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Concept of a Fuel Injector Control System Based on Electric Current Signals in OBD

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This work presents a concept for controlling the injectors of internal combustion engines. It is possible to observe electric current signals with high repeatability on the coil of fuel injectors. Mechanical changes observed in these signals indicate the presence of certain anomalies, allowing for fault detection. A precise analysis of characteristic points in the signal enables diagnosing the injector's condition in the next control loop.

The analysis of characteristic values in such signals has demonstrated the possibility of diagnosing fuel injectors under normal operating conditions. For this purpose, an additional measurement system must be connected to the injector, along with the implementation of algorithms on a controller to process the recorded data samples. These data could improve dosing precision by improving the understanding pf the injection process itself. Knowing the precise beginning and end of the injection process as well as ensuring proper injector function, allows for an accurate determination of the fuel dose injected into the combustion chamber and the detection of any potential damages. This concept could lead to a better understanding of the injection process and enhance combustion process, which can potentially reduce emissions of harmful substances in exhaust gases.

Keywords: fault-tolerant control; injection system; injectors; FTC.

1. Introduction

This article discusses the concept of a control system that tolerates damage to fuel injectors in spark-ignition engines, with an indirect injection system in real-time. Based on a literature review, current methods of controlling fuel injectors have been identified in [2]. Commonly used methods rely on a standard control system with a feedback loop. The proposed concept is based on the diagnostic method for fuel injectors described by Więcławski [9]. This method describes in details how electric current and voltage characteristics recorded on the injector coil correlate with its mechanical parameters of its operation. In this system, the mechanical element that cuts off fuel flow is the needle. The electric current flowing through the injector coil generates a magnetic force that lifts the needle, thereby opening the fuel flow. Its resistance forces are counteracted mainly by the fuel pressure, the pressure of the spring that returns the needle to its closed position, and the damage to the injector itself. The work of the magnetic force used to lift the needle can be translated into mechanical quantities, such as pressure, the timing of fuel flow initiation, and the final phase of flow closure [10]. This enables precise monitoring of injector operation and accurate determination of injection phases. Recording and analyzing these signals in real time enables the implementation of a fault-tolerant control (FTC) system that accurately regulates the fuel dose. Actual data on the beginning and end of the injection phase make it possible to identify the fuel dosing process. In the next iteration of the injector's operation, this information allows precise control to ensure the correct combustion process of the fuel mixture.

This provided an alternative to existing methods [2], which rely solely on analyzing system feedback; in this case, exhaust gas quality. The quality of the exhaust gases should be understood here as the percentage of oxygen in the exhaust gases. This is a parameter by which it is possible to determine the correctness of the combustion process. Injection timing correction are carried out through previously programmed maps in the controllers [2]. The goal of the approach described here is to use an additional control loop for injector control based on the FTC control scheme. Such a loop is aimed to record diagnostic signals, conduct diagnostics, identify the type of anomaly, as well as reconfigure the system to ensure the fuel dose calculated by the controller. Precise determination of the instantaneous parameters of injection phases enables injector diagnostics, which can be used to detect early-stage damage. Early detection is crucial as such damage may cause defects in the crank-piston system and an incorrect combustion process. At the same time, this emphasizes the importance of identifying damage in fuel supply system at an early stage.

The paper [4] discussed the design and analysis of injector control and power systems. The authors analyzed the supply voltage of the injectors, as well as the pressure values prevailing in the fuel system, using a specific pulse width modulated (PWM) control signal [6]. The aim of their work was to achieve maximum efficiency and stability in the operation of the fuel injectors. In contrast, the authors of [8] presented a method for adjusting the injector control strategy to offset the impact of changes in the resistance and inductance of the coil. Publication [5] discussed a patented signal processing technique for measuring fuel flow, based on an innovative method using Coriolis flow meters (CFMs) for this purpose. The implementation of flow velocity measurement through individual injectors enables an accurate assessment of the injection process. The discussed works are examples of a body of research on methods for assessing the performance of fuel injectors. Ensuring the correct and precise operation of fuel injectors allows for proper combustion process of the fuel-air mixture. As a result, this can have a positive impact on the reduced emission of harmful substances in exhaust gases.

In addition, faulty operation of injectors, beyond causing incorrect combustion process and increased emission of harmful substances, can lead to destructive degradation process of the crank-piston system or the exhaust gas cleaning system (such as catalytic converter). Proper diagnostics of injectors can prevent this, while precise control ensures the correct combustion process and reduces the risk of damage to other systems. The remainder of the paper discusses an innovative control system for fuel injectors, based on the diagnostic method described in [9].

