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FUEL INJECTOR DIAGNOSTICS BASED ON OBSERVATIONS OF MAGNETIC FLUX CHANGES

Krzysztof WIĘCŁAWSKI[1], Jędrzej MĄCZAK[2], Krzysztof SZCZUROWSKI[3]
Warsaw University of Technology, Warsaw, Poland
[1] krzysztof.wieclawski@pw.edu.pl; [2] jedrzej.maczak@pw.edu.pl;
[3] Krzysztof.szczurowski@pw.edu.pl

Abstract

The article discusses mutual relations of the dosage characteristics, current intensity characteristics, and voltage characteristics in the fuel injector electromagnet. Changes in current in the electromagnet's coil were monitored in the course of dosage by means of the Hall sensor. Change in the Hall voltage is proportional to the changes in density of the magnetic flux generated around the injector coil during its work. The model of the current dependencies was used to determine the injector technical state in the actual time. The presented diagnostics proposition was created on the basis of the injector dosage characteristics obtained due to experimental research. Change in characteristic values, recorded during generation of the fuel dose allows for determination of the injector technical state, regarding both, the current-related and the mechanical parameters. Controlling in the actual time enables corrections in control parameters as a response to changes, as well as quick detection of damage resulting in switching the injector off the operation. This prevents the faulty operation of the injector, which may result in damage to subsequent components depending on its operation, such as the catalytic reactor.

Keywords: injector, diagnostics, magnetic flux

DIAGNOSTYKAWTRYSKIWACZA PALIWOWEGO NA PODSTAWIE OBSERWACJI ZMIAN STRUMIENIA MAGNETYCZNEGO

Streszczenie

W artykule przedstawiono wzajemne relacje charakterystyk dawkowania z charakterystykami natężenia prądu i napięcia w elektromagnesie wtryskiwacza paliwowego. Zmiany prądowe w cewce elektromagnesu, w trakcie dawkowania obserwowano za pomocą czujnika Halla. Zmiana napięcia Halla jest proporcjonalna do zmian gęstości strumienia magnetycznego, generowanego wokół cewki wtryskiwacza podczas jego pracy. Model zależności wielkości prądowych wykorzystano do określania stanu technicznego wtryskiwacza w czasie bieżącym. Przedstawiona propozycja diagnostyki, powstała na podstawie charakterystyk dawkowania wtryskiwacza uzyskanych dzięki badaniom eksperymentalnym. Zmiana charakterystycznych wartości, zapisywanych w trakcie generowania dawki paliwa, pozwala na określenie stanu technicznego wtryskiwacza, w zakresie parametrów zarówno prądowych jak i mechanicznych. Kontrola w czasie bieżącym, pozwala na korektę parametrów sterowania w odpowiedzi na zmiany oraz szybką detekcję uszkodzeń, skutkującą wyłączeniem wtryskiwacza z eksploatacji. Zapobiega to nieprawidłowej pracy wtryskiwacza, co może spowodować uszkodzenie kolejnych, zależnych od jego pracy podzespołów, takich jak reaktor katalityczny.

