Model based diagnosis of gasoline injection engine

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Abstract. The paper approaches one of the most effective diagnosis solutions used on engines equipped with sensors, actuators and microcontrollers. The principles and advantages of this type of diagnosis are outlined. Functional models and possible fault types are presented. Differential equations for dynamic operation of sensors and actuators are deduced. It presents the problems related to the isolation of the faults, as well as the one corresponding to the generation and evaluation of the residual. The aspects related to fault detection are highlighted. The case of diagnosing the engine air supply system is exemplified. There are presented various schemes and relations of calculation corresponding to the model-based diagnosis. Important theoretically and practically conclusions are drawn. The paper benefits from the experimental data obtained on the tests of an A6 Audi car equipped with a gasoline engine. During the experiments, various faults of some constructive parts of the engine were deliberately made.

1. Introduction

The thermal engines manufactured today have an electronic control management, due to equipping them with sensors, actuators and microcontrollers, all of which ensure the diagnosis and control of the real-time operation [3; 5].

The constructive solutions of the current engines and those from the perspective put the diagnosis first, following which according to the data received the on-board computer decides on the control. Thus, the engine control solution in case of fault presence was launched, being named FTC (Fault Tolerant Control).

According to this control strategy, the existence of faults, inherent in real operating conditions, is tolerated, and the on-board computer sends commands to the execution elements in accordance with those found after the diagnosis. It can be said that a high performance engine has a set of control techniques that ensure its ability to meet the proposed objectives despite the occurrence of failures. Subsequently, the algorithm appeared has improved, with the diagnostic solution by reconfiguring the control.

The definition of the fault must be mentioned, according to IFAC (International Federation of Automatic Control): a fault / defect is called a not allowed deviation of at least one characteristic property / variable of the system from the acceptable / usual / standard / nominal behavior. As it can be seen from this definition, a fault means a deviation from the nominal value of a parameter; As a result, the fault is the quantitative measure of a failure. Instead, a fall means a permanent interruption of the system's ability to perform a required function under specified operating conditions. As it can be seen
from the ones presented, the fault appears in the physical plane, the error in the informational plane, and the fall in the user plane.

The diagnosis process is based on the operation called Fault Detection and Isolation (FDI). The possible source of a defect is called a candidate. The detection of the fault therefore means to determine if there are defects in the system, as well as the detection time (the time of occurrence). Isolating the fault means determining its location, for example which component is defective, as well as the type of defect.

By identifying the fault, it is meant to determine its size, so a quantitative assessment of the occurred fault. Thus, the notion of fault detection, isolation and identification (FDII - Fault Detection, Isolation and Identification) has appeared. As a result, the term of fault diagnosis can be defined. In the literature there are three variants of definition [2]: the first of these includes the detection, isolation and identification of the fault, the second includes only the isolation and identification of the fault, and the third means establishing the origin of the fault. In the case of fault-tolerant control (FTC), the ones presented are complemented by the fault adjustment, which means reconfiguring the system (through the reconfiguration control) so that the operation can be maintained within acceptable limits despite the existence of a fault.

Thus, another notion has appeared, called fault detection, isolation and accommodation (FDIA - Fault Detection, Isolation and Accommodation).

From the presented results, the diagnosis mainly concerns the defects, which are often characterized by the description of their variable behavior over time; this is called in the literature the imprint of the fault.

2. Main concepts related to the model-based diagnosis of the engine

Model Based Diagnosis (MBD), with the general scheme of figure 1, is one of the most used methods in the field of gasoline injection engines [2; 5], because it has important advantages, the main ones being: it is insensitive to disturbances; faults can be detected no matter how small they are, and the detection time is very short; allows very good isolation of multiple faults; the diagnosis is made in real time during engine operation.

As shown in figure 1, this diagnostic method works with three types of mathematical models:
- model 2 that describes the normal operation of the engine 1; so, in the absence of faults this model is known a priori and defines the normal process (a normal operating mode).
- model 3 that describes the actual operation of the engine (with or without faults); this model is not known a priori and is based on the experimental data provided by the transducers and the built-in execution elements. This model results from systems identification procedures, knowing the input data \( u \) (control-specific commands) and the output data \( y \). It defines the observable process and allows the estimation of state parameters \( \hat{x} \), output parameters \( \hat{y} \) and characteristic parameters \( \hat{\theta} \) (in figure 1: references 5, 6 and 7).
- model 4 that describes the malfunction of the engine. This model is, in fact, a database of faults that may occur during engine operation; therefore, the model is known a priori and calls for mathematical modeling of faults (their imprint).

