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EXPERIMENTAL AND ANALYTICAL STUDY OF PETROL ENGINE ELECTROMAGNETIC INJECTORS CONTROL SYSTEM

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Summary. *A laboratory stand for the study and diagnostics of the fuel supply system functional elements and for the education process efficiency improvement of laboratory research has been developed. The laboratory stand design is an illustrative one and can be used for the general assessment of the ICE selected control system quality. The assessment of parameters characterizing the fuel injection efficiency by separate injectors of the engine in several operation modes has been made using the stand under discussion. The experimental research has been conducted and main characteristics of the fuel supply by electromagnetic injectors of the engine under study for some operation modes have been obtained. The modeling has been conducted using the well-known techniques of regression analysis.*

Key words: *laboratory stand, fuel injection system, electromagnetic injectors, engine complex control system, regression analysis.*

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Introduction. Distributed fuel injection of petrol engines has contributed to the improvement of stoichiometric mixture formation in the engine cylinders. Nevertheless, some partial breakdown of injection electronic system caused by the change of electromagnetic injectors operation characteristics can result in worse performance indices of the engine and motor vehicle performance in general [1, 2]. One can find a breakdown and determine the cause of the failure only due to the system operation diagnostics. One should perform the diagnostics of the injection system elements removed from the car to obtain more parameters and characteristics. Special stands, testers and other equipment and facilities [3, 4] have been used to do this and they usually possess a number of different functional capabilities defining their cost. These circumstances restrict their use in practical investigation of the educational process. Thus, the development of rather cheap and informative-diagnostic specialized equipment is very important to improve the educational process efficiency in laboratory experiments making by students dealing with the operation characteristics of the car engine control systems [5].

The operation parameters of fuel injection electronic systems components have been checked by similar techniques [6, 7, 8]. The results of the tests have been compared with the specified characteristics given in the technical documentation of the correspondent systems [8, 9]. The electromagnetic injectors operation characteristics have been studied, their efficiency has been checked (fuel consumption per certain time unit), the quality of fuel spraying by the injectors (fuel spray angle) and fuel injection by injectors, leak resistance (fuel leakage check under pressure conditions) have been controlled by special equipment use. These parameters stability under different operation modes conditions has been described in the following references [3, 4, 6, 7].

The purpose of the paper is experimental study and analytical modeling of main characteristics and operation parameters of multifactor system of fuel injection by electromagnetic injector (efficiency, quality and stability of the fuel injection process under different operation modes conditions) and assessment of technological capabilities and efficiency of the developed

Study outcomes. The laboratory stand for the ICE complex control system study has been constructed on the basis of Opel Vectra B [8, 9] (fig. 1).

An electric drive with a drive pulley of 1500 *r/min* rotation frequency is available on the stand to obtain signals from the sensors of electronic systems timing according to the position of the crankshaft and the distributing shaft. Besides, the stand is also equipped with modulator of actuating impulses number *11* which are received by the control block *12* to imitate the operation modes of an internal combustion engine at different rotation frequency of the crankshaft. The value of the imitated rotation frequency is controlled by the measurements of a revolution indicator being found on the meter panel *8*. The pressure produced by the electric pump in the fuel supply system is determined by the fuel pressure indicator measurements *3*, the pressure in fuel rail *7* is controlled by the additional fuel pressure indicator. The throttle blade is controlled by the accelerator pedal (see *5*, *14*). Visual control of electromagnetic injectors control signal is provided by the correspondent light-emitting diodes switch on (see *6*). The quality of fuel spraying by separate injectors can be observed through the clear flasks (see *16*) in whose bottom part the measuring flasks *15* are fixed to determine the fuel amount supplied by each injector per certain period of time. After measurements the fuel is poured into fuel tank *18* the through the shut-off cocks. The measurements of electrical parameters on control points of the stand electrical circuit are provided by the portable multiple-purpose meter connectors *2*. A diagnostic connector *9* is available on the stand to make possible the external diagnostics of the electronic system operation be conducted.

