OVERVIEW OF ENGINE MISFIRE DETECTION METHODS USED IN ON BOARD DIAGNOSTICS

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Summary. This paper presents various methods of misfire detection in engines equipped with OBDII/EOBD systems both being already in mass production and those still under development. It describes operational principles of specific methods. The conclusion consists of an evaluation part, in which the methods under discussion are compared, their merits and drawbacks stated, and difficulties in implementation mentioned.

1. Introduction

The introduction of the Three-way Catalyst in motor vehicles has entailed a radical increase in the importance of misfire detection. In the case of a misfire, uncombusted fuel accesses the exhaust system, where its combustion in the catalyst causes a dangerous increase of temperature, which may result in damage to the catalyst due to its thermal overload. Moreover, it may also lead to an increased emission of toxic substances.

According to both the European and American legal regulations, motor vehicles equipped with On Board Diagnostics are required to monitor and detect misfires as well as to locate the cylinders where combustion is not complete. At present, it is compulsory that a 100% misfire detection cover the activity of the engine within all load and speed ranges.

Misfire Detection constitutes an essential ingredient of On Board Diagnostics. Its implementation entails the use of sophisticated measurement methods and the processing of the measured signals. Misfires tend to be related to the faulty ignition system (defective ignition plugs, leaking secondary insulation, damaged ignition control module or high voltage wires). Yet there are still a wide spectrum of other possible causes of misfire, not connected with the spark generation circuit. Misfires of that category may arise, for example, due to the leaky intake manifold, mechanical damage to the engine, damage to the valve of the Exhaust Gas Recirculation system, poor quality of fuel, inappropriate Air-to-Fuel Ratio, exhaust restrictions, damaged crank case ventilation system (PCV), damaged injector, damaged intake or outlet valves or their improper control timing, etc.

If misfires occur with such high frequency that the excessive quantity of un-combusted fuel accessing the catalyst threatens to damage it, the blinking malfunction indicator lamp (MIL) will make the driver aware of the extent of the damage the vehicle has sustained as well as how hazardous and expensive the prolonged use of the vehicle may turn out. According to the EPA regulations, a departure from this requirement is permitted on condition that she system is already furnished with other functions protecting the catalyst from damage (for example, by switching off the control of the injector in the cylinder). Misfire monitor is numbered among monitors conducted continuously (irrespectively of the engine performance conditions). Whenever it is detected that the allowed threshold limit of the deteriorated combustion cycles has been exceeded the PCM controlling device sets and stores in its memory the error codes ranging from P0300 to P0312. The P0300 code denotes detection of random misfires or the inability of the system to identify the cylinder number in which the misfire has occurred. The other codes from within the mentioned range contain the identified number of the cylinder in their 2 last digits (e.g. P0301 – denotes a misfire in the first cylinder, P0302 – in the second, etc.).

2.Misfire Detection using Analysis of the Instantaneous Crankshaft Angular Velocity.

One of the misfire detection methods (commonly used in engine mass production) is analysis of the instantaneous angular velocity of the engine crankshaft [11]. No combustion of the fuel mixture in one engine cycle results in the decrease of the torque and the crankshaft instantaneous rotational velocity value (fig. 1).

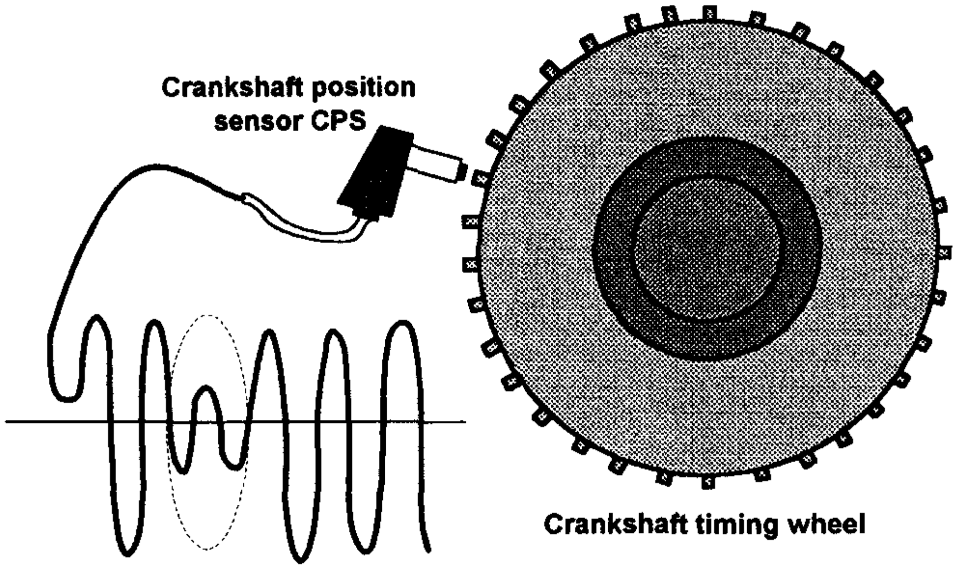

Figure 1 Recognition system for misfire detection on the basis of changes in crankshaft speed [15]

This method has to be invulnerable to disturbances and distortions caused by the following factors:

- sensor wheel tolerances
- torsional oscillations
- oscillations in the engine cycles following the occurrence of misfire,
- dynamics speed and load changes transferred onto the engine crankshaft,
- the effect of the road roughness on the engine crankshaft angular velocity,
- changes of timing in the ignition circuit caused by the function of the active combustion knock controller.

Misfire Detection System is divided into functional blocks (fig. 2). The input block effects both compensation of the sensor wheel tolerances as well as cancellation of the effect of the torsional oscillations of the shaft. The corrected signal is then processed further with the use of various methods, depending on the working conditions of the engine. For low rotational velocity and heavy loads a different algorithm is used than for high rotational velocity and light loads. The both algorithms use the general methods of feature extraction from the signal, which are then appropriately classified. Another block is to analyze the engine working conditions, and stop the method which is in the given conditions inapplicable. The other blocks control switching on and off the MIL lamp.

