Variations in health of piezoelectric elements of the Common Rail electric hydraulic nozzles in the operating conditions

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Abstract. The article discusses operational reliability of piezoelectric elements of the Common Rail electric hydraulic nozzles. Attention is paid to the piezoelectric element’s health and its influence on the output injector parameters. It was assumed that capacity of the piezoelectric packet can be used as a diagnostic parameter. The studies carried out in the operating conditions identified failures of some elements of the electro-hydraulic nozzles, patterns of variations in capacity of the piezoelectric packet exposed to short or long-lasting heat treatment. Based on the data obtained, conclusions about the frequency of monitoring of the piezoelectric element’s health were drawn.

1. Introduction

One of the key problems of road transport is harmful emissions of exhaust gases, including carbon dioxide. To meet stringent environmental requirements for exhaust emissions, modern engines are equipped with electronic fuel control systems. In order to meet the Euro-6 emission standards, diesel engines are equipped with battery-powered fuel supply systems with a high injection pressure.

Currently, the leading manufacturers of fuel systems produce Common Rail systems with piezoelectric nozzles. According to the BOSCH Company, they can reduce fuel consumption by 3\%, harmful emissions of exhaust gases by 20\%, engine noise by 3 dB, and increase power by 7\% [1]. In addition, the piezoelectric injector is characterized by stable multiphase fuel injections, minimal portions of preliminary injections, short intervals between preliminary and main injections and a compact design [2,3]. Compared to the electromagnetic nozzle, piezo nozzles consume less fuel and have higher efficiency [4].

BOSCH piezo injectors are the most common injectors. Their piezoelectric transducer consists of 350 quartz plates with a thickness of 90 microns. When DC voltage is applied, each plate is extended by up to 0.13 microns. The maximum (total) elongation of the piezoelectric packet can reach 4.5 \mu m [5]. The initial size of the piezoelectric element is restored when stress is removed from the plates.

During long-term operation, battery fuel supply system’s health worsens. This violates the law of fuel supply and changes the environmental characteristics [4,5]. It is important to minimize emissions of harmful substances and carbon dioxide at the design and production stages and during the life cycle of the car. Currently, a lot of publications deal with the issue of optimization of the fuel supply systems and their injectors. The issue of operational reliability is understudied. In this regard, it is necessary to study the issue of reliability of electro-hydraulic nozzles with a piezo drive and search for methods of regular monitoring of health parameters.
2. Problem statement.
A block diagram of the Bosch injector with a piezoelectric element, which shows the elements affecting the fuel supply process (grouped by their functions), is presented in Figure 1.

![Figure 1. The block diagram of a piezo injector.](image)

1 – high pressure connection; 2 – edge filter; 3 – back leak channel; 4 – feed channel; 5 – piezo driver; 6 – hydraulic amplifier; 7 – control valve; 8 – nozzle

For the electro-hydraulic nozzle with a piezo driver, such elements (Fig. 1) are an atomizer, a control valve, and a piezo driver.

The most wearing part of the CR BOSCH piezo injector is a control valve [6-9]. During operation, cones of the valve plate and fungus wear out (functional node 7, Fig. 1). This violates tightness of the nozzle and changes operation parameters.

The second problem is nozzle shut-off cones (functional node 8, Figure 1), which create droplets when the nozzle works and is out of work, because the fuel is under pressure.
With long-term operation of the piezo nozzles, characteristics of the piezoelectric elements worsen, which changes (decreases) the value of movement of moving elements, including the sprayer needle. This affects the cyclic fuel supply.

3. Theoretical background.
When the piezoelectric element operates as a control valve actuator, voltage is applied to it [10,11]. The force developed by the piezo drive can be determined by the following expression:

\[
F_{\text{piez}} = \frac{d_{33} \cdot E \cdot A}{t} \cdot V - \frac{E \cdot A}{N \cdot t} \cdot x - b \cdot \dot{x}
\]  

(1)

where \(d_{33}\) - piezoelectric strain constant
\(E\) - modulus of elasticity of the material
\(V\) - driving voltage
\(A\) - cross sectional area of the piezo actuator
\(t\) - thickness of each individual layer
\(N\) - number of stack layers
\(b\) - damper configuration
\(x\) - tip stroke

The damper configuration is calculated by formula

\[
b = \frac{\sqrt{k m}}{Q}
\]  

(2)

where \(m\) - piezo weight
\(k\) - stiffness of the piezo element
\(Q\) - mechanical quality factor

\[
Q = \frac{d_{33} \cdot E \cdot A}{t} \cdot x - C^S V
\]  

(3)

The relationship between the electromechanical coupling factor and the dielectric constant can be expressed as follows:

\[
C^S = \frac{\varepsilon_T A N (1 - K_{33}^2)}{t}
\]  

(4)

where \(\varepsilon_T\) is the dielectric constant
\(K_{33}\) is the electromechanical coupling factor calculated by formula

\[
K_{33} = \frac{E}{\sqrt{\varepsilon_T}}
\]  

(5)

An analysis of expressions (1)-(5) allows us to conclude that capacity of the piezoelectric element can act as a parameter describing its health and properties.

4. Materials and methods.
The data on failures of the piezoelectric hydraulic nozzles were collected in 2017-2018 in Irkutsk. Mileage was recorded for each set of nozzles, after which they were checked on the test desk. In total, over 500 electro-hydraulic nozzles with a piezoelectric element produced by the BOSCH company were tested.

