Fuel controlling system concepts in modern diesel engines based on smart materials

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Abstract. The article describes potential ideas of the use of electroactive polymers as elements of the diesel engine control system for minimization of harmful emissions. The first results of testing electroactive polymers for above-mentioned aims are presented.

1. Introduction
One of the urgent problems of human civilization is the atmosphere-protection from harmful gas emissions in particular from internal-combustion engine of motor transport. One of the possible ways to solve the problem of reducing the total harmful gas emissions of diesel engines on vehicles is creation new more efficient electronic fuel control systems which will integrate modern smart materials, in particular, electroactive polymers [1, 2].

Electroactive polymers (EAP) are such polymers that are able to change their shape by applying an electric voltage to their structure. Currently, EAP have already become actively used in robotics as linear actuators (artificial muscles) and as the main elements of various sensor devices in mechanical engineering.

The complexity of electronic controlling systems and the creation of prototype serial production design, as well as pilot testing of electronic controlling systems of internal-combustion engine require using the modern approaches to the design and application of the so called innovative smart-materials.

One of the modern and effective directions is using of high-speed sensor-devices that can quickly transmit signals for their subsequent processing by the microcontroller. Among all EAP-types materials, for electronic fuel controlling systems of the internal combustion engine’s needs, the dielectric elastomer class are best suited. Their ability to withstand high-voltage fields at low power consumption, as well as the response in a few parts of milliseconds provides unlimited opportunities to create new actuators for alternative electronic fuel controlling systems of the internal-combustion engine.

2. Problem formulation and main results
Electrohydraulic injector as the main executive mechanism of the internal-combustion engine is a closed system with a control valve integrated in it and is the most responsible component of the injection system. Its functioning is connected to the hydromechanical and electromagnetic processes taking place simultaneously.
The injector uses a combination of hydraulic and spring locking of the nozzle needle to operate within whole speed and load range of the diesel engine. The fuel supply process is controlled by command of microcontroller to turn on the valve located in each electrohydraulic injector and communicated with the control chamber in which the pressure creates the necessary locking force of the needle.

When the electric control signal is applied, the valve reduces the pressure in the control chamber. Under the influence of the fuel pressure force the electrohydraulic injector needle rises and the fuel is injected through the nozzle holes of the atomizer into the engine cylinder. Because the area of the piston in the control chamber of electrohydraulic injector is much larger than the cross-sectional area of the needle when the control signal is switched off and the solenoid valve returns to its original position, the fuel pressure force affecting on the piston ensures a quick seating of the needle on the valve land, stopping thereby the fuel injection process. When the diesel engine is not running, and the fuel pressure is low, the needle is pressed to valve land by return spring.

Now the main place in the market is occupied by electro-magnetic and piezoelectric nozzles (see figure 1) [3, 4].

![Figure 1. 3-D piezoelectric nozzle model (left) and electromagnetic (right) injector (longitudinal section).](image)

One of the main requirements for the nozzle is its high velocity. The operation of the electromagnetic nozzle is carried out in pulse mode at a frequency of operation from 10 to 200 Hz, while the frequency of operation of the piezo-injector amount to 200 KHz at conditions of high temperatures and vibration. At the same time a high metering accuracy is required. The injector on average should produce about 600 million actuations for the entire time of operation. This is a very high number of cycles for an electromechanical device.

The executive electromagnetic mechanism is responsible for this requirement, but due to the high voltage control currents that are used to meet the requirement of necessary fuel supply law, these
devices overheat and fail. The replacement of the electromagnet is the usage of piezoactuator as an execute element, but these devices have a very high price.

Among the main modern variants of fuel supply control systems the following should be noted:

1) Electromagnet. It is a solenoid consisting of a fixed magnetic conductor and a movable armature (or keeper, see figure 2). Such solenoids provide a response time of 0.1 millisecond during the armature movement no more than 0.5 mm. The main disadvantage of solenoid’s electromagnets is the inability to increase the electromagnetic force without increasing the size and inertia due to the saturation effect of ferromagnetic materials of magnetic conductors. The development and design debugging of electromagnets does not allow achieving required speed for abovementioned reasons.