Difficulties with proper misfire detection in the conditions of high values of engine crankshaft rotational velocity and low load values arise due to distortions originating from the absence of combustion affecting many consecutive engine cycles and from the deteriorating quality of the logged signal (signal-to-noise ratio falls, which results from the quantization error). To improve the signal-to-noise ratio, a range of solutions are adopted. The simplest possible approach employs digital band-pass filtering. Another method applies order analysis utilizing frequency analysis based on the current rotational velocity value. Such process detects the fact that continual misfires in one cylinder will cause in the measurement data the occurrence of the effect of the dominant frequency related to the shaft revolutions (first order effect). With the application of discrete Fourier transform (DFT) a complex transform is obtained, whose phase features make it possible to identify the cylinder. However, this method proves ineffective in detecting individual or single misfires.

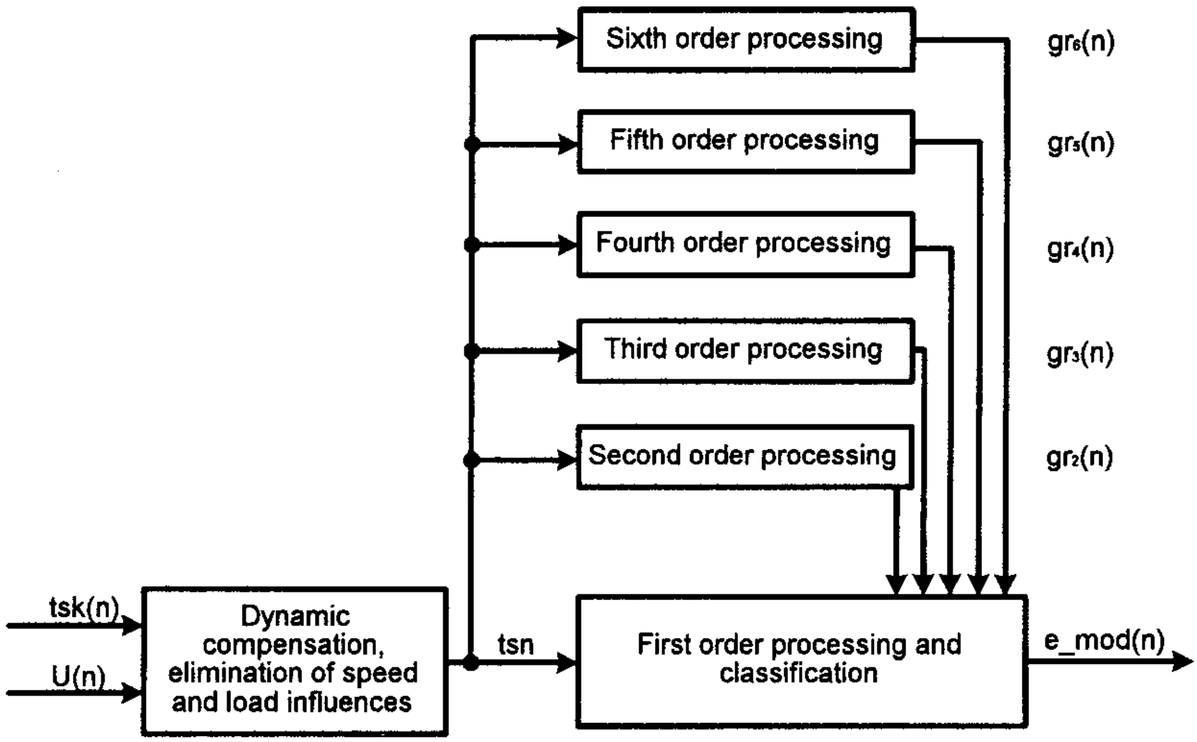

Figure 2 General Overview of Modulation Method [11]

Processing the rotational velocity signal rests on modulation and order analysis method (fig. 2). The first block cancels the effect of the roughness of the road and loading. Further processing is conducted for each order of the signal separately., whereby classifying the signals if performed by the block of the first order. In order to extract signal features there are used the number of blocks corresponding directly to the order of analysis that the system is to conduct (depending on the number of the cylinders in the engine). The clock generates the reference signal, which is multiplied with the standardized signal. The result of this operation is subjected to low low-pass filtering with the use of the digital filter of finite impulse response. The shadowed blocks are used for detecting single misfires and are present only in the block of the first order.

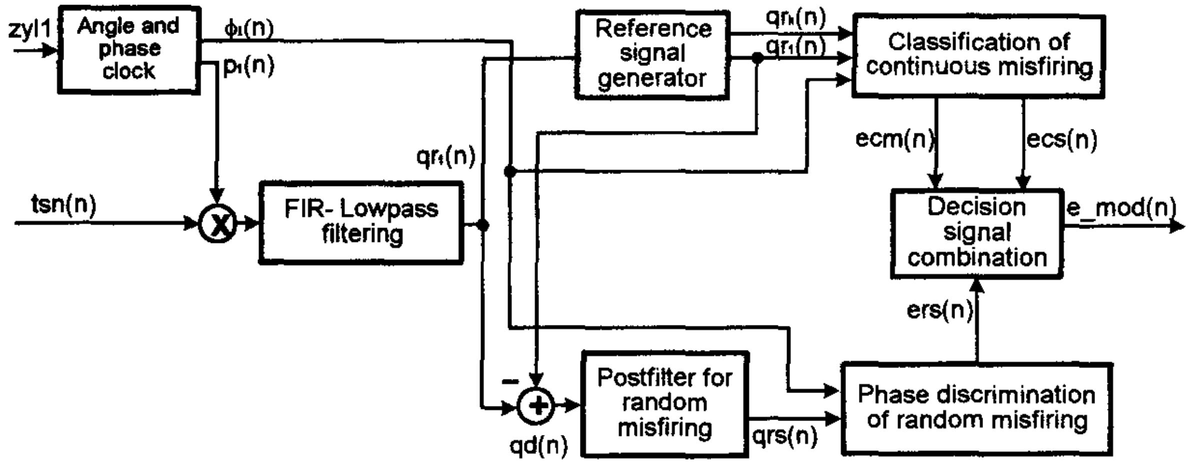

Figure 3 First Order processing [11]