Słowa kluczowe: wtryskiwacz, diagnostyka, strumień magnetyczny

1. INTRODUCTION

The article presents analysis of changes in the current-related parameters observed in the course, of generating the fuel dose, particularly changes in the magnetic flux and in inductance of the core of the injector coil during movement of the needle. Tests were conducted using gas injectors designed for the dual-fuel engines with compression ignition, additionally supplied with gaseous fuel. The applied method of observation of current-related values is universal for various electromagnetic fuel injectors. Observation of current-related values allows for determination of the actual needle position [1]. The time of real fuel flow can be determined, as well as the injector phase position, with a microsecond resolution. Specific values of the current intensity and voltage correspond to the resultant fuel flow [2, 3]. This is due to the fact, that the magnetic flux caused by the current flowing through the injector coil lifts the needle initiating the flow after overcoming all the forces counteracting its lifting. These include: the elastic force (the needle spring), the force resulting from the fuel pressure, the needle friction force, the needle inertial force. After activating the pulse powering the injector coil, the current and the resultant magnetic flux grow exponentially, in accordance with the differential equation based on the Kirchhoff's law (1). The force resulting from the injector electromagnet operation, after overcoming the resistant forces, causes lifting of the needle and initiation of the fuel flow. The value of current over time reflects the overcome forces, thus the mathematical model describing changes in the current in the injector coil in the course of the flow relates to the obtained doses and the mass fuel flow. The fuel dose implemented depends on the injection parameters. The effect of injection pressure on changes in mass flow of fuel was determined [4]. Mass flow of fuel also depends on the geometry and design of the injector [5]. Problems with precise determination of the fuel dose appear when using short injection times, below 2 ms [6]. The shorter the injection duration time, the greater the impact of the delay in opening and closing the injector relative to the preset time, therefore the flow diminished by certain value is obtained. The correct choice, of injection parameters and the design of the injector, allows you to limit irregularities the process of burning fuel in the engine combustion chamber and reduce the emission of soot and unburnt hydrocarbons [7]. Therefore, different types of injectors are compared. A good comparison indicator there are empirical models of the current waveform in the coils of the injectors [8, 9, 10]. The obtained fuel dose can be assigned to the characteristics of voltage and current on the injector coil, during dose generation. Current-related parameters can be easily controlled, and the determined characteristic points of the current waveform may be used in diagnostics of the injector's technical state [11, 12, 13]. In vehicles, the task of monitoring the operation correctness of the engine control system is performed by the OBD (on-board diagnostics) system. Some of the failures, however, particularly in the initial phase, are not properly recognised by the original brand systems. In the diagnostics of the injector's technical state, a vibroacoustic signal [14] can be applied, as well as adaptive information of the engine control system [15]. The diagnostics of the injector's technical state suggested in the article herein, is based on observation of the magnetic flux around the injector's electromagnet with the help of the Hall effect sensor. Proportionality of the Hall voltage to the magnetic flux density is used. The Hall effect sensor is easy to apply and provides precise information which can be used in actual time, during injector's operation.

2. CHARACTERISTIC POINTS OF THE INJECTOR'S CURRENT-RELATED WAVEFORM

Figure 1 shows the record of the current-related changes (in current intensity and voltage on the injector coil). Voltage was registered directly on the injector (green line), by means of the measuring module by National Instrument, with the frequency of 51,2 kHz. The current intensity (red line) was determined with the help of the Hall effect sensor. After activating the control pulse (Fig. 1, point A_{CP}), increase in the current takes place, in accordance with equation (1):

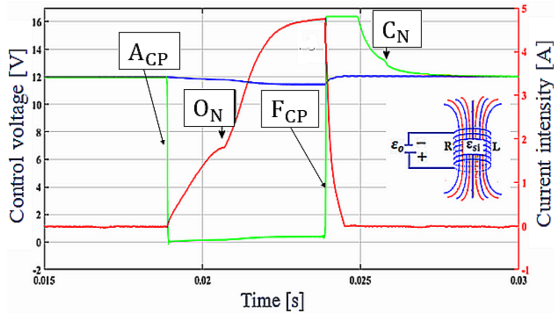

Fig. 1. Waveform of the injection current at time duration 2,6 ms

$$I = \frac{\varepsilon_0}{R}\left(1 - e^{-\frac{R}{L}t}\right) \quad (1)$$

$$\varphi = LI \quad (2)$$

where:

I - electric current

ε_0 - electromotive force of the source

R - resistance

φ - magnetic flux

L - magnetic circuit inductance

t - time

Flow of the current results in generation of the magnetic flux and its variations are the reason why the stream of self-inductance occurs, with the sense opposite to the primary stream (Fig. 2). The blue lines denote the primary magnetic field flux, the red – stream of self-inductance with the opposite sense. The electromotive force resulting from the resultant stream lifts the injector needle at point O_N (opening nozzle), (Fig. 1), where it overcomes all resistant forces. The line denoting the current, ceases to be smooth for approx. 200 microseconds in this place. The fuel flow starts. From point O_N, the current grows exponentially, going to the maximal value:

