engine [1].

Traditionally, control of internal combustion engines has been based on the sensing of variables such as engine speed, intake manifold pressure, exhaust oxygen concentration, coolant temperature etc. and using these variables to adjust variables such as spark timing, exhaust gas recirculation rate, EGR, and fuel flow to a baseline engine condition that is measured on a test engine.

This approach has several drawbacks. Firstly, an engine will diverge from the baseline test engine due to production variation and component wear. Secondly, cylinder-to-cylinder variation may be significant. And thirdly, it appears that future engine combustion systems may render the traditional control approach inadequate.

An alternative approach is to implement a control system with the capability to adjust for changes in the individual engine cylinder operating characteristics. Such a control system is possible using cylinder pressure sensors and applying feedback control to ignition timing, dilution gas rate and fuel rate.

The computerized electronic management disposed by the current engines involves the utilization of a very large number of sensors and transducers that measure and transmit, in real time, the values of these parameters to the electronic control unit (Engine Control Unit - ECU). Based on the real values obtained by measurement and comparing with the optimal values stored in the internal memory for each operation regime, ECU controls a series of actuators through which is ensured the perfect operation, in all regimes, of the engine [2, 3, 4, 5, 6].

The new legislative norms in US and Europe will impose the engines in the future more and more drastic pollution limits. Just from this very reason, alongside the $NO_x$ and particle filters, will become absolutely necessary the implementation of some sensors that should offer information, about the mode in which takes place the combustion in the combustion chamber. In this context, the need to optimize the combustion of the air-fuel mix from the internal-combustion engines is an important objective. Numerous combustion-related parameters must be known, measured and, in the last, controlled, by framing within proper values intervals. One of the very important parameters, and, however, inaccessible up to a given moment, is the pressure inside the combustion chamber. Its monitoring during the compressing and combustion/expansion times helps the engine's management system to control better the combustion processes, and thus to improve the engine's global performances.

In the past, different measurement methods were used to examine the mixture formation and combustion in combustion engine. One of technologies developed for these examinations, the pressure-based indicating measurement, has become the standard and is an integral part of the engine development process today.

Robust and precise high pressure and high temperature sensors provide reliable and precise results to analyze the combustion, indicated mean effective pressure, peak pressure, combustion noise and knocking as well as other phenomena. Today, all these values play a critical role when using an existing engine in specific power trains and vehicles, as the steadily increasing performance and the simultaneously stricter exhaust gas and quality standards forces the optimal utilization of the combustion in all operating points. Variable value drive systems, variable intake port geometry flexible injection systems and advanced combustion concepts provide a large amount of flexibility, but simultaneously results in more complex combustion system. Can this complexity be solved with the conventional indicating systems.

In this case, the modern indicating systems are the basis for methods that exceed the conventional cylinder pressure combustion analysis by far and provide new insights into the combustion processes.

The main problems related to the development of a solution in this respect were connected until now by the extremely solicitor environment inside the combustion chamber. The very high temperatures and pressures produced at ignition and expansion stresses at maximum all the elements that get in direct contact with the flame front [7].

A solution for measuring the pressure inside the combustion chamber, variable during the motor cycle, consists in integration in the cylinder-head gasket, on the bore's superior edge, of a pressure sensor.

Another solution, applicable on diesel motors, has been developed by Siemens VDO and Federal Mogul and consists in integrating the pressure sensor into the glow spark plug body (fig.1).

The interior construction of the "glow spark plug – pressure sensor" module is made so as to allow a corresponding sensitivity of the sensor, and at the same time to comply with the geometric requests of the heating element. There are two mainly different products, namely:

- The variant "glow spark plug – combustion monitoring sensor" (GPCS – Glow Plug Combustion Sensor) which does not measure directly the pressure in the heating room but the combustion head strain, caused by the pressure variation in the cylinder.
- The variant "glow spark plug – pressure sensor" (GPPS – Glow Plug Pressure Sensor) which offers measurements of a higher accuracy than the previous one, by the sensor's direct exposure on the tip of the glow spark plug [7].

Regarding the spark-ignition engine (operating by Otto cycle), there are producing companies of experimental equipment that put available to the researchers pressure sensors integrated in spark plug's component, through which can be recorded and measured the pressure inside the combustion chamber [8,9,10] (fig.2).

