Fault simulation of the sensors in gasoline engine control system

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Abstract. The control system of the gasoline engine requires the information about its current condition. These are the information which have to be transferred into electric signals. In the mechatronic control systems of the combustion engines, non-electric quantities are changed into electric signals by way of the converters called sensors. Like all technical devices, sensors can be damaged. They are also the subject of the aging process based on the change of the converting characteristics. If the breakdown is based on the change of the sensor characteristics, it will indicate the value of the measured quantity with a certain error. The system of on-board diagnostics is supposed to detect the faults including wrong indications of the sensors. Unfortunately, not all the faults are detected and some of them are masked by the adaptive function of the control system. The aim of this project is to prove that there are many possibilities of the detection of wrong indication of the sensor. It is possible even in case when its signal is within the voltage limits defined for it. It requires the analysis of several signals simultaneously. Comparing a current value of the signal with a typical one for a particular point of work will allow us to detect possible indication error of the sensor. Typical values have to be in the shape of database as a function of other signals (e.g. in the shape of so-called maps). This project presents the studies based on the simulation of faults of chosen sensors. Based on the analysis of several signals simultaneously, it is possible to deduce the accuracy of the indication of a particular sensor.

1. Introduction

Controlling the gasoline engine relies on the survey of many quantities depicting its condition in every time and on controlling the subassembly providing proper working. Measured quantities depicting the condition of the engine include: rotational speed, temporary crankshaft position, intake manifold pressure, throttle angle, contents of oxygen in the exhaust, temperatures and many more. Controlled actuators of the engine are: fuel injectors, ignition coils, throttle actuator, EGR valve etc.

Precise measurement of all quantities depicting the condition of the engine allows to control actuators. It provides optimal conditions to preparing and burning the air-fuel mixture and, as a result, high engine power. Nowadays, environment protection is emphasized. Low emission of toxic components and carbon dioxide is a desired feature of combustion engine. The second desired feature is proper dynamics, i.e. high and „flat” torque and high power. Such requirements can be met by controlling the work of engine precisely. Controller fills a function of supervising and controlling executive subassemblies. It is an electronic device working on the basis of electric signals. All information concerning the condition of the engine must be delivered to the controller in the form of electric signals. Sensor fills such function.
Many sensors are used in the system of controlling the gasoline engine [1]. They convert non-electric quantities into electric signals. Therefore, they are converters located in proper case, e.g. thermistor is the converter of temperature into electric size (electrical resistance). Wrong indications or lack of strategic sensors (e.g. of crankshaft position) preclude the work of engine. Signals from the remaining sensors (e.g. of flowmeter) burdened with an error cause an inappropriate working of the control system and non-optimal work of the engine.

Controllers of gasoline engines fill the function of self-control, i.e. so-called on-board diagnostics [2]. The role of the on-board diagnostics is a supervision over all elements of the control system including sensors. As all technical devices, sensors can be damaged. The system of the on-board diagnostics should inform about the occurring faults in case of every damage of the sensor. Unfortunately, not all damages are detected by self-control system. Some of them, which rely on the shifting the signal of the sensor by a constant value up or down, remain unnoticed. Some of them are masked by adaptive (learning) control system [3, 4].

2. Types of damages of the sensors

Damages of the sensors can take place because of many reasons. There are mechanic damages easy to visual identification. Electric damages of the sensors undetectable visually are very frequent. Such damages can result in the signal giving wrong information or the lack of the signal. If as a result of wrong working of the sensor its output signal goes beyond the bounds accepted for the particular sensor, the system of the on-board diagnostics interprets it as an error of the sensor. If wrong working of the sensor is based on the shifting its characteristics but the output signal does not go beyond the bounds accepted for it, such damage remains unnoticed.

Self-control system is an algorithm realized in the controller which is supposed to detect faults. It analyses signals coming from the sensors. It may be possible that wrong value of the signal is not the result of damaging the sensor but the wire linking the sensor with the controller. Damage to the wires can be based on: shorting, interruption and appearing a certain resistance between the wires or between the wire and car body. The system of on-board diagnostics can detect the first two damages from those ones mentioned above and will indicate the fault. In case of appearing a certain (finished) resistance between the wires, the signal from the sensor can be moved by a constant value (figures 1 and 2). In such situation, damage will not be detected and the engine will be controlled on the basis of false information.

The controller will work in the same way when as a result of faulted sensor its signal is changed by a certain value. The shifting of the signal by a constant value usually occur in the entire extent of the output signal. Damages of the sensors can also be based on the change of its characteristics. Most frequently in case of linear characteristics, this is a change of its slope and/or shifting by a constant value (figure 1). In case of sensors of non-linear characteristics, shifting by a constant value of the output signal strongly disturbs the survey only for low or high measured values (figure 2).

Aging sensors work in a similar way. Their characteristics submit to little changes with time. This is a process which concerns most of the sensors during the life of the car. Controllers are equipped with the adaptive control system to minimalism errors of controlling the engine as a consequence of the aging sensors. The adaptive system „learns” during the maintenance of the car and corrects controlling of the engine taking account of the indication changes of the aging sensors.