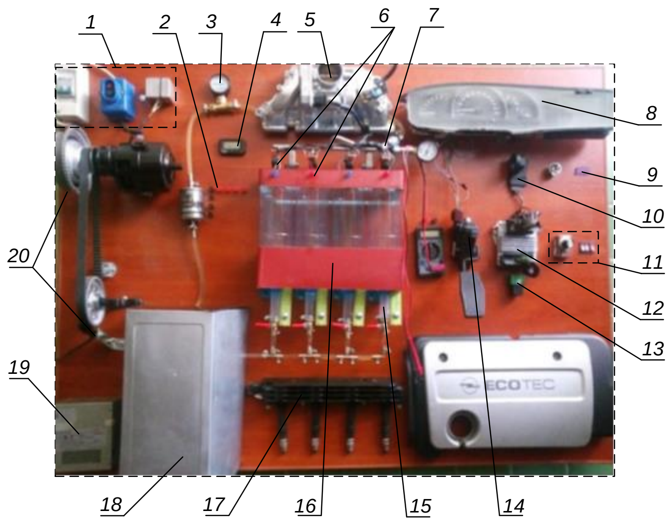
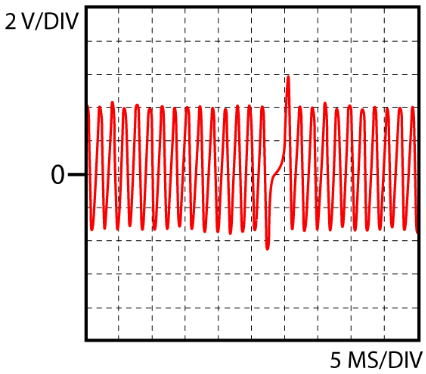
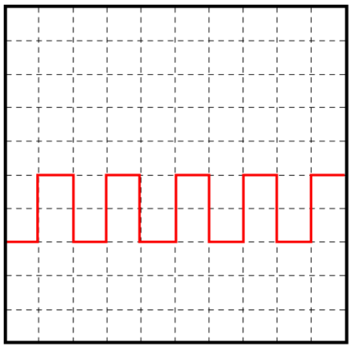


Figure 1. Stand for electromagnetic injectors operation characterization of distributed injection system of car petrol engine [12]: *1* – stand switch on panel; *2* – connectors for measurement of control points parameters of the stand electrical circuit; *3* – fuel pressure indicator; *4* – timer; *5* – intake manifold with a throttle blade; *6* – electromagnetic injector and injector operation indicating light; *7* – fuel rail; *8* – meter panel with a tachometer; *9* – diagnostic connector; *10* – immobilizer; *11* – impulse regulator; *12* – control block; *13* – pump and injectors relay; *14* – accelerator pedal electric unit; *15* – measuring flask; *16* – flasks for detecting the fuel injection quality; *17* – injection module; *18* – fuel tank with an electrical-petrol pump; *19* – power supply unit of automobile electrical equipment; *20* – sensors of electronic systems timing with ICE crankshaft position

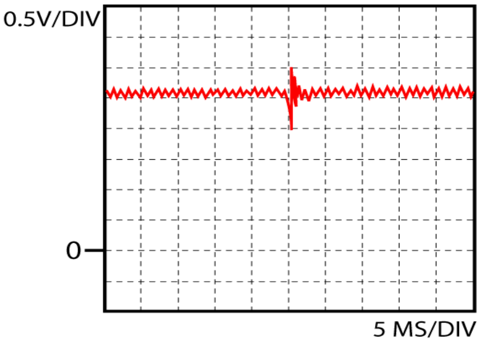
The characteristics of the engine complex control system have been studied by means of a scanner tool as an oscillography recorder. The oscillography traces recorded by the scanner tool in the oscillography recorder mode are given on fig. 2. The laboratory stand has enabled us to diagnose the parameters and characteristics of certain elements of petrol engine injection system (distributing shaft position sensor (fig. 2, a), crankshaft position sensor (fig. 2, b), detonation sensor (fig. 2, c), lambda-sensor (fig. 2, d), air mass sensor (fig. 2, e), dilution sensor (fig. 2, f). The Multec-S system sensors oscillography results agreements with the sensors of real oscillography records of the system under consideration have proved their operability.