2. Fault-tolerant control systems

Fault-tolerant control (FTC) systems are designed to manage the control of an object while incorporating fault detection and isolation (FDI) to detect and identify undesirable phenomena, and then introduce a change into operating parameters so that the assumed task can still be implemented. Such a control system allows the object to continue functioning despite the impact of damage, preventing it from immediately becoming unsuitable for operation (Fig. 1).

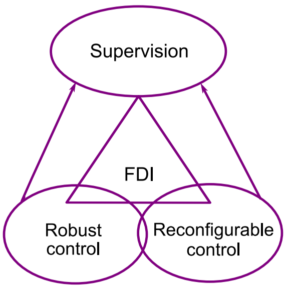

Fig. 1. Fault-tolerant control system [1].

In this type of control system, the phenomenon of redundancy is often used and can be classified into two types:

- direct, i.e., one in which redundancy occurs in physical form, for example, when using several sensors measuring the same parameter, even though only one would be enough; this approach is used, for example, in aviation [1];
- analytical, i.e., one in which real devices are not used, and instead the work of an algorithm acting as an observer is used.

The use of redundancy enables more accurate control of the system, especially in terms of safety and reliability. However, using redundancy is not always feasible due to factors such as the high cost of building a control system with multiple elements or the specific location of the system. A good example of inefficient redundancy would be the use of two engines in a vehicle – this would be economically unjustified, and the vehicle's design would not accommodate such a configuration. However, for the injector control case discussed in this article, redundancy is possible if we assume that the remaining cylinders of an internal combustion engine can compensate for irregularities in the operation of a single cylinder. In such a situation, we do not consider the control system as that of an engine, but rather as a system composed of multiple injector-cylinder system assemblies.

According to the literature [3, 11], two types of fault-tolerant control systems can be distinguished:

- passive, i.e., systems in which the controller has an appropriate range of built-in resistance to damage, as shown in Fig. 2;
- active, i.e., systems that are able to detect and identify damage and make appropriate changes in the implementation of the control process to maintain the continuity of the system, as shown in Fig. 3.

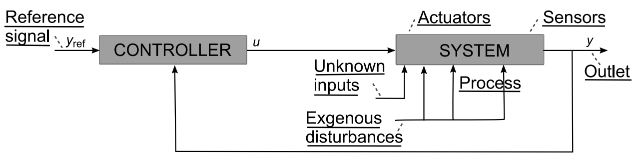

Fig. 2. Passive fault-tolerant control system [10].

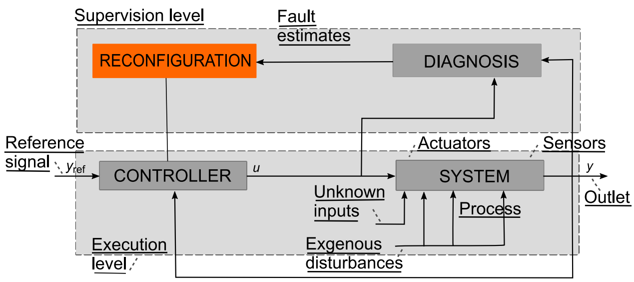

Fig. 3. Active fault-tolerant control system [10].

The control system described in this paper is based on the active FTC system shown on Fig. 3. FTC systems have already found applications in aerospace [11]. Taking into account the development of autonomous vehicles and the proactive approach to the operation of current vehicles, it can be concluded that such systems could be effectively used in the automotive industry. In addition, such systems could enhance user comfort and safety while reducing repair costs.

3. FTC implementation for fuel injector controller

As discussed in the previously mentioned work [2], the control of fuel injectors in an internal combustion engine with indirect injection is primarily based on feedback to the controller in the form of oxygen content in the exhaust gases [7]. Information about the oxygen concentration in the exhaust gases allows to assess the effectiveness of the combustion process for the controller. While this information is not precise, it is simple enough to allow controller to quickly and easily assess the engine's fuel demand. It is assumed that the proper combustion process in a standard internal combustion engine with spark ignition occurs for a stoichiometric mixture, i.e., one in which there is exactly 14.7 kg of air for every 1 kg of fuel burned. This value is referred as the air-fuel ratio (AFR). As a result, if the controller, based on the received signal from the sensor, determines that the oxygen concentration in the exhaust gases indicates an incorrect mixture, it can to modify parameters such as the timing of fuel injection and its duration time. The modifications are made by changing the pulse width modulation (PWM) signal controlling the injector. Changing these parameters allows for a quick change of the assumed amount of the fuel supplied, commonly known as "correction". Figure 4 presents such a control system, as described in the literature [2].