The relatively high price of such a sensor (approximately 4500 Euro), to which is added the electronic acquisition equipment (approximately 6200 Euro) led to the development of an alternative in this respect, the authors achieving a study based on an own idea.

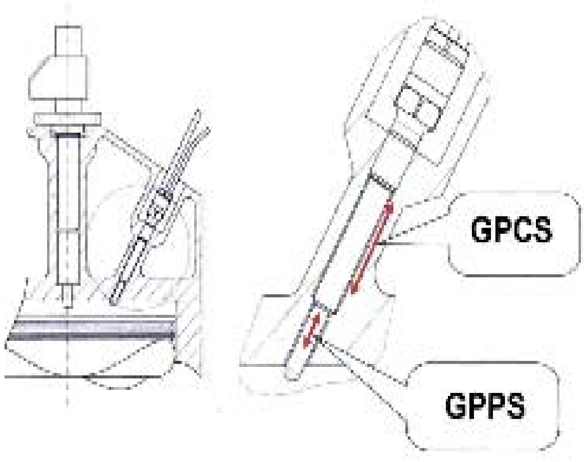


Fig.1. Glow spark plug – pressure sensor module

Fig.2. Pressure sensor integrated in the spark plug

The present study's objective consists in conceiving of a new monitoring methodology of the pressure inside the cylinder of a spark-ignition engine, testing the utilized pressure transducer and studying the influence of the chosen solution upon the pressure variation in the cylinder.

## 2. Fundamental demands of combustion in the engine cylinders

Combustion is the fundamental functional process of the internal combustion engine, the circumstances in which the ignition and combustion take place determining the motor power, profitability, level drive, without vibrations, noxe and operation safety regime.

The demands on combustion are numerous, but they can be structured in three more important ones:

1. The combustion to be as complete as possible, because the incomplete combustion reduces the energetic availabilities obtained from the reaction heat and with it the machine work developed.

The incomplete combustion gives birth to noxious substances: carbon monoxide, acreoline, benzpirene, soot, etc.

2. For a most efficient transformation of heat into machine work, combustion must be as short as possible and must take place when the piston is around the TDC.

If the combustion takes place later, during rebound, the degree of transformation into machine work decreases, the load temperature in the cylinder increases, and the temperature of the main organs rises, which can lead to the destruction of the motor through seizing (the assembly piston – segments – cylinder), through thermal load (piston – combustion head – combustion room – segments), or even through combustion (valve darner).

3. The combustion must take place at moderate speed.

If the combustion is violent, then the forces apply on the motor mechanism shockingly, which will lead to the increase in the mechanical loads, in extreme cases the destruction of the motor being possible.

At the same time, the motor will have a very annoying hectic noisy drive, especially for the motor vehicle on which it is installed.

An average rate of pressure increase can be calculated between the point of maximum pressure and the one of compression end (fig.3).

$$\frac{\Delta p}{\Delta\alpha} = \frac{p_{max} - p_c}{\alpha_{p_{max}} - \alpha_{p_c}} \qquad (1)$$

The immediate speed of pressure increase is:

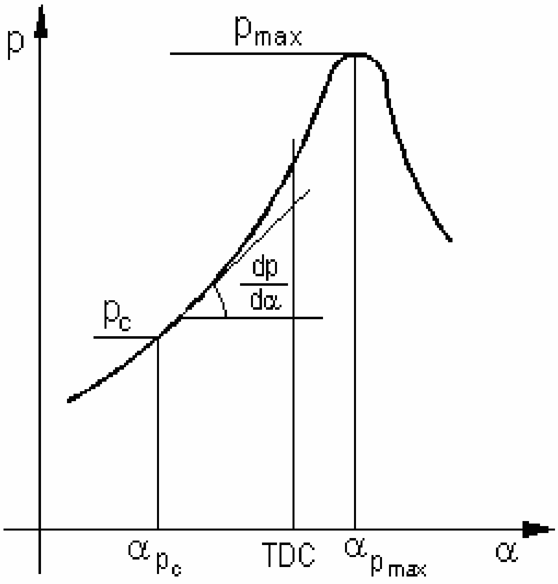


Fig.3. Pressure variation in the cylinder around TDC

$$\dot{p}_\alpha = \frac{dp}{d\alpha}. \qquad (2)$$

According to the manner in which the combustion develops inside the motor we identify:

- regular combustion;
- irregular combustion (detonation combustion and, respectively secondary ignition combustion);

*Regular combustion* is characterized by propagation of the ignition front step by step into the mixture mass, with speed flame between 30÷40 m/s, with increasing of pressure and temperature step by step, when the performance of the engine and the wear of mechanical organs are the same.