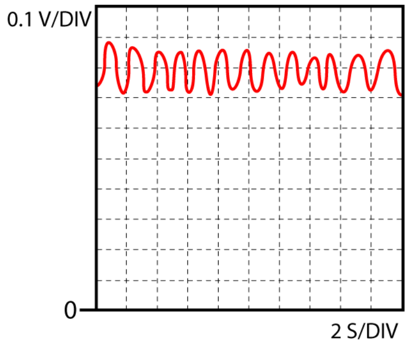
a) distributing shaft position sensor oscillography record



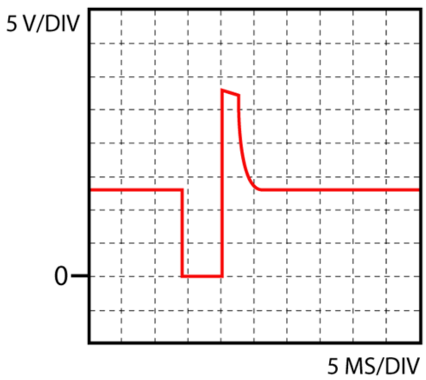
b) crankshaft position sensor oscillography record



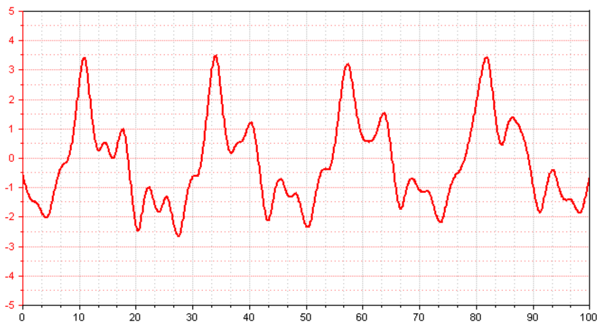
c) detonation sensor oscillography record



d) lambda-sensor oscillography record



e) air mass sensor oscillography record



f) dilution sensor oscillography record

Figure 2. The Multec-S engine complex control system sensor oscillography records have been recorded by a scanner tool in the oscillography mode in the study under discussion

The fuel amount with different time intervals (time of measurement is decreasing at frequency increase) for each injector has been measured three times in each operation mode. The maximum time of injectors operation is found to be 20 seconds being fixed every 10 seconds at determining the fuel amount dependence on the injection time, at crankshaft rotation 1000 *r/min* (fig. 3). At crankshaft rotation 2000 *r/min*

At the crankshaft rotation 2000 *r/min*. the time (filling time) period is longer with 15 seconds interval of fixation respectively (fig. 4). At the crankshaft rotation 3000 *r/min*. the time (filling time) period is longer with 30 seconds interval of fixation respectively, as it is shown on the graph (fig. 3).

As the injection pressure of each injector is the same, the dependencies of the true amount of fuel on the injection time at certain rotations (simulated) of the crankshaft have been obtained. The visual observation of the fuel spraying quality characteristics and spraying cone of each electromagnetic injector has been carried out as well.

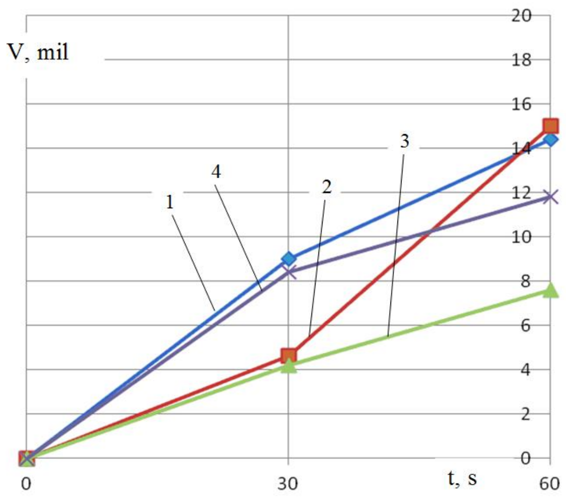


Figure 3. Fuel amount dependence on the injection time, at crankshaft rotation *1000 r/min*