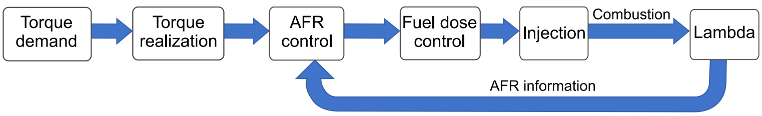

Fig. 4. Diagram of the injector control system based on AFR.

The control concept presented in this article is based on the use of an additional real-time loop, using the FTC system described in Sec. 2. An example of this application is presented in Fig. 5.

As with any fault-tolerant system, there is also a diagnostic, identification and reconfiguration component. The diagnostic and identification processes operate on the basis of the methodology for diagnosing injectors described in [9], where the possibility of comparing current and voltage signals recorded on the fuel injector coil with its physical parameters is discussed. It has been demonstrated in [9] that on the basis of these signals, it is possible to precisely determine the moment of fuel flow opening, its closure, and even the fuel pressure right before and inside the injector system. With this information, we are able to accurately calculate the volume of the fuel stream injected into the cylinder,

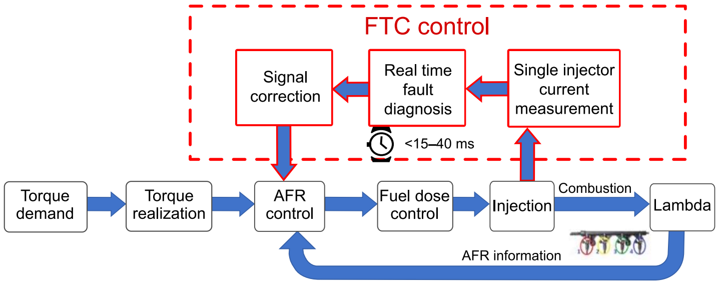

FIG. 5. Diagram of the injector control system based on AFR and the additional loop of the FTC system.

denoted as $\dot{m}$. This relationship is described in Eq. (3.1). In addition, the diagnostics suggested in [9], when implemented in the controller in the presented way, enable early detection of even the smallest damage, thanks to which we are able to ensure the highest possible efficiency of the entire system:

$$\dot{m} = \rho_p \cdot S \cdot f_{s-c} \cdot \sqrt{\frac{2 \cdot (p_p - p_a)}{p_p}}, \tag{3.1}$$

where ρ_p – fuel density, S – injector nozzle cross-section, f_{s-c} – flow coefficient, p_a – atmospheric pressure, and p_p – fuel pressure.

The flow coefficient through the injector surface is denoted as f_{s-c}. It takes into account the transitions when the nozzle cross-section is covered by a needle, which disrupts the fuel flow. This factor determines how much of the cross-section is available for fuel flow. The relationship for this coefficient is given by Eq. (3.2) [9]:

$$f_{s-c} = 2 - \exp\left(\frac{t_{op}}{t_{inj} \cdot t_{cl}}\right), \tag{3.2}$$

where t_{op} – injector needle lifting delay time, t_{inj} – preset injection time, and t_{cl} – injector needle closing delay time.

Correct identification of damage leads to reconfiguration. Due to the simplicity of the system, which in this case involves a coil whose work can be controlled by a PWM signal, there are limited possibilities for adjustment. However, it turns out that this method is completely sufficient. The characteristic values for the PWM signal are duty cycle time and duration time, as shown in Fig. 6.

In the case of injector control via a PWM signal, the start of the duration time is estimated as the beginning of the injection. Assuming that the amplitude of the signal remains constant, we can influence the discussed parameters. For example, during the injection process, the controller records the current and

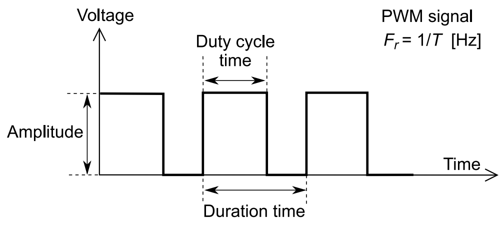

Fig. 6. Simple PWM signal.

voltage signal from the injector coil. On the basis of the AFR system [2], we receive information about the percentage of oxygen content in the exhaust gases. Assuming that the administered fuel dose is less than the driver's request, the feedback will indicate excess oxygen. As a result, the controller [2] will increase the dose in the next injection and modify it in every iteration to aim for a stoichiometric mixture. The introduced correction usually consists in extending or shortening the duty cycle time parameter or shifting the beginning of the injection timing.