*Irregular combustion* in the spark ignition engine is characterized by unusually high speeds of the ignition front, by sudden increases in temperature and pressure, the power and profitability of the motor being penalized, the motor ageing degree increasing rapidly [1].

## 3 Experimental stand

Acquisition and procession of data necessary for the study were achieved on an experimental stand from the Laboratory of Internal-Combustion Engines, within the Faculty of Engineering from Hunedoara, „Polytechnic" University Timisoara.

The experimental stand was conceived to serve for measuring of an as largest possible number of functional parameters of a spark-ignition engine and is composed by two distinct components:

- The engine itself, mounted on a chases that allows its operation completely safety (fig.4);
- The electronic equipment used for measuring, recording and computerized processing of experimental data (fig.5).

### 3.1 The spark-ignition engine

The engine mounted on the stand is with spark-ignition, Dacia brand, model 810.99, 4-cycled, having 4 vertical cylinders in line, with camshaft in the engine block.

Fig.4. The spark-ignition engine

The bore is of 73 mm, and the piston's stroke of 77 mm. The engine has a cylindrical capacity of 1289 cm$^3$.

The compression ratio is 8.5:1. The engine develops a maximum power of 54 CP (DIN) at the speed of 5250 rot/min, and the maximum torque is reached at 3000 rot/min and is 95 Nm.

### 3.2 Electronic equipment used for measurements

The electronic equipment used for measuring, recording and processing of experimental data was conceived by CBM Electronics and achieves the following functions:

1. Memorizes the measuring conditions formed by sets of values imposed for the following parameter:
    - speed;
    - resistant moment;
    - test duration;
2. Measures and displays simultaneously the momentary values of 17 parameters that describe qualitatively the engine's operation.

These parameters refer in greatest part directly to the engine, but are also parameters that feature the environment conditions as well as the measuring stand itself. The parameters measured and displayed are: temperature of the water from the engine's cooling circuit [°C], oil temperature [°C], waste gas temperature [°C], environment temperature [°C], pressure in the combustion chamber [bar], oil pressure [bar], fuel pressure [bar], intake vacuum pressure [bar], waste gas static pressure [bar], waste gas dynamic pressure [bar], atmosphere pressure [mmHg], resistant moment [Nm], speed [rot/min], temperature of the braking water [°C], consumed fuel quantity [g], relative humidity of atmosphere air [%], advance angle [$^0$RAC].

Fig.5. The electronic equipment used for measuring, recording and processing of experimental data

3. It creates a database for each measurement session in which memorizes the values of the measured parameter, date and time when was made each measurement set.
4. It creates and lists three types of reports, containing the measured values, their average values (calculated for the measuring time intervals) and the values corresponding to the maximum load conditions for a selected engine.

Component parts:

- 17 transducers for the measured parameters;
- a multiplexor module provided with connection cords at the 17 transducers;
- a PLC;
- a display device, that offers the possibility to visualize 4 simultaneous parameters;
- a computing unit together with a color printer;
- installation kit of the software package that contains the application.
- a digital color oscilloscope METRIX MTX 3354 produced by Chauvin – Arnoux, France.

The equipment's base element represents the high-pressure transducer which undertakes the variable pressure from inside the combustion chamber.

### 3.3 Reduction joint for pressure's assay from the combustion chamber

The cylinder head configuration of the engine installed on the stand, as well as the existence of the cooling channels from its walls, makes practically impossible the access inside the combustion chamber by punching the cylinder head's walls, concerning the installation of the high-pressure transducer.

