High-performance Computing for Simulation Testing of Smart Materials for Their Further Employment in Modern Diesel Engine Fuel Supply System

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Abstract

The article presents the results of the investigation of smart materials (electroactive polymers (EAPs)) using simulation testing of stiffness properties based on the trained two-layer neural network. EAPs were modeled as control elements of diesel engine injectors based on certain criteria. The output data were the quick-action of the nozzle. The final part of the article presents the main results of the initial stage of the project to introduce smart materials into fuel supply systems and the prospects for using high-performance computing, modern software and computer systems for mathematical modeling in solving current scientific and technical problems of developing and monitoring motor vehicle technical systems.

Keywords 1

Smart materials, magnetoactive elastomers, electroactive polymers, electroactive elastomers, simulation testing, neural network, fuel supply system, control systems

1. Introducing the problem and setting the task

As it is noted in modern literature [1, 2, 3], one of the ways to minimize harmful emissions of exhaust gases from internal combustion engines (ICE) in city and road transport is the usage high-speed sensor devices that can quickly transmit signals for their subsequent processing by a microcontroller. Of all the types of electroactive polymers (EAP) for electronic control systems (ECS) of ICE, materials such a class of dielectric elastomers are best suited.

Constantly increasing requirements for energy efficiency and environmental safety of automobile engines stimulate the development of research into the improvement their workflow, including the works aimed at improving the performance of fuel supply actuators and injectors. Table 1 provides a comparative analysis of electronic fuel systems of engines with fuel injection into cylinders. It contains data on the main characteristics of control of electronic fuel systems in internal combustion engines and their structural elements.

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Table 1
Comparative analysis of electronic fuel systems of engines with fuel injection into cylinders

Name / Key differences	Continuous control	'Common rail' battery	Pneumodriving	Hydraulic drive	Mechanical drive systems	Smart systems
Executing elements	High Pres-sure Fuel Pump	Nozzles and high-pressure line	Injectors	High Pressure fuel pump and medium pressure line	High pressure line	Nozzles and high-pressure line
Type of management	Continuous	Pulse injectors and continuous pressure	Impulse	Continuous pressure and pulse with other parameters	Impulsive	Pulse injectors and continuous pressure
Controlled independently						
Pressure	-	+	-	+	-	+
Advance	+	+	+	+	+	+
Type of characteristics	-	+	+	-	-	+
Differences	-	+	+	+	+	+
Simplicity of design	+	+	+	-	+	-
Easy to adapt to the engine	+	+	-	-	-	-
Fail-safety	-	-	+	-	+	-

Comparing the set of parameters given in Table 1, it should be noted that the most optimal design is the one featuring the "Common Rail" battery fuel systems with two types of performing elements, namely: either a piezo-actuator or an electromagnet. Based on this suggestions, the authors set the following task: to create a control element for the electronic fuel system of the internal combustion engine based on the smart material of the electroactive polymer type, which has the same speed as a piezo-actuator, but possess a more flexible form of the control signal, which helps to avoid problems with inductance that occur when the nozzle is excited in electromagnetic drives and at a lower cost of the structural unit as a whole.

At this stage of investigations the problem of choosing a test sample of a certain composition and properties required for carrying out primary tests of electroactive polymers that has been complicated by the relative novelty of the material under study, insufficient knowledge of the properties such class of composites, and the absence of a clear classification (at the level of such regulations as State Standard or Technical Specifications) the chemical properties or other parameters, in particular stiffness, prompted the authors to apply the modern methods of simulation, taking into account the experimental data they previously had, in particular, those for similar smart materials of magnetoactive elastomers.

The object taken under consideration for implementing smart material is the control element of the nozzle. Its main functional characteristics are presented in Table 2. It served as the initial data for the motivated selection of the control element of nozzle.

Table 2
Initial data for choosing the control element of the nozzle

P, [MPa]	Ignition feed, [mm^3]			The main feed, [mm^3]		
	Electromagnet	Electropolymer	Piezo drive	Electromagnet	Electropolymer	Piezo drive
120	0,49	0,31	0,28	0,72	0,47	0,41
180	0,59	0,3	0,27	0,83	0,4	0,31
220	0,68	0,54	0,47	1,17	0,77	0,63

2. Algorithm and methodology. Key results

During the selection of the most suitable prototype, the following main criteria for choosing the EAP were established:

- the filling should vary 25-30 [%];
- the size of the polymer should be 1-10 [microns];
- it is advisable to correlate the chemical composition of the matrix with its inherent stiffness parameter – the elastic modulus *E*;
- the structure of the test sample must be anisotropic or isotropic. It should also be considered in the context of the value of the elastic modulus *E*;
- the operating area of the material must be comparable to the size of the sample itself;
- it is advisable to take into account the speed of mechanical adjustment of the sample structure;
- the value of the voltage applied to the EAP must be 3-5 [kW · mm^{-1}].

The control element, as well as the nozzle, were considered (respectively, simulation conditions were created) not as separate elements (for example, on a simulation stand), but as assembled with the engine design. The mounting scheme of the nozzle under study is given in Figure 1.