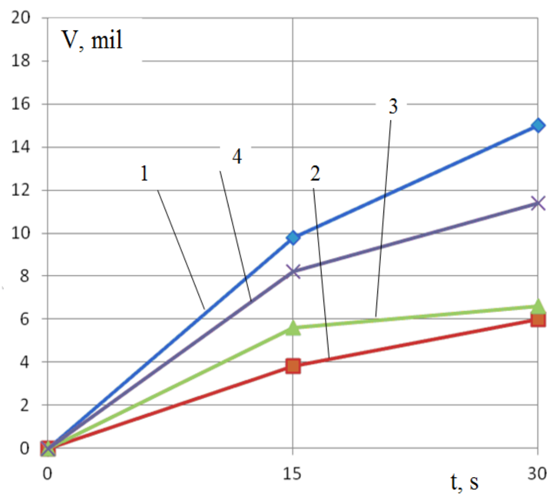


Figure 4. Fuel amount dependence on the injection time, at crankshaft rotation *2000 r/min*

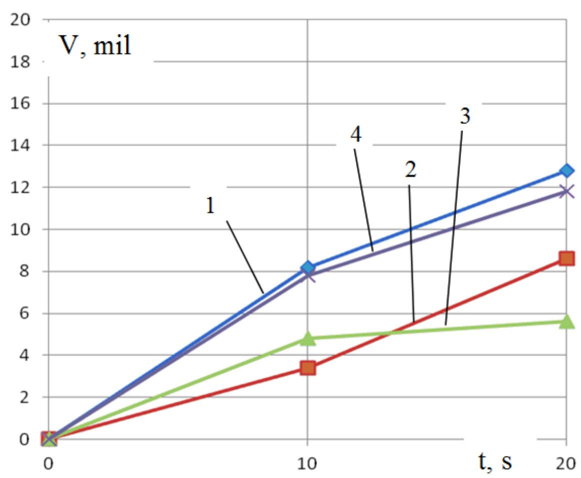


Figure 5. Fuel amount dependence on the injection time, at crankshaft rotation 3000 *r/min*

The investigation of the fuel injection by the system for three modes corresponding to the crankshaft rotations 1000, 2000, 3000 *r/min* and fuel pressure in the fuel distributing rail 220–280 kPa has been conducted in the paper under discussion. The full-factor experiments have been made to estimate the impact of structural parameters (independent factors x_i) of a petrol engine distributed injection system electromagnetic injectors operation characteristics on its efficiency. The electromagnetic injectors efficiency dependence on three main factors change has been determined, namely: crankshaft frequency change n, fuel pressure in distributing rail P and electromagnetic injectors time interval t, i.e. $Q = f(n, P, t)$. The processing of the obtained experimental data has been performed using the well-known techniques of regression analysis. The correspondent plan of a full-factor experiment has been chosen to obtain the regression models of the optimization parameters. The response function, i.e. the electromagnetic injectors efficiency $Q = f(n, P, t)$ found by experimental method has been represented as a mathematical model of a complete quadratic polynomial.