![Figure 2. The solenoid injectors A-04-011-00-00-0 production AZPI (Altay plant high-precision product).](image)

It should be noted that amount of fuel injected through the nozzle depends on the duration of the electric pulse, the fuel pressure, the supply characteristics of the nozzle (its hydraulic resistance) and the inertial mass of its moving parts, as well as the inertia of the electromagnetic system. On the grounds of abovementioned in a real system, the moments of the beginning and end of the injection process do not correspond to the beginning and end of the control electric pulse (see diagram at figure 3).

![Figure 3. Oscillogram of opening and closing of the electromagnetic nozzle.](image)
2) Piezoactuator. This design uses reverse piezoelectric effect – changing the size of dielectrics in electric field (see figure 4). They convert electrical energy into mechanical energy. To ensure that the control voltage does not exceed 400-600 V, the thickness of the single piezoelectric elements should not exceed 0.33 mm.

![Piezoelectric nozzle 7H8H4SG manufactured by BOSCH.](image)

**Figure 4.** Piezoelectric nozzle 7H8H4SG manufactured by BOSCH.

To obtain the necessary displacement, single piezoelectric elements are combined into a column. Between the piezoelectric materials there are metal plates which are connected in a parallel way and receive the controlling electric pulse applied to them (see figure 5).

![Piezoelectric element at the absence (and supply) voltage to it.](image)

**Figure 5.** Piezoelectric element at the absence (and supply) voltage to it.

As was mentioned above, one of the main parameters that can improve the running of diesel engine is actuator’s speed. Due to evidence fact that the nozzles with a piezoelectric element have a comparably higher cost than the electromagnetic, the authors offer the following more low-consumption injector design.

3) Smart materials. Electroactive polymers may be regarded as alternative replacement to overcome the inertia of the electromagnetic system. An electroactive polymer of the abovementioned class of production (of State Scientific Research Institute of Chemistry and Technology of Organoelement Compounds “GNIIChTEOS”) was taken as a test sample (see figure 6). It should be noted that the study of magneto-controlled elastomer manufactured by GNIIChTEOS showed that it can also be electrically controlled. It is characterized by the effects of both magnetostriction and electrostriction [5].
Figure 6. Sample of electroactive polymer.

Moreover, it is not the electroactive polymer itself as a separate working substance, but a set of several layers (see figure 7), or a so-called sandwich panel, in which a thin layer of only several tenths of a millimeter alternates with copper contacts.

![Figure 7. The sandwich panel structure of electroactive polymer (1 – electroactive material, 2 – material of electrode, A – permutation power).](image)

Such working substance allows the most effective usage of the magnetostriction effect and realize the required displacements at the operating voltage characteristic of the electrical car’s supply.

3. Conclusions and recommendations
Preliminary experiments on the reception and fixation of response signals from the electroactive polymers showed on the model that the desired response in the required ranges is possible, as well as the achievement of required displacements in the design of execute mechanism produced by electroactive polymers.

Optimal quantity of “packets” the sandwich panel (copper contact – polymer – copper contact) should be in range of 30-35. The initial estimation was carried out with a packet of 32 dielectric layer (copper contact thickness of 0.05 mm alternate with equal thickness of electroactive polymer); structure gage of sandwich panel – cylinder 32 mm height and 25 mm diameter.
The average number of stress cycles for series of electroactive polymer during which both packet and the elastomer keep the regulated properties (cyclic flow, cyclic strength etc.) was determined.

Currently experimental investigations in order to choose an electroactive polymer of a certain chemical composition are in progress, as well as the experiments for a more precise definition of response characteristics, the optimal number of EAP-layers in a sandwich panel and for the development of an executing element based on such smart materials.

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