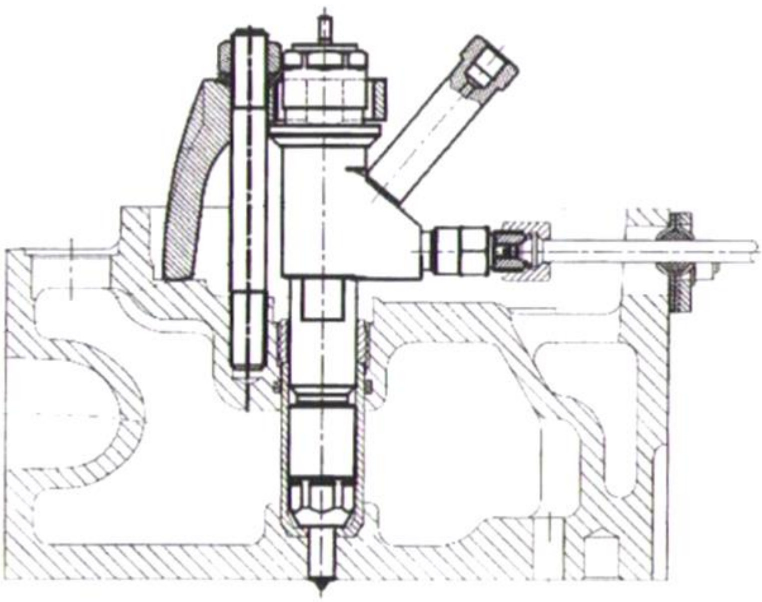

Figure 1: Fixing the nozzle under study to the engine cylinder head

The tests conducted were complex in character. When testing samples, they were assigned various characteristics (from the abovementioned ranges) and the output indexes indicated in the table were evaluated.

The simulation algorithm included the following sequence of actions:

- filling of test samples were simulated by selecting parameters with a certain chemical composition and method of filling elements (based on the technological capabilities of the equipment of JSC «GNIIChTEOS»);
- element thicknesses were selected in a certain range based on the design features of the nozzle drive shape chosen for the study (0.1 – 0.5 mm);
- based on the obtained maximal forces that occurred at samples, a package with a sizeable number of EAP elements was selected for further modeling, in which the thickness of an individual element did not exceed 0.1 – 0.15 mm.

The graph in Figure 2 illustrates the maximum strain occurring at the sample depending on the height variations. As noted above, cylindrical samples of EAP with the height of 40, 27 and 13 [mm] and the mass of 94.9, 62.3 and 32.1 [gram] (respectively) were used as prototypes of the executive nozzle's design element. The simulation test experiment consisted of two stages. At the first stage, the sample was modeled under the influence of a constant magnetic field. In the graph below these are positions 1-69565 (see the bottom line of the graph). At the second stage of the experiment, the sample was tested without magnetic field influence. At both stages, a high-frequency current supply (about 10 kHz) was simulated, and the resulting strain transmitted by the samples due to their deformation were considered as output data. Vertical values of forces (in [N]) are marked on the graph. As illustrated directly on the graph, the colored lines separate the blocks of the series of experiments of different types: the yellow line describes the case of induced magnetic field and without this field; the blue line is for the previously specified height of the sample and the red line is for the corresponding mass of the sample.