$$I = \frac{\varepsilon_0}{R} \quad (3)$$

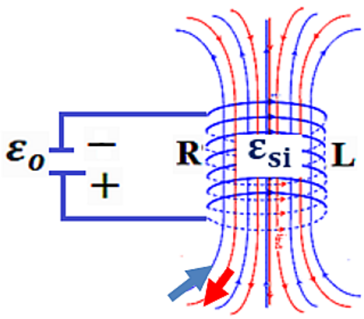

Fig. 2. RL circuit of the injector with magnetic field lines visualised

At point F_{CP} (finish control pulse), the current control pulse is terminated. As a result of disconnecting the circuit, the inductance-related voltage spike takes place and the drop up to the decay, in accordance with the equation:

$$|U_L| = \varepsilon_0 * e^{-\frac{R}{L}t} = L\frac{dI}{dt} \quad (4)$$

where:
U_L - voltage on the coil.

Voltage decay is related to the needle's movement These both phenomena, occurring in accordance with equation (4), take place simultaneously to point C_N (closing the nozzle) from Figure 1. At this point, the needle settles on the nozzle. The fuel flow is terminated and so is the change in the inductance of the injector's coil core. As a result of these changes, the line representing the voltage decay ceases to be smooth for approx. 100 microseconds, then the voltage decays completely.

3. DEPENDENCE OF TUEL FLOW AND CURRENT WAVEFOR

Observation of the current waveforms, changes in the magnetic flux, and in the injector's inductance during voltage decay, allows for determining the model for the injector's work for the preset parameters of pressure and injection time, that determines correctness of its operation.

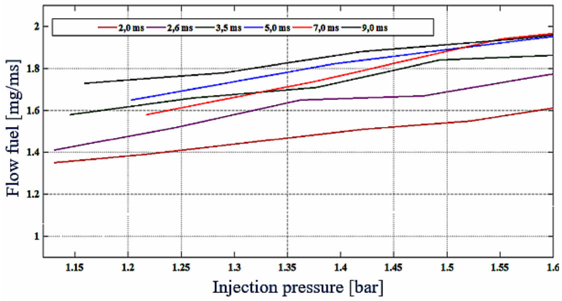

Fig. 3. LPG doses in relation to the injection pressure, at different injection times (duration)

The specific waveform of the changes in current corresponds to the specific fuel dose obtained. Figure 3 shows distribution of streams flowing through the injector nozzle, resulting from the defined, current-related parameters recorded during flow of the generated fuel streams. Figure 4 shows increasing ranges of the current waveform, whose colours map the increasing streams.

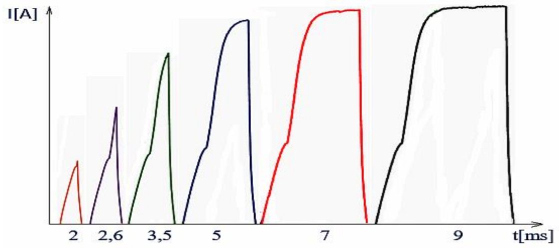

Fig. 4. Increase in the current waveforms from 2 ms to 9 ms, corresponding to the streams from Figure 3

4. DIAGNOSTIC INFORMATION

Figures 3 and 4, show that the current waveform can define the obtained stream of the fuel flow. The expected magnitudes of the current-related parameters for a given injection duration time and injection pressure, can constitute the diagnostic information about the injector's technical state. Characteristic quantities, such as the current intensity value at the needle opening point, as well as the time, after which the opening takes place (change of the time constant of the injector τ):

$$\tau = \frac{L}{R} \tag{5}$$

define changes in the injector's technical state or the lack thereof. Damage to the fuel injector can be divided into two groups: mechanical and electrical. Each of these types of damage can be defined by means of analysis of the current-related parameters. In Figure 5, the characteristic current points of the injector are marked. Point O_N, specifies the nozzle opening, point C_N closing. Labels from 1 to 6, indicate the next cases of injector injuries discussed below:

1 – needle seizing
2 – needle faltering
3 – increased connector resistance
4 – short-circuit in coil winding
5 – break in the coil circuit
6 – fatigue changes in the needle spring

Labels have been assigned to points that will change with given damage.