Unfortunately, the adaptive character of the control system can mask damages of the sensors not coming from the process of their aging. In such case, controlling the engine will be corrected on the basis of changed characteristics of the sensor what will not give optimal results of its working. Deterioration of the engine performance can be based on the increase of the emission of toxic compounds, the loss of power and torque and the increase of fuel consumption.
measured quantity

output signal of the sensor

linear characteristics of the efficient sensor
displacement of the characteristics to the fixed value
minor change of the gradient with the displacement to the fixed value
big change of the gradient with the displacement to the fixed value

Figure 1. Linear characteristics and its exemplary changes for damaged sensor

non-linear characteristics of the efficient sensor
big change of the characteristics for the minor values of the measurand
big change of the characteristics for the big values of the measurand

Figure 2. Non-linear characteristics and its exemplary changes for damaged sensor
3. Detection of the indication errors of the sensors

Sensors are some kind of non-electrical gauges describing the work of the engine. Precision of their indications is determined by the quality of controlling the combustion engine. It is crucial to supervise the work of the sensors continuously to provide optimal controlling.

When a signal from the sensor is within the voltage limits defined for it, it is likely to give reliable information about measured value. However, if the characteristics of the sensor changes (shifts), its indication will be burdened with an error. How to detect the indication error of the sensor when its output signal is within the limits defined for it?

One of the methods is the analysis of many signals in the control system. It is based on the comparison of the indication of the sensor and its typical value determined by other signals. This method requires placing a series of dependencies (e.g. maps) of every signal from two others in the on-board diagnostics, e.g. the signal of manifold pressure from the engine rotational speed and the throttle position. If the distinction between the indication of the sensor and the value which other signals point to is higher than hesitation of the survey, the indication of this sensor should be considered to be wrong [5-11].

The example of the relation between manifold pressure, engine rotational speed and the throttle position is one of the dependencies in controlling the spark ignition (SI) combustion engine. Conducting research of the engine, it is possible to assess how many such dependencies occur between the values in the control system. An interesting conclusion will be the answer to the question if the signals of all the sensors can be saved as the variables of the signals from the other sensors.

Measuring some values describing the work of the engine, it is possible to find the answer to the question if unambiguous dependencies in case of damaging of two sensors simultaneously can occur.

4. Tests

Some investigations were planned in order to verify the method of sensors fault detection in the control system of the SI engine with the gasoline direct injection (GDI). It differs from the fuelling system of the SI engine with the indirect injection of fuel. The basic difference is the work of the engine with very poor mixtures. It takes place at low and medium rotational speeds and loads. Then, laminar mixture is burned in the engine. Average composition of such mixture determined by factor λ varies from 1,8 to 2,5. Surveys were conducted in a situation when the engine was working with homogenous mixture.

The sensors submitted to examination include: volumetric air flowmeter, the air pressure sensor, the air temperature sensor, the manifold pressure sensor, the engine temperature sensor and the fuel pressure sensor. The survey of the work parameters of the engine with the entire functional control system was carried out. Next, faults of particular sensors were simulated and the survey was conducted one more time.

Taking into consideration the fact that the indication errors can be displayed at different rotational speeds of the engine as well as at different loads, the studies were carried out at three loads and seven rotational speeds. The loads were given by setting the voltage at the output of the accelerator pedal position sensor. Some voltages were in a line with: no-load running, 17%, 34% and 100% of the extent of its variability. The rotational speed was set by applying the brake load to the engine. The surveys were conducted with the speeds of: no-load running, 1000, 1500, 2500, 3000, 3500 and 4000 rpm. The following indication errors of the sensor were simulated:

- moving the characteristics of the air temperature sensor by adding additional resistance in a way that it pointed 44ºC for 31ºC (damage indicated with letter b),
- shifting the characteristics of the air temperature sensor by adding additional resistance in a way that it pointed 19ºC for 33ºC (damage indicated with letter c),
- shifting the characteristics of the liquid coolant temperature sensor by adding additional resistance in a way that it pointed 106ºC for 86ºC (damage indicated with letter d),
• shifting the characteristics of the liquid coolant temperature sensor by adding additional resistance in a way that it pointed 58°C for 87°C (damage indicated with letter e),
• shifting the characteristics of the air pressure sensor by shifting the output voltage in a way that it pointed 109kPa for 98kPa (damage indicated with letter f),
• shifting the characteristics of the air pressure sensor by shifting the output voltage in a way that it pointed 87kPa for 98kPa (damage indicated with letter g),
• change of the characteristics of the volumetric flowmeter by partial obscuring the measuring channel (damage indicated with letter h),
• shifting the characteristics of the fuel pressure sensor by decreasing the output voltage in a way that it pointed pressure 2MPa higher than the actual one (damage indicated with letter i),
• shifting the characteristics of the fuel pressure sensor by increasing the output voltage in a way that it pointed pressure 2MPa lower than the actual one (damage indicated with letter j),
• changing manifold pressure by making little leakiness (damage indicated with letter k),
• changing manifold pressure by making bigger leakiness (damage indicated with letter l).