The nozzle was tested on the Dieselland CR-JET desk, where the cyclic supply and control flow were determined according to the test plan. The following parameters of the piezoelectric element were determined using the Cristina Piezo instrument (Figure 2):
The temperature was determined using a pyrometer. The piezoelectric element and nozzle were heated up to 500°C for 8 hours during 7 days. Mathematical data were processed in the MatLab environment (MathWorks).

5. Results and discussion.
After checking 500 nozzles, it was found that the injector life varies for one car and injector failures are caused by wear of the control valve, defects of the atomizer and piezoelectric elements. Not all failures are recorded by the self-diagnosis system. The processed experimental data allowed us to establish the share of worn control valves (38%), atomizers (23%), and piezoelectric elements (10%). (Fig. 3) The nozzle malfunction is due to the wear of one or several elements. About 29% of causes of wear were functional (see Fig. 3).

![Figure 3. The diagram of correlation of failures of the electro-hydraulic piezo nozzle Common Rail.](image-url)
Depending on the mileage, injector’s failure probability distribution densities were built for the piezoelectric element, the atomizer and the control valve. The distribution laws and statistical characteristics were determined. These data are summarized in Table 1. Figure 4 shows the piezoelectric elements’ failure probability distribution density depending on the mileage of a vehicle equipped with the Common Rail power supply system with piezo-drive nozzles.

![Figure 4](image-url)

**Figure 4.** The diagram of failure probability distribution density for the piezoelectric elements of electro-hydraulic nozzles depending on the vehicle mileage.

**Table 1.** Statistical characteristics of the failure distribution laws for the elements of electro-hydraulic nozzles.

| Element         | Distribution law | Math. expectation, thousand km | Mean-square deviation, thousand km | Variation ratio | Confidence interval, thousand km (p=0.95) |
|-----------------|------------------|--------------------------------|-----------------------------------|-----------------|---------------------------------------------|
| Valve           | Norm             | 166                            | 57.3                              | 0.34            | 51.4…280.6                                  |
| Nozzle          | Norm             | 171                            | 56                                | 0.32            | 59…283                                      |
| Piezo-element   | Norm             | 171.7                          | 55.3                              | 0.32            | 61.1…282.3                                  |

To confirm the theoretical assumptions about the relationship between piezoelectric packet’s capacity and health, malfunctioning injectors were checked. The nozzles were divided into two groups:
1. Malfunctioning nozzles which have no cyclic feed in maximum load conditions.
2. Technically sound (which may have deviations from the standards values of the test plan). In order to determine the range of values corresponding to technically sound and malfunctioning conditions, statistical characteristics of the laws of distribution of capacity of the piezoelectric element were identified (Fig. 5). The data are summarized in Table 2.

![Figure 5](image.png)

**Figure 5.** The diagram of probability density distribution for capacity of the piezoelectric element of technically sound (with deviations from the standards) and malfunctioning nozzles (without cyclic feed).

**Table 2.** Statistical characteristics of the failure distribution laws for the piezoelectric elements of electro-hydraulic nozzles.

| Health                              | Statistical Characteristics          |
|-------------------------------------|--------------------------------------|
|                                     | Distribution law | Math. expectation, uF | Mean-square deviation, uF |
| Technically sound (with deviations) | Norm                 | 2.23                   | 0.120                     |
| Malfunctioning                      | Norm                 | 1.727                  | 0.07                      |

By heating various modifications of the piezoelectric injector, the dependence of capacity of the piezoelectric packet on its temperature was determined (Fig. 6).
Figure 6. The diagram of dependence of nozzle piezo-packet’s capacity on temperature.

Figure 7. The diagram of dependence of capacity of the piezoelectric element on the duration of temperature exposure.

An analysis of the data shown in Figure 5 allows us to conclude that capacity of the piezoelectric element increases with an increase in temperature. Statistical data obtained after processing the test results of more than 50 nozzles “116” show that the numerical range of capacity of the technically sound nozzle is 2.1-2.4 uF at room temperature.

The nozzles were exposed to longer temperature effects. During 7 days, these nozzles were heated up to 50°C. The temperature dependence is shown in Fig. 7.
6. Conclusion

1. Life cycle is different for different nozzles. Up to 30% of nozzles tested may be suitable for further operation during the intercontrol run.

2. The largest share of failures is due to wear of the control valve (38%) and abrasive wear of the control valve, the atomizer and the piezoelectric element.

3. Failures of the elements of piezoelectric injectors are governed by the normal distribution law and can occur jointly or separately. For each element, the statistical characteristics are similar.

4. The average life cycle of these injectors is 166 thousand km, the coefficient of variation is 0.32-0.34, the standard deviation is 55.3 thousand km.

5. The optimal frequency of monitoring is 50-60 thousand kilometers. It should be timed to the next scheduled maintenance.

6. Capacity of the piezoelectric packet is an informative diagnostic parameter of the electro-hydraulic nozzle’s health; when developing the distribution laws, the error area was <3% of the total area of the distribution law. The mathematical expectation of capacities of the piezoelectric element: for the technically sound injector, the mathematical expectation is 2.23 μF with a standard deviation of 0.120 μF; for malfunctioning injectors (without cyclic feed) - 1.727 μF with a standard deviation of 0.07 μF.

7. With an increasing temperature, capacity of the piezoelectric element increases according to the logarithmic dependence

8. During operation, capacity of the piezoelectric packet decreases due to the degradation of properties of the piezoelectric packet.

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