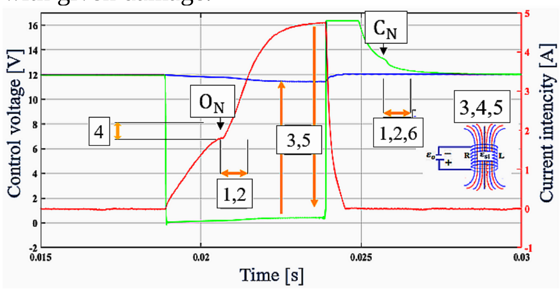

Fig. 5. Characteristic diagnostic points in the current waveform. Preset injection time 5 ms

4.1. Needle seizing

In the case of the injector's needle seizing, at the increasing current waveform after controlling the injector, no change in the smoothness will occur at points O_N and C_N (Figure 5, 6), resulting from the needle movement. In spite of increase in the current and the magnetic flux, the needle is not lifted, the flow does not take place. The plot of the current increase up to the current pulse termination is of the exponential character, with no bending point (Figure 6), with exact mapping of equation (1).

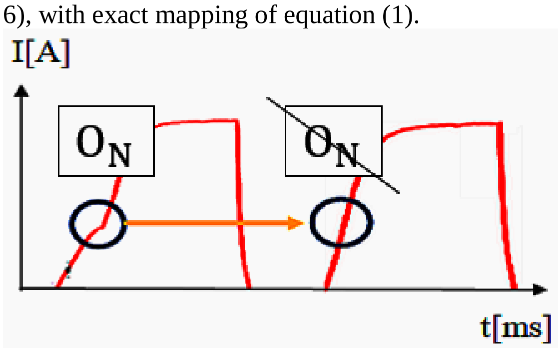

Fig. 6. Steady increase in the current intensity due to the needle seizure

4.2. Needle faltering

In the case of the needle faltering (not the complete blockage), the points where the plot of the current intensity and voltage decay is bent, will be shifted (point O_N and O_C in Figures 5 and 7), at injection parameters not corresponding to such changes. The result of the above will be misfiring, or the mixture too lean or too rich, depending on the position of the needle.

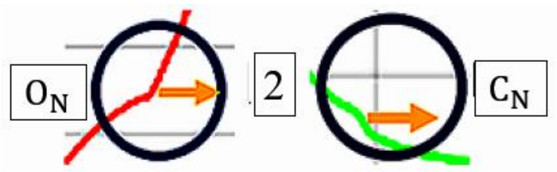

Fig. 7. Shifting of the needle opening point (O_N) and needle closing point (C_N)

4.3. Increased connector resistance

As a result of soiling the electrical connection of the injector coil (increase in the resistance of the contact), the current intensity and magnetic flux will decrease (3, Figure 5) or irregular pulsating changes will occur.

4.4. Short-circuit in coil winding

Short-circuit in coil winding or shorting to the negative terminal (shortening of the coil winding), is a reduction in the number of winding turns, as a result of which, the injector coil inductance is decreased, in accordance with equation (6):

$$L = \frac{\mu_0 \ * \mu_R \ * N^2 * S}{l} \qquad (6)$$

where:

μ_0 - magnetic permeability of the vacuum

μ_r - the relative permeability of a substance that fills the solenoid

N - number of scroll;

l - the length of the coil

S - surface area;

Depending on the extent of damage, the magnetic flux will be decreased or will disappear completely. In the case of a partial short-circuit, inductance is decreased but simultaneously along the reduced coil resistance. In order to obtain the flux needed to lift the needle, a greater current will be necessary, in accordance with equation (2), (point 4, figure 5 and 8).

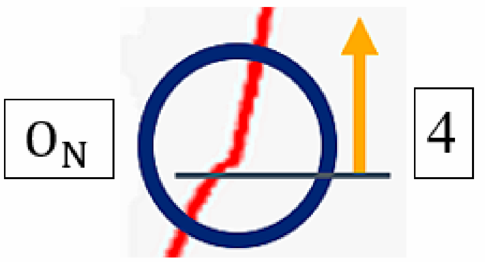

Fig. 8. Greater current value at the point of lifting the needle

4.5. Break in the coil circuit

Break in the coil circuit is the lack of the current flow and of the magnetic flux. This is a type of change defined by the on-board diagnostic system. (point 5, figure 5).