3.Misfire Detection using Analysis of Instantaneous Engine Exhaust Gas Pressure

During each engine phase the outlet valve opens once to exchange the charge in the combustion chamber. The pressure in the outlet duct increases owing to the abrupt release of combustion products (the phase of initial combustion) and owing to the motion of the piston while the exhaust valve is open. The pressure fluctuations depend on the combustion features and outlet duct properties. In the event of a misfire the exhaust-gas pressure falls rapidly on account of the absence of combustion and the resultant lower pressure in the cylinder. Pulsacje ciśnienia zależą od parametrów procesu spalania i właściwości układu wylotowego.

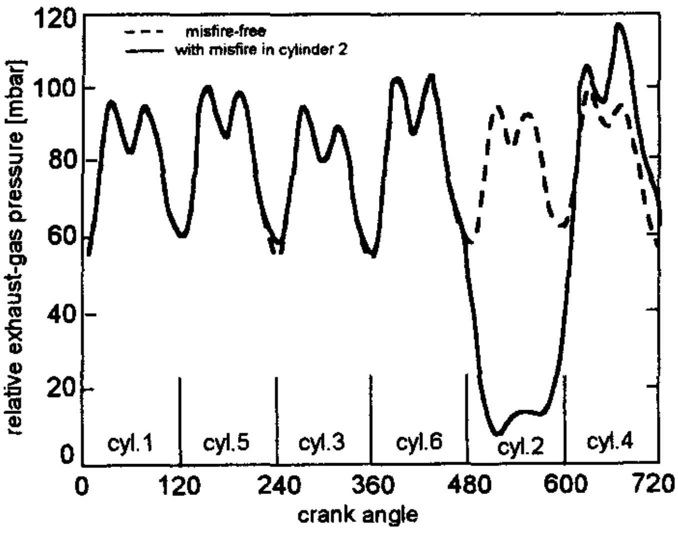

Figure 4 Comparison of the relative exhaust-gas pressure measured in the catalyst mixing tube without misfires and with a misfire in cylinder 2, engine speed 3000rpm, mid-load [6]

The primary oscillation of frequency of the exhaust-gas pressure is a resultant of the number of cylinders and instantaneous rotational velocity of the engine. The amplitude spectrum of the pressure signal in the outlet duct with the engine performing properly differs to a large extent from that with the occurrence of misfires (fig. 5 and 6).

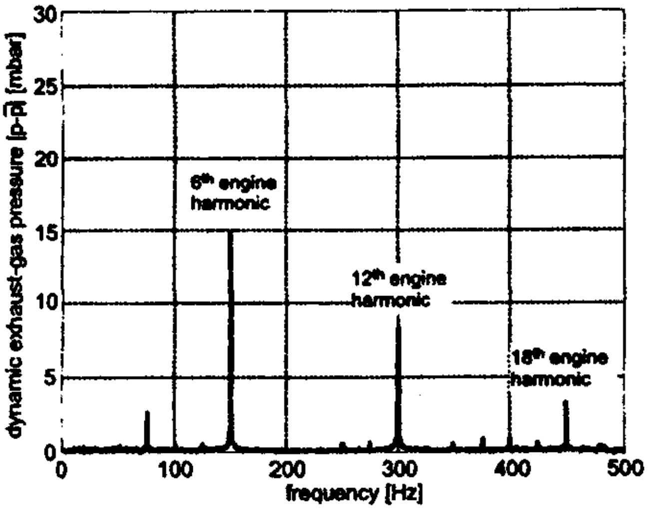

Figure 5 Amplitude spectrum of the exhaust-gas pressure measured in the catalyst mixing tube without misfires, engine speed 3000 rpm, mid-load [5]

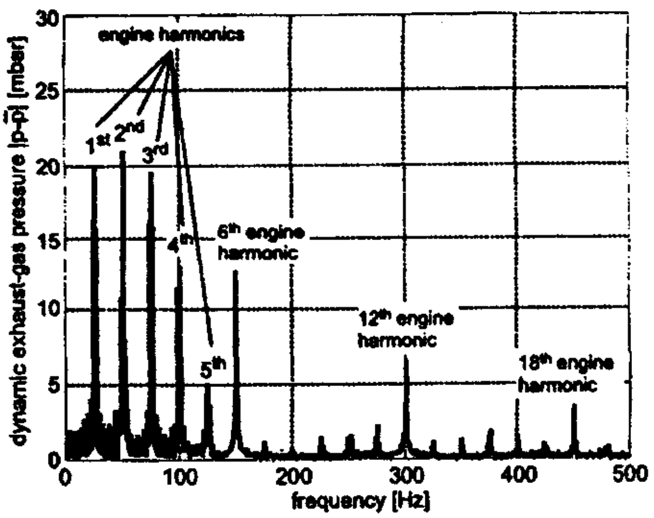

Figure 6 Amplitude spectrum of the exhaust-gas pressure measured in the catalyst mixing tube with misfires in cylinder 2, engine speed 3000 rpm, mid-load) [5]

The pressure is measured with the pressure transducer connected to the outlet duct through a short flexible connector and a Tee-joint pipe. In contrast to sensors mounted on the engine block, in this case a cooling circuit is not necessary. Owing to that fact, an inexpensive pressure transducer can be used. The requisite band frequency range for transmitting the registered signal depends on the dynamics of the processes in the outlet manifold. The cut-off frequency of the sensor should be at least 200 Hz. Of much importance are also the construction and quality of the sensor connector as well as its signal distortion damping properties. The sensor can be feasibly mounted in the part of the exhaust system between the outlet manifold and the catalyst. It is not advisable that the measurement point be positioned behind the catalyst for the latter distorts pressure pulsations making it impossible to analyze the combustion process on the basis of the signal logged there. The best results have been achieved mounting the sensor with a 165-mm-long connector. The highest temperature of the diaphragm of the sensor in this case was 85°C.