The general view of regression equations of the electromagnetic injectors efficiency depending on the crankshaft frequency change n, fuel pressure in distributing rail P and time interval t on the injectors performance, namely $Q_{(x_1,x_2,x_3)} = f(n, P, t)$, according to the results FFE 3^3 in code values during electromagnetic injectors operation of a petrol engine distributed injection system looks like:

$$Q_{(x_1,x_2,x_3)} = -3,0001 - 0,0001x_1 + 0,0249x_2 - 0,0089x_3 + 0,361\cdot10^{-6}x_1x_2 + 0,22\cdot10^{-5}x_1x_3 - \\ -0,896\cdot10^{-4}x_2x_3 + 0,2\cdot10^{-8}x_1^2 - 0,52\cdot10^{-4}x_2^2 - 0,98\cdot10^{-4}x_3^2; \quad (1)$$

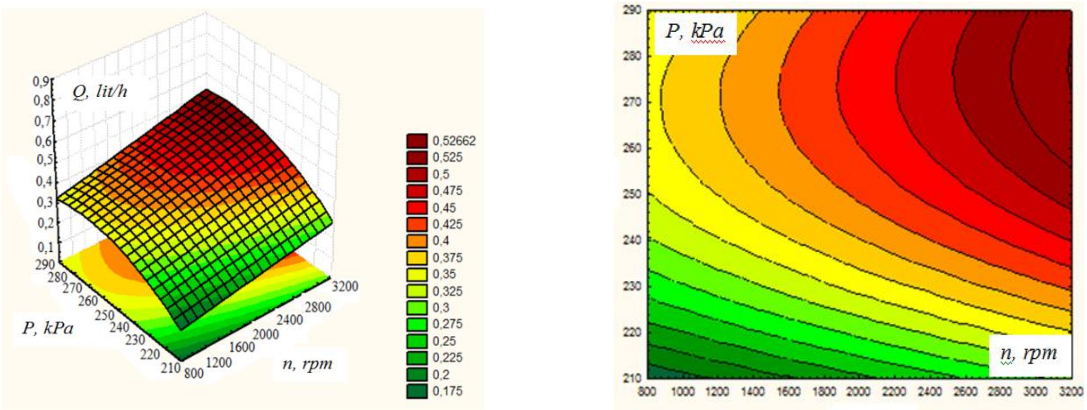
Respectively in natural values (coordinates) the regression equation (1) of the electromagnetic injectors efficiency of a petrol engine distributed injection system after the expression transformation and simplifying has been assumed as:

$$Q_{(n,P,t)} = -3,448 + 0,0265P + 0,19\cdot10^{-5}nt - 0,52\cdot10^{-4}P^2 + 0,65\cdot10^{-4}Pt - 0,12\cdot10^{-3}t^2 \quad (2)$$

The obtained regression equation (1) and regression dependence (2) can be used for determination of the electromagnetic injectors efficiency Q dependernce on the crankshaft rotation frequency n, fuel pressure in distributing rail P and time interval t of petrol engine distributed injection system electromagnetic injectors opeartion within the following change limits of the incoming factors: $1000 \le n \le 3000$ (r/min); $220 \le P \le 280$ (kPa); $15 \le t \le 60$ (min).

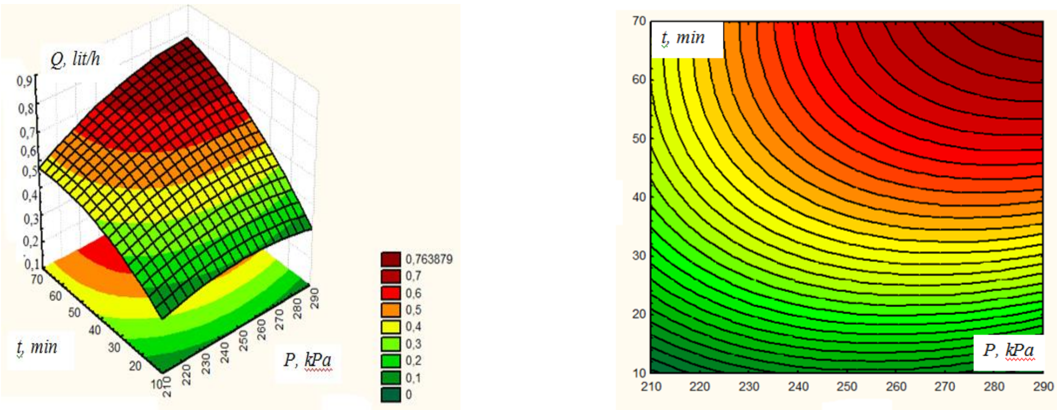
To estimate the impact of main structural parameters of the electromagnetic injectors on their efficiency the software «Statistica» has been used for PC which helped to construct the graphic reconstruction of some intermediate general regression models as quadratic response surfaces and their two-dimensional cross-sections of the efficiency Q as a function of two variable factors $x_{i(1,2)}$ with constant level of the correspondent third factor $x_{i(3)} = const$. The analysis of the given regression equations has proved that the main factors influencing the efficiency increase are the following: factors x_1, x_2, (n, P) and combinations of these factors. An increase of the factor x_3 (t) has resulted in operation instability. To increase the efficiency one should adjust the quantity of the crankshaft rotation frequency and choose the most efficient one.