4.6. Fatigue changes in the needle spring

If the force of the spring closing the needle is decreased, point C_N from Figure 5 will be shifted to the right, towards the subsequent closing (Figure 9).

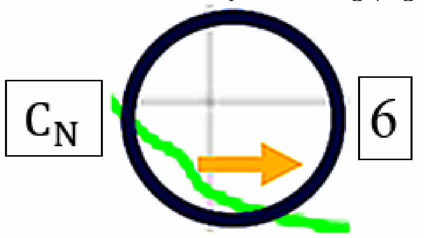

Fig. 9. Shift of the point of the injector needle closing

As a result, the mass flow will be increased, and the injection will be shifted in time by a certain value (Figure 10). In this case, also point O_N of the needle lifting will be shifted (Figure 5). It will be lifted faster (at the lower value of the current intensity).

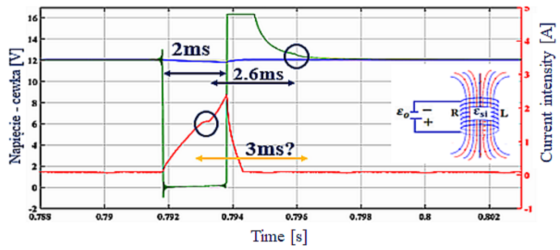

Fig. 10. Injection phase shift.
Preset injection time 2 ms

A vital factor in the discussed diagnostics is that all described variations of the current-related parameters can be controlled in actual time. The magnetic flux and current intensity are controlled by means of the Hall effect sensor. Measurements of voltage – directly in the controller. The algorithm can be implemented in the controller, detecting points of the needle opening and closing, taking place at the determined values of the current intensity and voltage during proper operation. The necessary condition for the detection of changes described above is the adequately high sampling time from 51 kHz, i.e., the analogue-to-digital converters must be employed, whose operational frequency is no less than mentioned above.

5. SUMMARY

The main objective of the article was analysing the possibility of defining the injector's defects, which are not diagnosed directly by means of the vehicle on-board diagnostic systems. Some of the failures are detected too late (misfiring), which can affect the technical state of the catalytic reactor and occurring changes in the exhaust gas purifying system. In the article, the current-related quantities, such as: current intensity, voltage of the injector coil, inductance, and the magnetic flux, have been shown to reflect and affect the fuel flow through the injector nozzle, and are closely related to the dosage parameters. After determining the values characteristic for a given injector and the injection time, this information can be used in diagnostics of its technical state. Change in the current-related values defines the type of damage to the injector, considering both the mechanical and electrical defects. Additionally, its technical state can be monitored in actual time because the application of the described measuring method is not particularly complicated, and even more so, if the modifications were implemented as early as at the production stage. The most expensive element of the system are fast analogue-to-digital converters that meet the standards of sufficiently high sampling frequencies. Employing such a measurement method may diminish the danger of environmental pollution resulting from the maintenance of the vehicle equipped with fuel injectors operating at the initial phase of damage and may complement the on-board vehicle diagnostics.

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Krzysztof WIĘCŁAWSKI received the title of MSc. in Warsaw University of Technology, Warsaw. Now he is an employee of Warsaw University of Technology, and runs his own company. His current research interests include control and fault diagnosis.

Jędrzej MACZAK,PhD, DSc Professor at the Institute of Vehiclesof the Warsaw University of Technology. Scientific interests: distributed diagnostic systems, machine diagnostics, mathematical modelling of power units and methods of analysis of vibroacoustic signals

Doc. Eng. **Krzysztof SZCZUROWSKI**, PhD is a postdoctoral manager at Integrated Laboratory of Mechatronics System of Vehicles and Construction Machinery of Warsaw University of Technology. His scientific interests include computational mechanics, sound and vibration and mechatronics.