Having in view the above, the optimal solution represents the access inside the combustion chamber through the hole for mounting the spark-plug. In this respect, was designed a reduction joint, through which to be able to be mounted both the spark-plug and the transducer, using only the hole for mounting the spark-plug, without being necessary the additional punch of the cylinder head's walls.

Using a reduction joint as the one from fig. 7, mounted at cylinder no.1, assumes an increase of the combustion chamber's volume and, as consequence a reduction of the compressing ratio ε:

$$\varepsilon = \frac{V_a}{V_C} \quad (3)$$

$$V_a = V_S + V_C \quad (4)$$

$V_a$ – cylinder volume;

$V_C$ – combustion chamber's volume, which will increase by mounting the reduction;

$V_S$ – unitary displacement,

$$V_S = \frac{\pi \cdot D^2}{4} \cdot S \quad (5)$$

$D$ – bore,

$S$ – piston stroke.

Relations (3)-(5) refer to the situation when the reduction joint is not mounted.

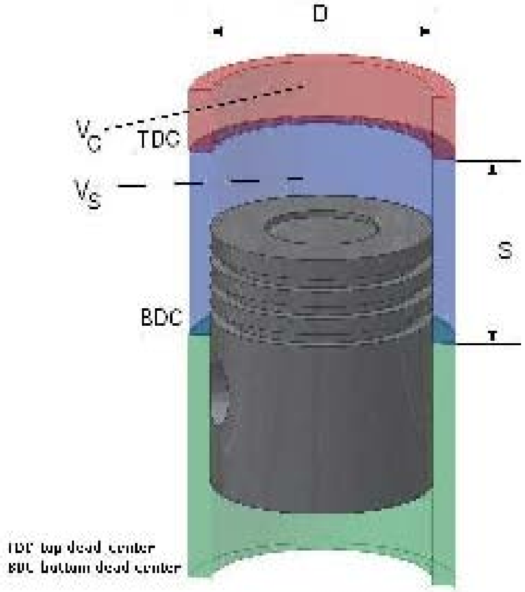
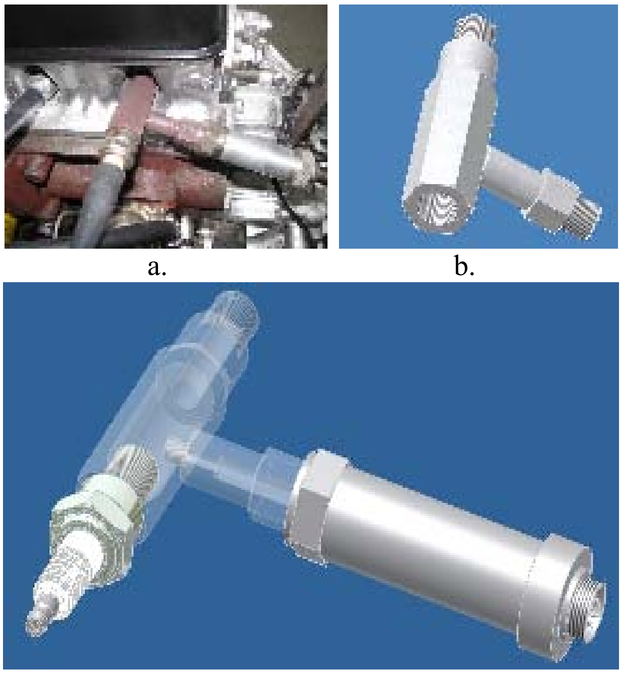


Fig. 6. Illustrating the unitary displacement and the combustion chamber's volume



c.

Fig.7. Reduction joint for pressure's assay from the Combustion Chamber: a – installed on the engine, b – model conceived in AutoDesk Inventor, c – detail regarding the interior which communicates with the combustion chamber (AutoDesk Inventor modeling)

In case when the reduction joint is mounted, the compression ratio for cylinder 1 modifies as follows:

$$\varepsilon' = \frac{V'_a}{V'_C} \qquad (6)$$

$$V'_a = V_S + V'_C \qquad (7)$$

$$V'_C = V_C + V_r \qquad (8)$$

$V_r$ is the reduction joint's interior volume.
Because $V_C$ = 42.97 cm$^3$, and $V_r$ = 12.52 cm$^3$, the combustion chamber's volume was increased by 29% by mounting the reduction joint, so as the compressing ratio became:ε' = 6.8.