In the case of the absence of ignition, the pressure in the cylinder is approximately three to four times lower than in the case of regular ignition and regular combustion. As the pressure in the cylinder in such a case is lower than in outlet duct, it is followed by a reverse movement of the exhaust gas from the outlet manifold to the cylinder where the misfire has occurred. This may explain a significant fall of the pressure in the outlet duct, which is illustrated in the diagram 5. The wave form of the spreading pressure depend on the dynamic properties of the outlet circuit. Dumping depends on the length of the outlet pipe from the engine to the catalyst, its cross-section, position and the number of connections. The outlet system forms an oscillation unit with its own characteristic resonance frequencies, for which the dumping falls down considerably, leading to the phenomenon of standing wave.

The pressure sensor is not connected to the outlet system directly at the outlet valves but approximately 1.5 meter away from them in the catalyst mixing tube. If the cylinder with faulty combustion is to be identified on the basis of the pressure signal, all occurring delays have to be taken into consideration. Bearing this in mind it is possible to establish the opening time of the valve responsible for the shape of the signal at the given measurement point for various working conditions of the engine. For the purpose of detecting and localizing misfires various methods of signal processing and recognition strategies can be employed. The results obtained by the authors [5] are very encouraging. The accuracy of misfire detection achieved ranged between 85-100% depending on the working conditions of the engine.

4. Misfire Detection Using Measurement and Analysis of the Ionization Signal in the Combustion Chamber

Measurement of ionization current provides the information about the quality of the combustion. On its basis it is possible to establish many parameters of that process (such as estimated pressure in the combustion chamber, Air-to-Fuel ratio at the beginning of combustion, fuel admixtures, and similar). In particular low value of ionization signal indicates the absence of combustion in the cylinder, which information may be taken advantage of in misfire detection. In spark ignition engines measuring of ionization current is relatively simple to execute without introducing major modifications to the engine. In this case the existing ignition plug can be used as a measuring probe. The measurement takes place after the period of spark generation by the ignition plug to ignite the mix when the energy in the ignition circuit is already discharged and combustion is proceeding in the chamber (fig. 7).

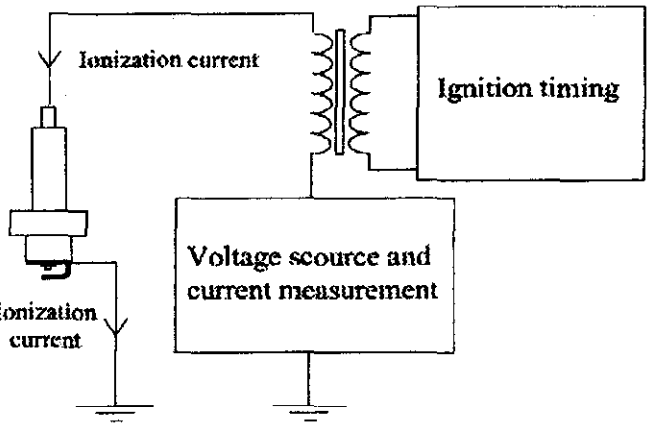

Figure 7 Measurement of the ionization current

To conduct the measurement, it is necessary to ensure DC voltage polarizing the plug electrodes at about 150 V. In a typical course of ionization signal three phases can be distinguished: the ignition phase, the flame front phase, and the post flame phase (fig. 8).

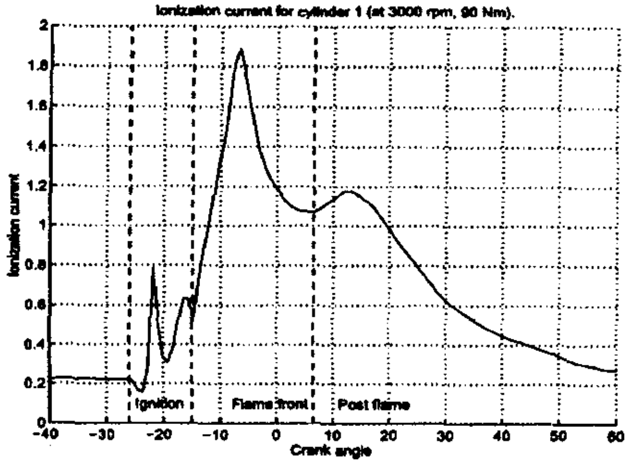

Figure 8 An ionization signal showing the three phases: ignition, flame front, post flame [7]

In the first, ignition phase, the signal is disturbed by the voltage impulse generated by the ignition coil. This phase fails to provide any opportunity to register the ionization signal in any reasonable manner, which stems from using the ignition plug as a sensing probe, the basic function of which, unfortunately, cannot be compromised or dispensed with.

In the second phase of flame front the ionization signal has a high amplitude owing to intense ionization occuring in the flame, where various kinds of ions are generated. These are differrent in terms of their durability (from the moment of their creation to their recombination). The flame only a short period of time is near the ionization sensor – the spark plug. This explains single, smooth signal peak. What remains afterwards is lasting, ionized product of chemical reactions.

The post flame signal phase is chiefly created from H_3O^+ and CO^- ions and their hydrates. In high temperatures, presuming a balance, a presence of electrons should also be expected. Ionization in the space being in the post flam phase is the sum of the remainder of ionization created in the flame and ionization triggered by the temperature and the pressure. The ionization signal alters mainly, in considerable correlation with changes of the temperature. As pressure and temperature are closely interconnected, the ionization signal in this phase follows the changes of the pressure.