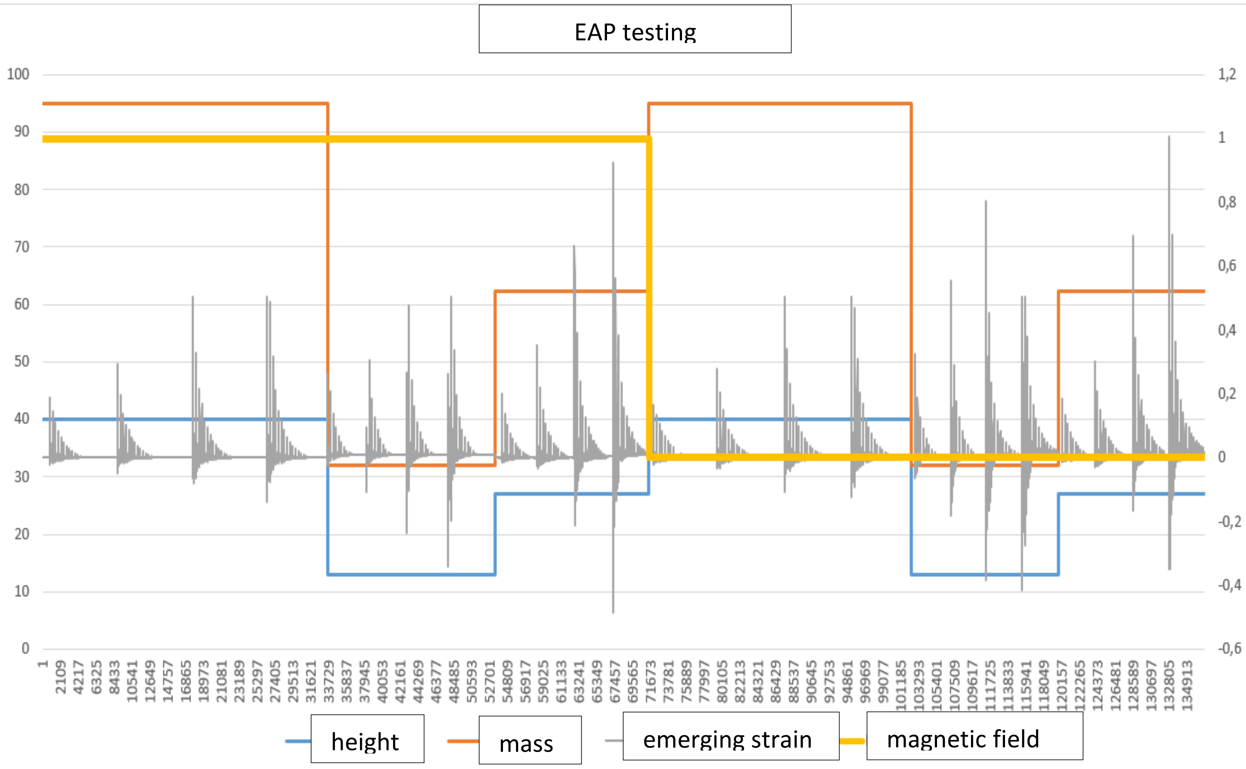

Figure 2: Testing of EAP samples for the resulting strain in the sample when a high frequency voltage is applied

The simulation algorithm was applied in the open software environment Octave, the current behavior of these samples was studied based on the trained 2-layer neural network using the data were obtained earlier during experiments with similar EAP samples.

The algorithm for processing and research included the following sequence of actions:

- processing of a "raw" data array. At this stage, it was necessary to identify similar experimental curves and remove the data that arose as a result of measurement inaccuracies or noise during signal processing;
- forming a representative sample of data that overlaps the range under study and the range of interest to researchers;
- dividing the data into input (height, mass, presence of magnetic field) and output (strain generated);
- choosing the appropriate neural network. A two-layer neural network (the simplest perceptron) was used for training due to the small amount of statistical data available to the authors at the moment. The use of other architectures led to the faster model retraining, which was fraught with offering results that could be physically unattainable.

The graph given is only a visual illustration of one of the dozens of simulated samples, based on which the data bank was compiled and optimal EAP options were selected for further investigation. It should be noted that this method of simulation tests is successfully used in the study of the actuators of internal combustion engine microcontrollers, but with other materials and with different software [4, 5]. Moreover, the simulation algorithm may include a sample selection block with pre-selected optimal characteristics. Depending on the problem formulation and the desired result, it is advisable to use software for supercomputer clusters based on a super-scalable parallel algorithm for calculating the properties of EAP, such as the one used by the authors and described in [6-9].

3. Conclusions and recommendations

Summarizing the abovementioned, the main results of the initial stage of the project for applying smart materials in fuel supply systems can be presented as follows:

- the analysis of the principles of construction and operation of modern fuel control systems for internal combustion engines has been conducted. The alternatives for improving the quality of management with the use of electroactive polymers have been identified;
- primary metamodels for EAP simulation testing have been developed in the Octave software. A comparative analysis of metamodels has been carried out taking the experimental data into account. The conclusions on the expediency of using EAP samples of a certain structural composition have been drawn;
- the list of requirements has been formulated and the approach to the EAP design that implements the fuel injector control concept has been determined;
- the test scenario has been developed for the possibility of carrying out further simulation tests in order to select an EAP sample of the optimal structure.

For further research, it is advisable to carry out the work on increasing the number of variable input parameters and accumulating a larger sample of data to use deeper network architectures.

It should also be mentioned that the use of high-performance computing equipment for modeling the behavior of the above-mentioned smart materials under external influences is due to their ultra-dispersed structure: a sufficiently large number of superparamagnetic and ferromagnetic particles combined into a system by means of a long-range dipole-dipole interaction is superimposed with an action of induced external electromagnetic field. Moreover, the acting elastic forces and external mechanical influences change the coordinates of the particles in the matrix, with subsequent changes in the distribution of the internal interaction fields and, therefore, changes in the properties of the material. The re-counting of the interaction of "all with all" under different external influences, the calculation of a new structure and the subsequent determination of the integral characteristics inherent in the modifiable modeled sample for it, is a simple, yet cumbersome calculation task in terms of the number of mathematical operations, which is not currently solvable based on the computing power provided by ordinary personal computers. That is why researchers usually limit themselves up to simplified models, in particular two-dimensional models with a small number of particles, but the progress made so far in the development of supercomputer methods allows us to solve such a class of problems. However, it should be borne in mind that such an integrated approach is meaningless without the mandatory verification of the developed model and comparison of the results of numerical experiments with the results of physical experiments. For verification, the authors have conducted the studies of the internal structure and properties of smart materials [9], which have been omitted in this publication of the conference proceedings as going beyond the scope of the topic.

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