Even if the mounting of the reduction joint brings on the above drawback, the engine operates at acceptable parameters, the pressure assay being possible.

The study's purpose is not to optimize the ignition in the cylinder, but to develop and test a methodology.

## 4 Experimental methodology

Further, is aimed the assessment of the signal generated by the high-pressure transducer mounted through the reduction joint from fig.7.b and the mode in which the increase of the combustion chamber's geometric volume, due to the reduction joint's mounting, affects the pressure variation in the cylinder.

Fig.8. Mounting of the speed transducer

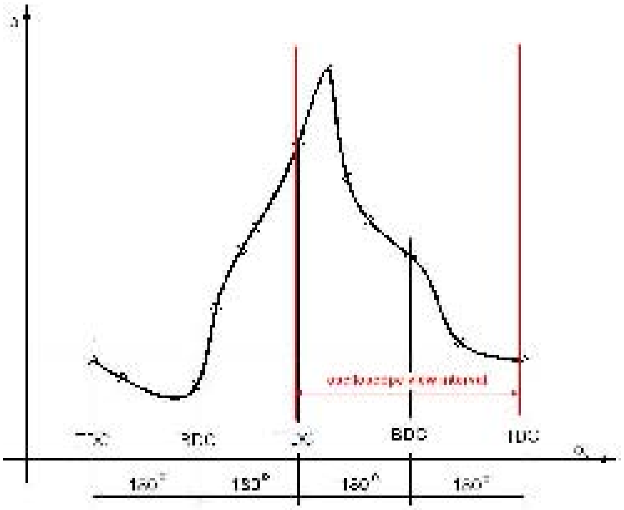


Fig.9. Theoretical pressure variation curve in the cylinder

The high-pressure transducer works in parallel with the speed transducer, the latest providing also the momentary position of the top dead-center. Mounting of the high-pressure transducer was illustrated in fig.7.a, c, and the one of the speed transducer, in fig.8.
The two transducers, of high pressure and speed, through some electronic devices, were connected to the digital color oscilloscope METRIX MTX 3354 then recorded on PC.

For making a comparison between the oscilloscope's indication and the theoretical variation of pressure inside the cylinder (without modifying the combustion chamber's volume), in fig.9 was represented the theoretical pressure curve depending on the crankshaft's rotation angle [1], by indicating the effective interval in which the

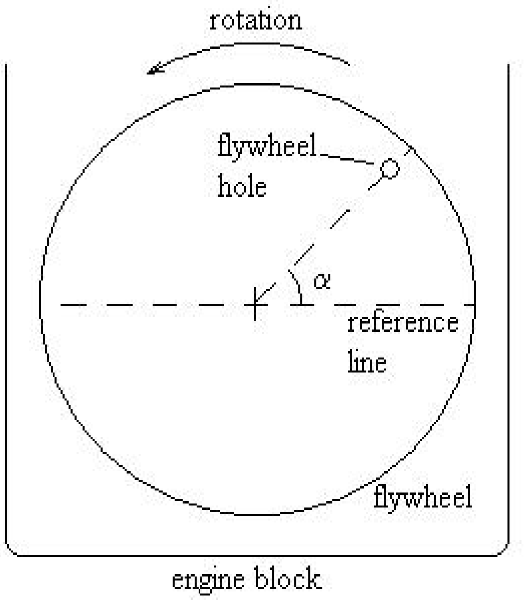


Fig.10. The measurement of engine crankshaft's angular position

pressure transducer has sent a signal towards the oscilloscope.

In automotive applications, sensors are in many cases the critical components for determining the correct measures.

The engine crankshaft's position is important to automotive measuring systems.

Measurements of the angular position or crankshaft's speed are common in automotive electronics.

It is important that these measurements to be made without any mechanical contact with the rotating shaft.

The non-contact measurements can be made in a variety of ways, but often is used the magnetic or optical phenomena.

The magnetic sensors are generally preferred in engine applications since they are unaffected by dirt, oil and temperature.