In order to extract from the logged signal the required features it undergoes analog and digital processing. With the use of analog processing the signal offset is removed from the signal. The information about combustion is held chiefly in low frequency offsets. The signal frequency is limited on account of using the fourth order Bessel filtering. The signal is processed to extract its features: its peak value and integral in a given measurement window. In order to avoid disturbances from the ignition, the measurement window is chosen in such a way as to start after the disappearance of the electric ark on the plug. On the other hand, the window should be sufficiently long as to record even late combustion. Optimal is thought to be the window of the length of around 360 degrees of the crankshaft revolution. Measurements in the normal conditions of the engine performance (stoichiometric mixture, optimal spark timing, ignition time duration 600 μs) have manifested that ionization level is the lowest in the conditions of idle.

Ionization signal features in the time function contain information about the process of ignition and misfires (fig. 9). The peak value is mapped over the X-axis, below the axis, there is the integral from the signal. There are represented recorded values from two cylinders. In the bottom part marked are those phases in which a misfire was generated switching off the injector. It is clearly visible in the registered signal. It is also noticeable is how small is the intensity of combustion (or at least of the ionization signal) in a number of consecutive engine phases, following misfires generated in such a way. This is explained with the fact of wallapplied film build up.

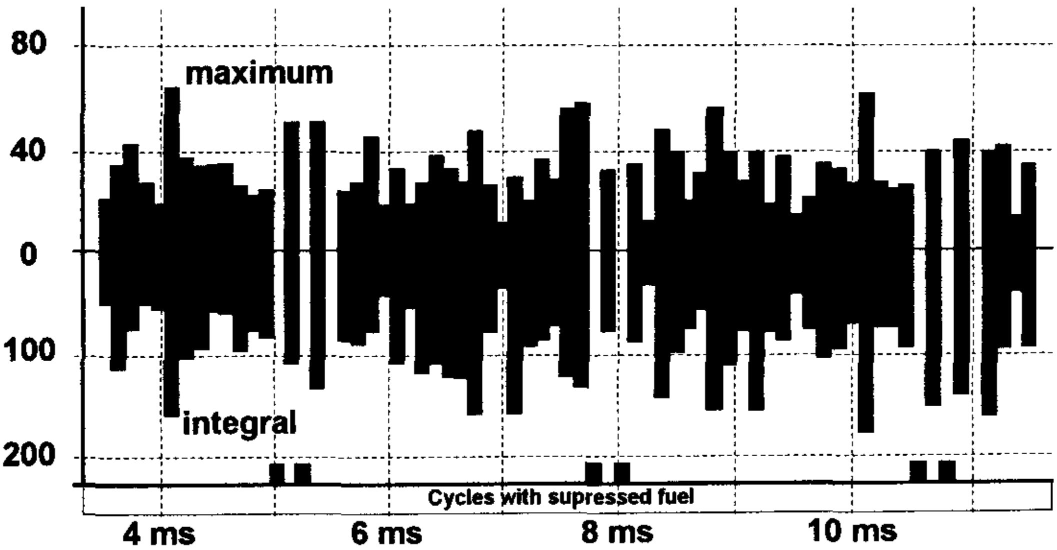

Figure 9 Sequence of calculated features in dependence of the time. Herein the results of 2 cylinders are alternately multiplexed [10]

5. Misfire Detection Using Measurement and Analysis of Torque

Another method of misfire detection is measurement of instantaneous net torque. Although such measurement is rarely implemented in the engines manufactured at present, modern measurement techniques make it possible to be introduced in mass production solutions [13]. Torque measurement can be conducted with the use of various sensors and various physical phenomena.

Instantaneous Net Torque measurement methods and sensors are as follow:

- **Sensors utilizing eddy currents**. High frequency current flows through the coil. This coil is aided by the elements in which eddy currents are induced, and which are placed on the part of the shaft working as flexible shaft. The mutual angular movement of these elements changes the inductive properties of the system and is detected by the measurement system. The advantage of that method consists in its invulnerability to dirt and high resolution of measurement.
- **Piezoelectric sensors**. They take advantage of the piezoelectric effect – the generation of a charge under the influence of a force deforming the crystal structure of the active element. They require the use of conditioning systems with high impedance and do not lend themselves to static measurements. They display low sensitivity to temperature changes (they can work in temperatures up to 500°C). They permit measurements of signals of relatively high frequencies.
- **Magnetic sensors**. They measure changes in the magnetic susceptibility of the crankshaft under the influence of the load carried. The net torque working on the shaft causes a torsional deflection and tensions in the shaft as well as proportional alteration of the measured feature (magnetic susceptibility). Measurement with this method relies heavily on temperature and the changes of width of the air-gap.
- **Measurement elements stuck onto the engine crankshaft**, they are made form materials of magnetic properties with strongly depending on mechanical tensions. To define the flow changes in the air-gap, additional sensors are used.
- **Analysis of instantaneous angular velocity of the engine crankshaft**, to estimate the torque value. A correlation has been found between torque and square difference of angular velocity in chosen positions of the crankshaft [14].
- **Measurement of the crankshaft torsional deflection** with the use of two measurement discs placed at its ends. This method is relatively inexpensive and simple in implementation. The crankshaft torsion detected with this method is directly proportional to the torque carried by the shaft.

The torque is a superposition of two factors: the pressure caused by combustion and the dynamics of the other rotational elements in the engine. Misfire detection using this method is impeded in some conditions of the engine performance. This occurs in high engine velocity and heavy loads. With high rotational velocities a decisive influence over the dynamics of the system has the inertia of rotating masses and it may disguise the decrease in torque resulting from misfires. Moreover, with small engine loads the influence effective torque from pressure in the combustion chamber also dwindles and causes results similar to those caused with high rotational velocity. The sample shapes of torque and ignition signal are shown in figures 10-13.