5. Test results
The on-board diagnostics (OBD) system has not detected any of simulated faults during the studies. The following one-second processes of signals were registered for the efficient control system and all faults of the sensors mentioned above:
• from the crankshaft position sensor,
• from the camshaft position sensor,
• controlling the fuel injector for the first cylinder,
• controlling the ignition coil of the first cylinder,
• from the volumetric flowmeter,
• from the manifold pressure (MAP) sensor,
• from the analyser of mixture composition MEXA-700λ,
• from the fuel pressure sensor.

Next, the following parameters in the control system of the engine were determined:
• average value of the rotational speed \( n \),
• average value of the angle of the spark lead \( \varphi_z \),
• average value of volumetric air flow rate filling the engine \( V_A \),
• average values of the injector opening angle \( k_{pw} \) and the duration of the fuel injection \( t_{on} \),
• average value of the manifold absolute pressure \( MAP \),
• average of the air-fuel ratio determined by the factor \( \lambda \),
• average fuel pressure in the board powering the injectors \( p_F \).

Attained results were presented collectively on the charts (figures 3 ÷ 8). Processes for 17% load given by acceleration pedal are painted blue. Processes for 34% load are painted green and the ones for 100% load are painted red.

Figure 3 shows the processes of the flowmeter signal. Only for the fault pointed by letter h (obscuring the measuring channel of the flowmeter) with a high load, the difference bigger than the hesitation of the survey is visible. Therefore, it is possible to diagnose this case as wrong indication of the flowmeter signal.

Figure 4 shows very big difference between a signal for the efficient control system and the indication of the MAP sensor connected with the fault marked by letter l (high leakiness of the manifold). It is visible with low and high loads. It increases along with the increase of the rotational speed. As far as low loads are concerned, there is also a difference bigger than the hesitation of the surveys for a signal from the MAP sensor connected with the fault marked by letter k (low leakiness of the suction manifold). Therefore, it is possible to diagnose wrong indication of the MAP sensor regardless of the cause of its occurring.
Figure 3. The volumetric flow as a function of the rotational speed for the efficient control system and all the faulty states marked by letters b ÷ l.

Figure 4. The manifold absolute pressure (MAP) as a function of the rotational speed for the efficient control system and all the faulty states marked by letters b ÷ l.
Figure 5. The fuel injection time as a function of the rotational speed for the efficient control system and all the faulty states marked by letters b ÷ l

Figure 6. The processes of the air-fuel ratio $\lambda$ as a function of the rotational speed for the efficient control system and all the faulty states marked by letters b ÷ l
**Figure 7.** The fuel pressure transported into the injectors as a function of the rotational speed for the efficient control system and all the faulty states marked by letters b ÷ l

**Figure 8.** The ignition angle as a function of the rotational speed for the efficient control system and all the faulty states marked by letters b ÷ l
Figure 5 shows the processes of the fuel injection duration per every cycle of the engine work. The differences of the injection time bigger than the hesitation of the survey for several faults in the control system are visible. All of them occur with high load. As far as low rotational speed is concerned, there are visible differences for the damages marked by letters: e (lowered indication of liquid coolant sensor) and g (lowered indication of air pressure sensor). When rotational speed is higher, there is visible the difference for the damage marked by letter i (lowered indication of fuel pressure sensor). In the whole range of rotational speeds, there is visible the difference for the damage marked by letter j (punitive indication of fuel pressure sensor). Therefore, in particular cases, time of fuel injection generated by the control system shows wrong indications of several sensors.

Figure 6 shows the air-fuel ratio marked by the factor $\lambda$. Very big difference of the mixture composition occurs only for low loads with the faults marked by letters k and l (low and high leakiness of the suction manifold). The air-fuel mixture was very poor then – it was on the brink of combustibility. The „falling out of ignition” occurred, that is why, there was the oxygen in the exhaust. It disturbed the survey of the factor $\lambda$ which equalled 2 in such survey.

Figure 7 shows the processes of a signal from the fuel pressure sensor. The difference is visible in case of wrong indications regardless of the rotational speed and the load.

Figure 8 shows the processes of the ignition angle. It is impossible to observe the influence of wrong indications of the sensor on this parameter. It is useless in diagnosing wrong indications of the sensors.

6. Summary and conclusions

The work of the control system is based on the indication of many sensors processing non-electric parameters connected with the work of the SI engine. The quality of the sensors work and their preciseness translate into the quality of controlling the engine. The on-board diagnostics system is supposed to detect wrong indications of the sensors. As it was concluded in the research, none of the simulated faults was detected by diagnostics system installed in the controller. The analysis of the conducted studies gives us the following conclusions:

- algorithms used in the system of on-board diagnostics do not allow to detect faults based on wrong indications of the sensors in many cases,
- wrong indications of the sensors are masked in certain range by adaptive control system, e.g. the change of fuel pressure is corrected by the duration of the injection,
- algorithms of the on-board diagnostics can be extended with simultaneous analyses of many signals to make the change borders of the indications of the sensors be always picked to current condition of the engine,
- not all faults came forward in the observed parameters and the angle of the spark lead did not indicate any faults,
- usage of more advanced algorithms of the detection of wrong indications of the sensors requires conducting further studies and analysis.

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