The principle in measuring the rotating crankshaft can be illustrated in fig. 10 [3, 4, 11,12,13].

In front of the crankshaft there is a large circular steel disk (ferromagnetic) called the flywheel.

The crankshaft's angular position α is the angle between the reference line and the hole made in the flywheel (fig.10). A hole (ϕ 5mm) can be practiced in the flywheel in the top dead-center position for a cylinder.

A full engine cycle from intake through exhaust requires two complete resolutions of the crankshaft ($720^0$).

It is important to measure the crankshaft's angular position with reference to the top dead-center for a cylinder for correct correlation with pressure's measure in the cylinder chamber.

A magnetic sensor to measure crankshaft's position consists of a magnet with a coil of wire wound around it. The passage of the hole corresponds to the top dead-center position of a cylinder on its power stroke. The sensor is of magnetic reluctance type [3, 4].

The flywheel disk provides a low-reluctance path, except when the hole aligns with the sensor axis.

The reluctance of this magnetic path is increased because the air permeability is very much lower than the flywheel's permeability.

This high reluctance through the hole causes the magnetic flux decrease and produces a change in sensors' output voltage. The hole passes under the sensor once for every crankshaft rotation.

The magnetic flux abruptly decreases, then increases as the hole passes the sensor. This generates a voltage pulse that can be used to measure the rotation speed of the crankshaft.

The maximum rotation speed measure with magnetic sensor is 10000 rpm. The type of rotation sensor is XS1M18NA370D Telemecanique.

To measure the pressure inside the cylinder chamber can be used a pressure sensor using a gauge load cell [11].

A bonded strain-gauge load cell is a device producing an electrical output depending on weight or applied force. The main part is the bonded-foil strain-gauge which is an extremely sensitive device, whose electrical resistance changes in direct proportion to the applied force.

If the sensitive element has a surface S and the force applied on the element is F, then the pressure may be calculated with:

$$P = \frac{F}{S} \tag{9}$$

A load cell comprises an elastic-element that may take many forms such as solid column, diaphragm, ring, etc.

The design of the element is dependent on the load range and loading type.

The gauges are bonded on the element to measure the generated strains and are usually connected into four-arm Wheastone bridge configuration.

The bridge configuration includes compensation resistors for zero balance and changes of zero and sensitivity resistors for difference temperature.

The resistance R for the sensitive element with length l, cross-section s and resistivity ρ is:

$$R = \rho \cdot \frac{l}{s} \tag{10}$$

When a strain Δl/l occurs, it causes a fractional change of resistance [11]:

$$\frac{\Delta R}{R} = \left(k + \frac{1}{\rho} \cdot \frac{\Delta \rho}{\Delta l}\right) \cdot l \tag{11}$$

where k=1.6÷2 for most metals.

The signal from the strain-gauge socket is of mV order.

For measuring with the strain-gauge socket, an adaptation and amplification device (interface) with transmission on three wires is used.

By using of this device, the output signal is approximately 200 times higher than the output signal from the bridge with the strain-gauge sockets [14].

In fig.11, E+, E- are the supply terminals of the bridge with strain-gauge sockets, and S+, S- are the terminals with the output signals (voltage of mV order) from the other ends of the bridge with strain-gauge sockets.

The signals' transmission towards the measuring part (oscilloscope) is achieved by current (4-20 mA), which passes through a gauged resistance (250 Ω).

The voltage drop on the resistance can be measured with the oscilloscope. The conductors between the bridge with strain-gauge sockets and interface, respectively interface and oscilloscope, are screened.

The interface's precision class is of 0.1%, linearity errors 0.01%, supply voltage 10V.

The maximum pressure measured with bonded-foil strain-gauge sensor is 1000 bar.