Comparing the normal process with the observable one, the residual \( r \) is generated (reference 8), which is the fault detector. Then, using model 4, which offers the imprint of the defect, the decision is made on it (the type and the time of occurrence of the defect - reference 9). Then the fault is diagnosed (reference 10), determining its location (what is defective), its size (quantitative assessment) and the cause. Finally, command \( u \) is issued using the FTC algorithm noted 11.

As can be seen from the ones presented, the essential thing in model-based diagnostics is the generation of the residual. The methods for generating the residual can be divided into two categories [1]: methods in parameter space and methods in signal space.

The methods in the parameter space are based on the fact that most often a fault is reflected by a change of a physical parameter.
The generation of the residual in the signal space is based on the analytical redundancy. This is defined as follows: there is analytical redundancy if two or more, but not necessarily identical, ways can be used to determine a variable, where at least one uses a mathematical model in analytical form.

A simple example of analytical redundancy is shown in figure 1. In this case the output data \( y(t) \) can be established in two ways: by measurement, i.e. \( y(t) \) and estimated by mathematical model, \( \hat{y}(t) \). Consequently, the residual is determined based on the expression:

\[
r(t) = y(t) - \hat{y}(t)
\]  

(1)

If a fault occurs, it will affect only the measured output data \( y(t) \), and not the estimated one based on the model \( \hat{y}(t) \). As a result, the residual will have a non-zero value and in this way the malfunction will be detected for the analysed situation.

Analytical redundancy is used almost exclusively in model-based engine diagnosis, as it does not require additional physical components such as hardware redundancy.

The analytical redundancy consists of a set of analytical expressions implemented in the memory of the on-board computer, which ensures the performance of the engine functions in the presence of faults. For example, if there is a malfunction in a sensor, then the operation is ensured by using information from the other transducers and using the expressions related to the analytical redundancy.

The expressions of analytic redundancy are also called parity relations or parity equations.

As we have seen from the ones presented, one of the key elements is the analytical mathematical model. All of these analytical models can be differential equations, transfer functions and algebraic equations. In addition, mathematical models can be input-output or input-state-output models [4; 6].
3. Experimental researches
The experimental researches were carried out using an Audi A6 3.0 TFSI Quattro. For the acquisition and storage of data during the tests, the VCDS tester was used. This is a VAG group specialized diagnosis tester, a device that helps the user to communicate with the vehicle control modules professionally; the figure 2 shows the connection of the OBD connector with the vehicle electronic control units.

The car is equipped with a V6 petrol injection engine, which has the following characteristics: maximum output power 245 kW, maximum torque 440 Nm, maximum speed of 250 km/h and fuel consumption of 9.8 liters / 100 km for the urban cycle, 6.0 liters / 100 km for the extra-urban cycle and 7.4 liters / 100 km for the mixed cycle.

![Figure 2. OBD connection](image)

During the experiments, 30 dynamic tests were performed without faults, with a duration of 600 s each and a measurement rate of 10 values/s. In this way, each sample has 6000 values for a functional parameter. Also, some tests were carried out in case of malfunctions in the sensors or transducers.

The following are graphs with some parameters measured during the experiments. Thus, in figure 3a the values of the speed $V$ are shown, and in figure 3b those of the distance travelled $S$ at the 30 dynamic samples without faults.

From figure 3a we can see that the speed varied in the range 29.0-173.9 km/h, and 85.8% of the total values were in the range 80-140 km/h. From figure 3b it is shown that the length of the samples varied in the range 15,036-22,128 km, with a total amount of 537,096 km.
Figure 3. Vehicle speed and distance on tests

Figure 4a shows the engine speed \( n \), and figure 4b the engine load through the throttle position \( \xi \). The graphs show both the extreme values of the parameters (minimum and maximum) and the range with the most values of them.

Figure 4. Engine speed and throttle position

It should also be mentioned that in the figure 3a and in the figure 4 are represented the respective parameters both by continuous representation and by their discrete representation.

The discrete representation is the real one, the experimental data constituting discrete dynamic series with a finite number of values. In addition, the discrete representation allows to visualize the range with the most values of the target size, as in figure 4b.