The solution discussed in this paper differs in that the injector's operation is immediately analyzed after the injection process is completed, based on the recorded current and voltage signals. The diagnostics [9] provide precise information about the actual fuel dose delivered to the combustion chamber. It turns out that the real injection time does not correspond to the duty cycle value (Fig. 7).

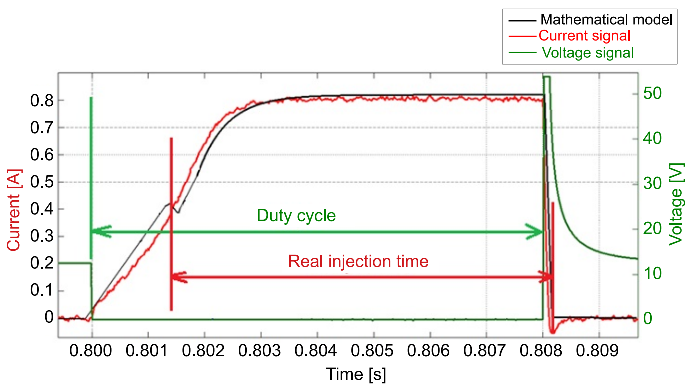

Fig. 7. Comparison of duty cycle and real injection time [9].

Knowing the exact fuel dose, we can determine how to apply the correction to a given injector so that, in the next work cycle, the actual dose corresponds to the injection calculated on the basis of the injection map in the controller. However, the correction itself, due to the simplicity of the system, takes place in the same way as before, with the difference being that in the next cycle of the injector, we are able to deliver the precise dose of fuel, based on the previous dose delivered. The only noticeable difference here is the method of injector diagnostics, aiming to determine the fuel dose. In fact, in such a system, damage detection is a side effect. The main task is to ensure such control that, despite the early phases of damage, ensures the proper functioning of the system. In addition, we obtain information for the on-board diagnostics (OBD) system about irregularities in the system, so that during the service control we can eliminate them. By observing current and voltage signals, it is possible to detect residual issues in these signals. Seven characteristic changes in the signal, due to damage to the tested object, can be identified (Fig. 8):

1) Change in steady-state current (maximum),
2) Time shift in the phase of current increase,
3) Change in current at the point of firing pin lift,
4) Phase shift of the firing pin lifting point,
5) Change in the slope of the current rise curve relative to the time axis,
6) Signal emission measurement (SEM) value at the maximum of the induction stroke,
7) Voltage change at the point of firing pin lowering.

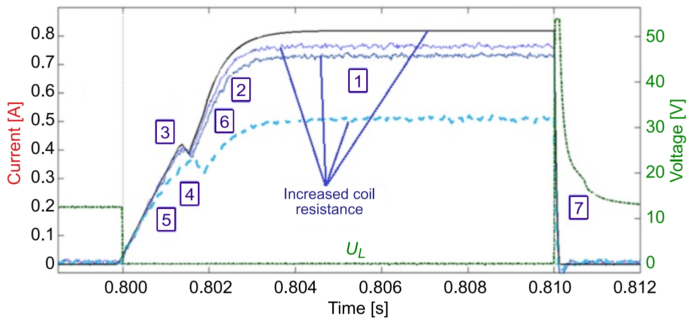

Fig. 8. Comparison of duty cycle and real injection time.

To ensure the real-time operation of this system, it is very important to use the loop shown in Fig. 5. The presented solution has two possible applications. We can look at the system under study as an injector–cylinder system or as the entire engine, as shown in Fig. 9.