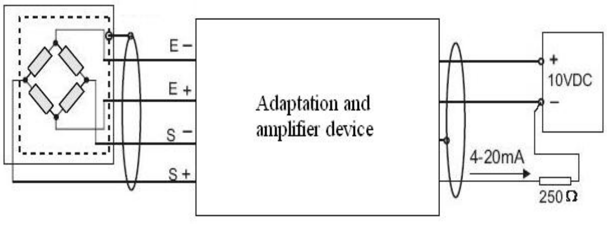


Fig.11. Adaptation and amplifier device for bonded-foil strain voltage

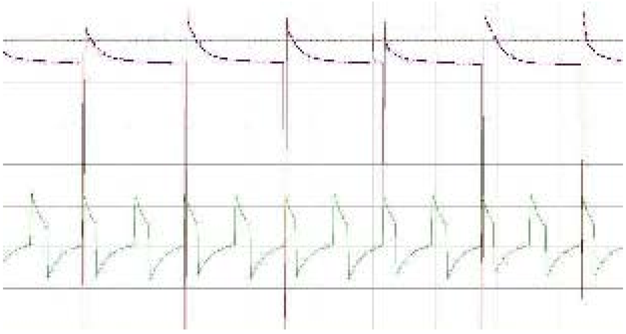


Fig.12. Measuring the pressure (up, 100mV/div) and speed (down, 10V/div) for n=729 rpm, 100ms/div

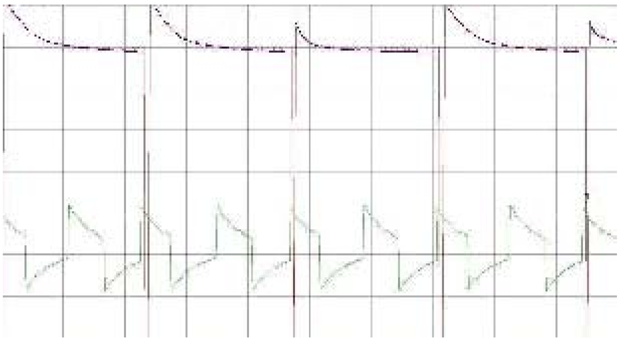


Fig.13. Measuring the pressure (up, 100mV/div) and speed (down, 10V/div) for n=1008.4 rpm, 50ms/div

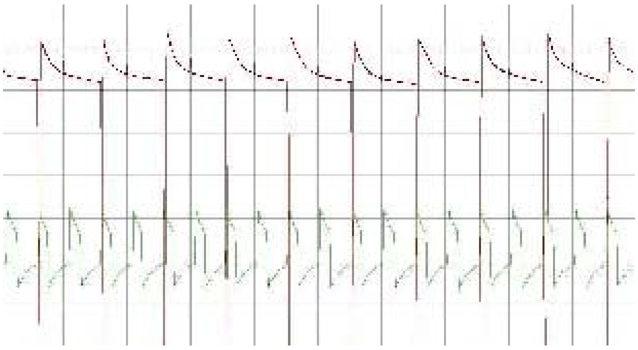


Fig.14. Measuring the pressure (up, 100mV/div) and speed (down, 10V/div) for n=1260.5 rpm, 100ms/div

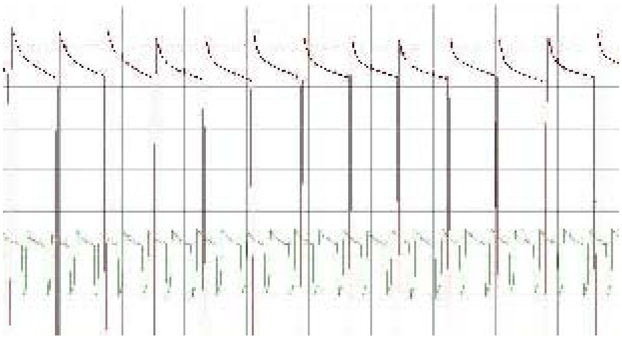


Fig.15. Measuring the pressure (up, 100mV/div) and speed (down, 10V/div) for n=1647.05 rpm, 100ms/div