The oscillative character of the torque response stemming from a misfire may be very similar to other shapes of torque logged in normal conditions of exploitation, for example triggered by the change of gear. Also this temporary state may disguise the response in the event of another absence of combustion within a short span of time from the first one.. With the rotational velocity of the engine at 5000 revolutions per minute it is very difficult to detect the decrease of the torque triggered by a misfire (fig. 13).

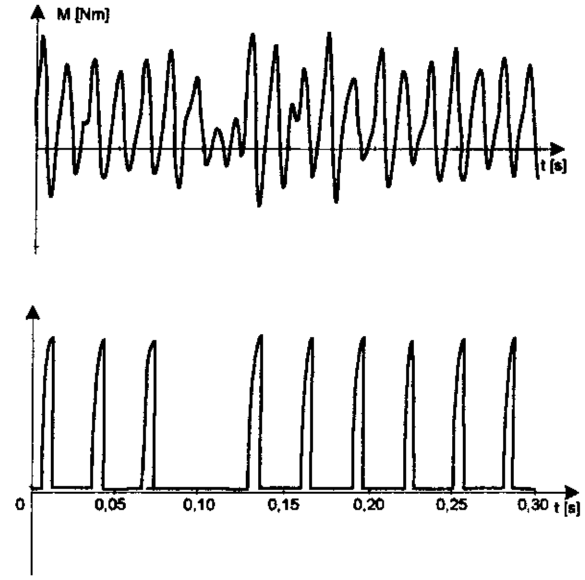

Figure 10. Torque and ignition signals for 2000 rpm, throttle 100%, 1 misfire [6]

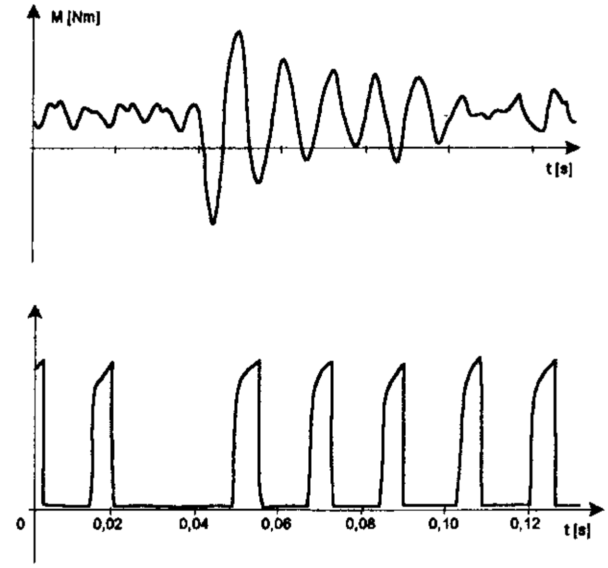

Figure 12. Torque and ignition signals for 3500 rpm, throttle 100%, 1 misfire [6]

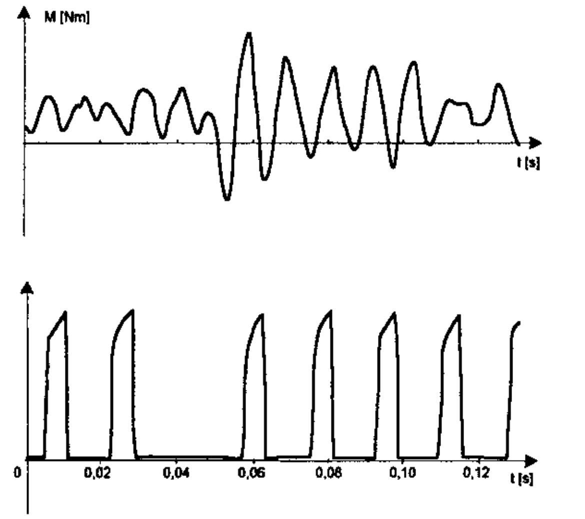

Figure 11. Torque and ignition signals for 3500 rpm, throttle 75%, 1 misfire [6]

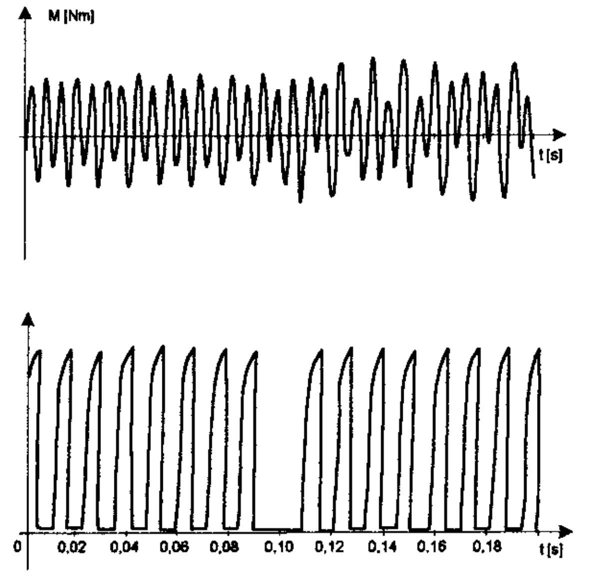

Figure 13. Torque and ignition signals for 5000 rpm, throttle 50%, 1 misfire [6]

6. Misfire Detection using Analysis of Combustion Chamber Pressure

The value of pressure in the combustion chamber remains directly related to the quality of combustion. The intrusive pressure sensors commonly used so far were riddled with serious drawbacks such as low durability and their use limited by the high cost. Although there has been a marked technological progress in this field, resulting in both the lowered prices and decreased size of such sensors, further progress in this area is likely to be inhibited by considerable limitations arising from the excessively difficult working

- direct access to the combustion chamber is not required,
- owing to the cooling system of the ignition plug the temperature of thus installed system is relatively low (up to 140°C),
- owing to the fact that it is mounted outside the combustion chamber, measurement is unaffected by many possible causes of errors resulting from extreme thermal conditions in the combustion chamber and high pressure (for example, in the engine transition phases)

The outer thread of the sensor is asymmetrical trapezoidal of patented construction, which ensures axial load of the sensor in order to maintain its linear characteristics. To minimize thermal interference errors, the sensor case is made from aluminum alloy with coefficient of expansion equal to that of the material of the engine head. The nickel plating of the surface protects from thread galling and corrosion.