During the experiments, a malfunction was caused in the turbocharger coupling clutch. For this case, in figure 5 the average values of some functional parameters are presented in the sample without fault and with the mentioned fault.
From figure 5a it is figured out that, in the desire to achieve the same speeds in the case of the mentioned fault, the driver pressed with 6.5% more on the acceleration pedal, which consequently opens the throttle valve with 10.4% more than in the case without malfunction (figure 5b), thus an increased engine load took place.

However, for the rest of the graphs, there is a decrease in the functional parameters, including those that define the engine performance, in presence of a fault. For example, the engine speed drops by 20.7% (figure 5c) and its power by 26.6% (figure 5e).

**The average values of some parameters, in the situations without fault and with clutch failure turbocharger coupling**

Another example of decrease in the functional parameters is exemplified in figure 6, which shows the experimental values of the intake air pressure \( p_{a} \) in the event of the turbocharger clutch fault, as well as the values estimated by calculation based on the mathematical model of the form \( p_{a} = f(n, \xi) \).

**Figure 5.** The average values of some parameters

**Figure 6.** Intake air pressure
4. Fault simulation and model-based diagnosis

The following is the case of a fault of the intake air pressure sensor (MAP - Manifold Air Pressure). In the specialized literature, sensors and actuators are considered the first order inertial elements. Therefore, their dynamic regime operation is described by a differential first order equation:

\[ T \frac{d y(t)}{d t} + y(t) = k y_d \]  

(2)

where \( T \) represents the time constant, \( k \) is the static transfer coefficient, and \( y_d \) represents the reference value of the targeted parameter \( y(t) \); therefore, the \( y_d \) parameter contains the values determined from the experimental data obtained when the engine runs without faults.

For example, the intake air pressure \( p_a \) has the following mathematical model:

\[ T \frac{d p_a(t)}{d t} + p_a(t) = k p_{\text{ast}}(n, \xi) \]  

(3)

In relation (3), the static characteristic \( p_{\text{ast}}(n, \xi) \) which offers the values of the intake air pressure depending on the engine speed \( n \) and the engine load \( \xi \) is presented in figure 7.

This graph shows the switching surface of the static characteristic, established by modeling based on the experimental data and expressed by the analytical expression (1) from figure 7:

\[ p_{\text{ast}}(n, \xi) = 14.5227 - 0.00017n + 2.3784\xi + 0.00000179n^2 - 0.0147\xi^2 \]  

(4)

In addition, in figure 7 the experimental data for the 30 dynamic samples without faults are presented.

![Spatial static characteristic of the intake air pressure sensor, Audi A6 car](image)

**Figure 7.** Spatial static characteristic of the intake air pressure

As a result, using an identification algorithm (for example ARMAX), the differential equation for dynamic operation mode of the intake air pressure sensor is obtained.

A fault may be detected not from the beginning, but during the experimental trial. For example, in figure 8 is presented the simulation of a 75\% failure of the intake air pressure transducer, a fault that occurs at time \( t=190s \).

As it can be seen from the graph, the appearance of the fault in zone \( C \) has as a consequence the decrease of the air pressure values \( p_a \) starting from this moment of time. In this case the average value decreases by 34.4\%, and the norm 2 of the pressure by 38.5\%. The graph shows the residual values \( r \)
(which is zero when there is no fault, up to \( t=190s \)), the time constant \( T \) and the static transfer coefficient \( k \), so the differential equation and the transfer function can be deduced.

![Simulation of a 75% failure of the intake air pressure sensor](image)

**Figure 8.** Simulation of a 75% failure of the intake air pressure sensor

5. **Conclusions**

Following the presented data, the theoretical and experimental research carried out, the following main conclusions are drawn:

- at present, the role of engine diagnosis has increased, the electronic management being based on the diagnosis results and a certain level of performance.
- model-based diagnosis is done in real time and benefit from embedded sensors, actuators and microcontrollers;
- because during the effective operation there are deviations from the nominal values, which represent faults of the component elements, the model-based diagnosis can detect these deviations and in this way allows the reconfiguration of the control so that the performances of the engine are not affected;
- the existence of faults has as a consequence the increase of the response time, therefore a decrease of the performances in dynamic regime. Therefore, model-based diagnosis in the presence of faults plays an important role;
- model-based diagnostics allows detection and isolation of multiple faults in the event of a concomitant existence;
- the detection of a fault can also call for time-frequency analysis;
- the paper also presents the way of establishing the imprint of a fault through mathematical models deduced on the basis of experimental data, using algorithms to identify systems and processes.

6. **References**

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