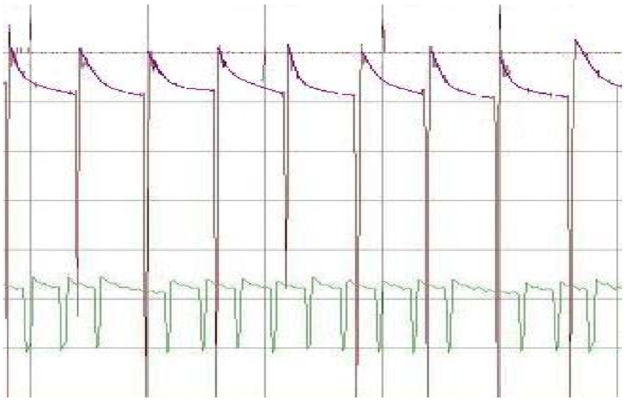


Fig.16. Measuring the pressure (up, 100mV/div) and speed (down, 10V/div) for n=2234.6 rpm, 100ms/div

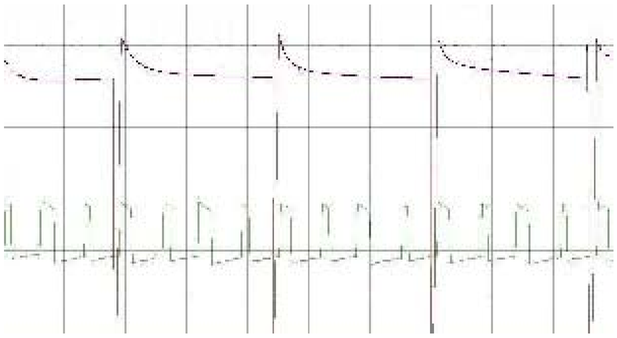


Fig.17. Measuring the pressure (up, 100mV /div) and speed (down, 10V/div) for n=4699 rpm, 20ms/div

The speed is measured, as regulated pulses of same dimensions, up to speeds of approximately 2000 rpm.

Over this speed value, the pulses modify their shape and dimension against the case of small speeds (fig.12-17).

At pressure's measurement are found differences between the theoretical variation curve (fig.9) and the variation curves of the measured pressure (fig.12-17).

This difference is due to the pressure transducer's operation principle (with strain-gauge bridge) being specialized for measuring of high pressures and a high response time.

At small speeds (<2000 rpm) is found a synchronization between the pressure's rapid increase and perception by the speed transducer of the hole in the flange.

Up to approximately 4000 rpm (fig.12-16), the pressure in the cylinder modifies periodically at 2 rotations of the crankshaft (a motor cycle for a 4-cycled internal-combustion engine).

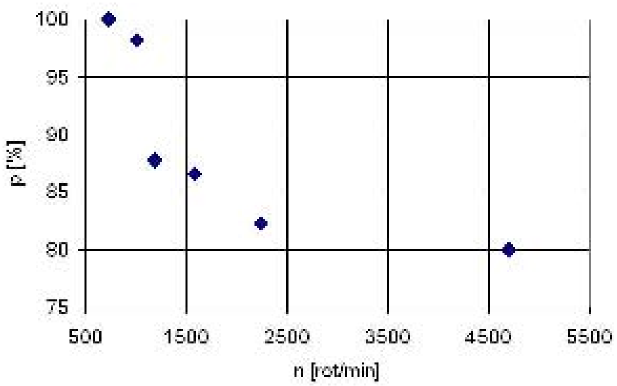


Fig. 18. Modification of the maximum pressure in the cylinder depending on the crankshaft's speed

Over 4000 rpm (fig.17) there is no more correlation between the measured speed and pressure (due to the large response time of the pressure transducer).

In fig.18 were measured the maximum pressures in the cylinder depending on speed.

The pressure is expressed in relative measures (for a nominal engine speed, the pressure can be estimated at approximately 50 bar).

Once with the crankshaft's speed increase, the maximum pressure in the cylinder registers a decrease. At idling, the maximum pressure in the cylinder has the greatest value.

## 5 Conclusion

Increasing of the combustion chamber's volume by mounting the reduction joint and movement of the point when the electric spark is released, influences negatively the combustion's evolution at the respective cylinder, and the maximum combustion pressure is diminishing against the theoretical one.

The pressure transducer introduces a significant error, due to the operation principle and the maximum measurement domain (1000 bar), at monitoring the pressure evolution between the piston's dead-centers, this perceiving a maximum of pressure at the interior dead-centre in the compressing stroke.

The pressure's maximum is moving towards right by speed's increase, situation according to the reality, because, by speed's increase, the combustion is moving more and more into expansion.

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