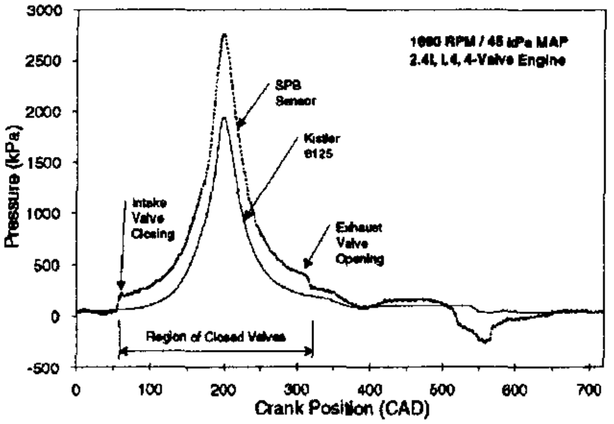

Figure 15. SPB Sensor and Kistler 6125 Signals Plotted as a Function of Crank Position for One Combustion Event at Part Throttle [12]

7. Misfire Detection Using Optical Methods

One of the ways of obtaining information about the processes occurring in the combustion chamber are optical methods [1]. This category includes the investigating optical methods consisting in registering or assessing the electromagnetic emission within the range of visible and thermal radiation. Vision methods are applied for the direct observation of such processes as the creation of air-fuel mixture, the charge movement inside the combustion chamber, the combustion progression (self-ignition, flame development).

These methods include stereography and video endoscopy, which at present are the most commonly used. An example of the utilization of stereoscopic photography is its application in investigating the flow of gases in the spark ignition engine. In order to gain information about the movement of the gases within the engine cylinder, a measuring system has been devised [2], furnished with a camera for rapid photo shots and cooperating with the system of five mirrors. Photos were taken of the traces left in combustion by the molecules of sodium added to the fuel. Subject to investigation was a one-cylinder engine with a piston head with a quartz window (fig. 16). Owing to the choice of a proper mix the progression of gases could be observed before and during combustion, which makes this method potentially useful for misfire detection (in research).

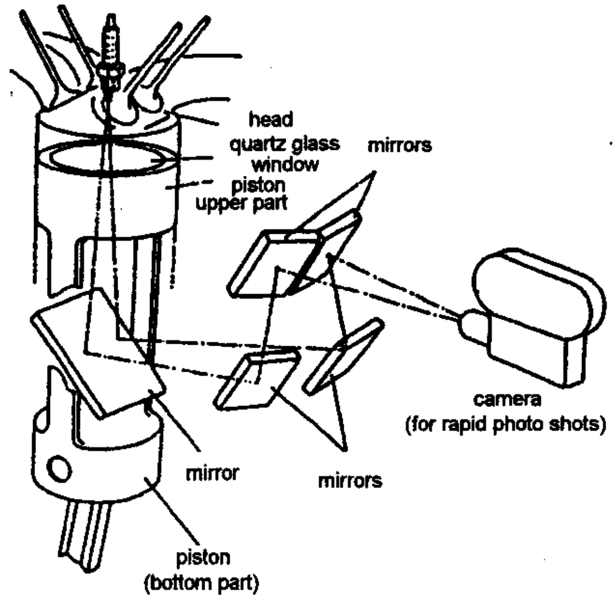

Figure 16. General overview of Stereography Method for Gas Flow Investigation [16]

The introduction of endoscopic methods enabled complete and continuous visualization of the processes ongoing inside the engine. Endoscopy combined with video technology allowed real time observation and recording of the cyclical processes, which constitutes a novelty in the process of researching internal combustion engines. However, this method of conducting observation of processes occurring in the engine relies on their periodicity, the photographs are taken in certain positions of the crankshaft over a number of consecutive engine cycles. Thus its applicability for investigating misfires is limited to laboratory conditions.

The mid-eighties saw the first reports on taking advantage of fiber optics in researching internal combustion engines. The intensity measurement is the easiest way of obtaining the analog electric signal; yet it is susceptible to disturbances and distortions resulting from temperature changes and pollution. Assessing the change in the wavelength is complicated and requires that the measurement channel be furnished with additional optical elements. Nonetheless the frequency measurement provides a very accurate and stable signal carrying the information about combustion. Owing to their specific properties, fibers may also be used for pressure measurements. This end is achieved by utilizing intensity changes of the reflected light transported through fibers or by direct signal phase modulation inside the fiber subjected to the activity of pressure. The optical methods denote measurement of radiation within a certain range of the light spectrum emitted during combustion and processing this signal in order to obtain its properties such as: wavelength, signal amplitude.

In order to investigate the optical processes during the combustion in the engine chamber a measurement device is applied which consists of pressure and optical signal intensity sensors as well as conditioning and measurement systems. (fig. 17). As a measuring probe a modified ignition plug fitted with fibers is used (fig. 18).