For the first solution for each system, there is a need to separate control system. This is beneficial due to the fact that there is no need to worry about the time needed to carry out measurement, diagnostics and reconfiguration, as it is sufficient even under extreme engine operating parameters. In addition, it provides redundancy for the system, allowing other components to compensate for the work of one that has become overused. In the second case, in turn, it is

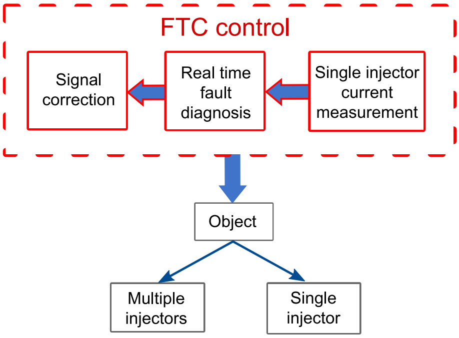

FIG. 9. Two types of FTC control concept.

necessary to ensure the mentioned working time for the correct operation of the system in real time. For example, with the assumptions of the most popular power units on the market, i.e.:

- Engine speed **<6000 RPM**,
- Number of cylinders (injectors) **4**,
- Injection time **<10 ms**.

In this case, the time interval is about 50 ms. This means that in order to ensure real-time operation of the entire system, the controller must perform the registration, diagnostics, identification and reconfiguration process in 50 ms for the specified parameters of the entire system. Assuming that the diagnostic signals are recorded against the same background and occur at the same time, the remaining time for the analysis of the collected data is about 40 ms. In the first variant, this time is more than four times higher under the given assumptions. Of course, an engine speed increases, the number of cylinders rise, or injection time (duration time) increases, and the time remaining for analysis decreases. Otherwise, if these factors decrease, the time for analysis lengthens. The use of hardware that allows a quick analysis of these signals and operating in real time is very important here.

4. Summary

The article discussed a control-diagnostic real-time system for fuel injectors used in internal combustion engines with indirect injection. The control concept fulfills the tasks assigned to FTC systems. For the purpose of implementing the FTC system, it is very important to define the control object. In the case of an internal combustion engine, specifically for controlling fuel injectors, two distinct control strategies can be considered. The first strategy assumes that we treat the entire set of all cylinders as a single object. In this case, it is necessary to consider the time required to analyze the collected data in such a way that the system works in real time. The second strategy, however, assumes that individual units of the injector and combustion chamber will be considered as separate components. In this case, we need multiple control systems-one for each object. This means that we need as many control systems as objects. Thanks to such a strategy, we obtain more time to interpret diagnostic signals and process control results in real time. The diagnostic signals are based on the characteristics of the current and voltage flowing through the valve coil. As demonstrated in the literature [9], it has been shown that, based on these, we can recognize the mechanical parameters of fuel injectors and determine the degree of their degradation. Thanks to the proposed diagnostic method [9], the first step toward the construction of the FTC system can be completed [3, 11].

The implementation of this diagnostic method is possible due to the registration of the previously mentioned signals in real-time during the operation of the system. In this study, an 8-cylinder engine was used; however, the analysis focused on a single-cylinder combustion process. Another key aspect of the FTC system [11] is the implementation of fault identification. At this stage, anomalies are calculated in relation to the reference or model signal. Based on this information, we know the scale of the problem and the exact dose of the fuel administered. The engine controller (ECU) can calculate the cylinder's fuel demand at any given moment on the basis of maps stored in memory. Information about the exact dose of fuel supplied by a given injector allows for more precise control, especially in relation to the system based on the AFR signal [2]. This enables to reconfigure the control system to ensure proper operation of the system and the correctness of the combustion process despite the presence of defects.

The injector, from a mechanical point of view, is a very simple component. To ensure its opening, a power supply should be applied to its connectors. The injector coil generates an electromagnetic force that moves the needle, allowing fuel to flow. As a result, the control of injectors is carried out by a PWM signal [2, 9]. The controller introduces the fuel dose modification by changing the pulse width of the PWM signal or by shifting the beginning of the injection control in time domain. By knowing the precise parameters of the dose delivered to the combustion chamber, this method ensures sufficiently high precision in fuel control.

This method of control and diagnosis ensures the early detection of damage, thanks to which helps maintain the correct parameters of the combustion process. In addition, the durability of the exhaust gas cleaning system (catalytic reactor) is increased and protects the crank-piston system of the internal combustion engine from the negative effects of damaged fuel injectors. The concept of the method described in this manuscript, after several changes to account for differences in current signals, could also be used for direct injection and common rail systems. Of course, in this case, it would be necessary to define another diagnostic parameters specific to the injectors of the other systems injectors. The method might not be suitable for diagnosing piezoelectric injectors due to their different operating mechanism, specifically the way the injector needle is opened. Refining the control and diagnostic algorithm for all types of fuel injectors can ensure longer lifespan of component as well as meet the latest emission standards.

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