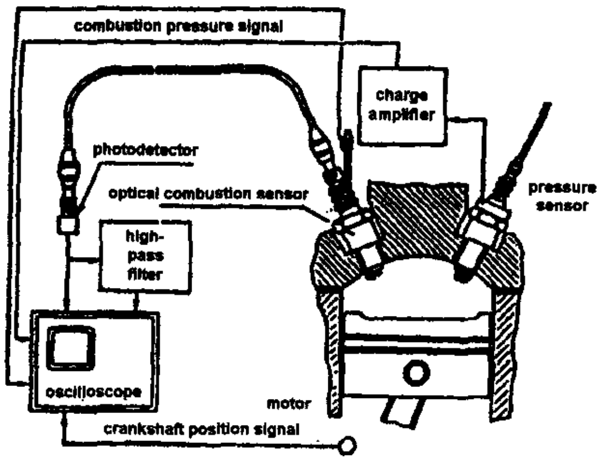

Figure 17. Schematic diagram of an Engine Combustion Investigation System

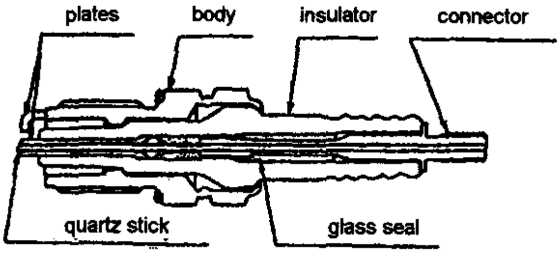

Figure 18. Fiber optic sensor integrated with spark plug [1]

The signal obtained at that point is correlated with the flow of pressure in the combustion chamber. It carries the information about the quality of that process, especially about combustion knock. The optical method as contrasted with the classical measurement of indicated pressure displays a superior sensitivity to combustion knock. The schematic engine control system proposed by the authors [3] uses fiber optic measurement sensors. The optic sensor of combustion supplies many various signals regarding the absence of combustion, combustion knock, spark retard, mixture composition, combustion temperature and pressure inside the combustion chamber.

Another possible use of the fiber to collect data about the combustion process is its integration with the ignition plug gasket [4]. Such a sensor is immune to disturbances emitted by the ignition plug, which phenomenon was noted in the case of using piezoelectric sensors. A choice of a special fibers enables it to work in high temperatures. The minute flexures of the loop of the fiber placed between the two parts of the plug gasket caused optical signal modulation (figures 19 and 20).

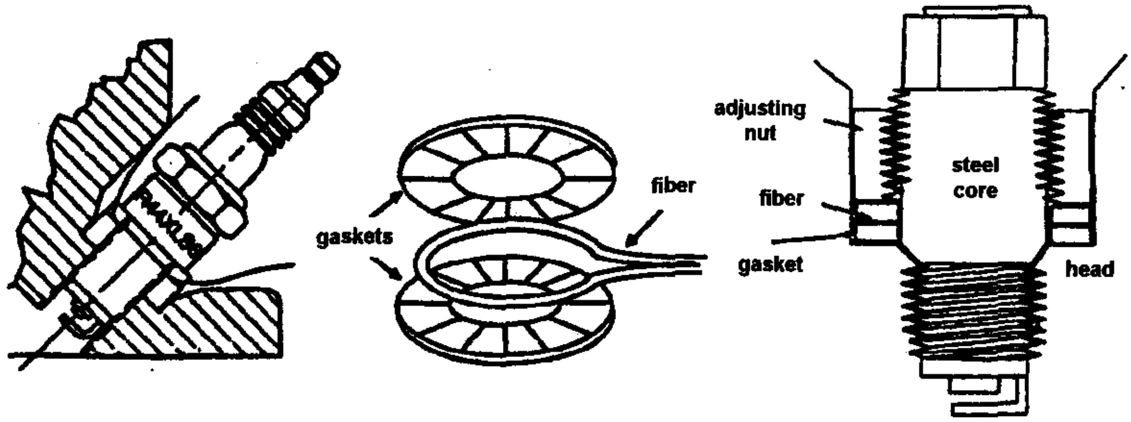

Figure 19. Fiber optic sensor integrated with the gasket [18]

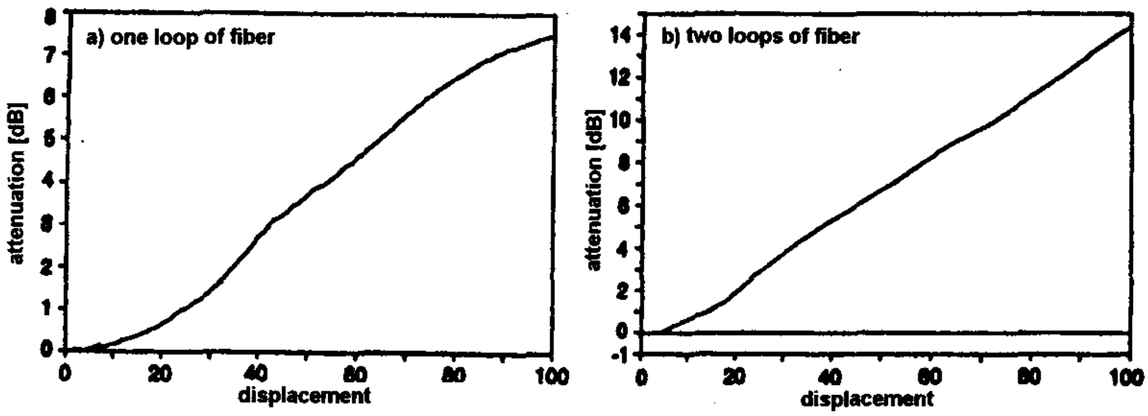

Figure 20. Magnitude function of the fiber optic sensor [18]

8. Conclusion

The misfire detection methods presented here differ from one another in terms of difficulties in their implementation as well as the costs of their introduction into automobile mass production. The method founded upon measurement of the instantaneous rotational velocity is relatively the most inexpensive one. It is commonly in application in currently manufactured motor vehicles equipped with OBD II system. However, it is vulnerable to distortions and disturbances in all working conditions of the engine. The optical methods are utilized chiefly in laboratory research; however, their simplified and refined implementations may find practical application in the future. The method resorting to the measurement of the ionization current is a novel method and appears to be holding quite a prospect. Interesting and promising seems also the method using pressure measurement in the outlet duct, yet its application would entail additional pressure sensors, which would reduce the likelihood of its successful adoption on a larger scale. The spectrum of combustion diagnostics methods appears to be relatively wide, so the automobile manufacturers are unlikely to encounter problems in satisfying new, more challenging legal requirements in this regard.

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