According to the obtained regression equations the response surfaces have been constructed and their two-dimensional cross-sections of the efficiency dependence on the two factors change for $x_3 = const$. The graphical values of results of electromagnetic injectors efficiency dependence using the program «Statistica» are shown on fig. 6–8.



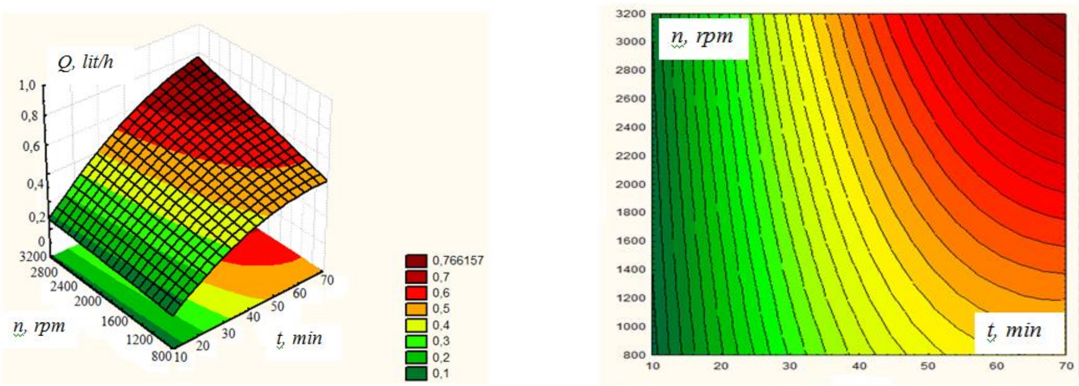
a) b)

Figure 6. Response surface (a) and response surface two-dimensional cross-section (b) dependences of electromagnetic injectors efficiency of petrol Multec-S distributed injection system Multec-S on the ICE crankshaft rotation frequency and the fuel pressure in distributing rail



a) b)

Figure 7. Response surface (a) and response surface two-dimensional cross-section (b) dependences of electromagnetic injectors efficiency of petrol Multec-S distributed injection system Multec-S on the fuel pressure in distributing rail and time of injectors injection



a) b)

Figure 8. Response surface (a) and response surface two-dimensional cross-section (b) dependences of electromagnetic injectors efficiency of petrol Multec-S distributed injection system Multec-S on the ICE crankshaft rotation frequency and time of injectors injection

As it is shown on Figures 6–8, the higher rotation frequency of the crankshaft the more increased efficiency value is. In this case the increase of pressure in the rail up to 260 kPa has resulted in the efficiency increase.

The dependencies of average values of fuel supply indices on the engine crankshaft rotation frequency, found due to the measurements results, have been shown on Figures 8, where each of four injectors has its own order number.

The maximum value of a petrol engine injection system electromagnetic injectors operation efficiency was equal to 0,76 l/h whereas its minimal value was found to be equal to 0,5 l/h at the minimal crankshaft rotation frequency and minimal fuel pressure in the distributing rail.

The studies of a car petrol engine electromagnetic injectors operation efficiency have been carried out. The fuel amount supplied by each injector has been found to be increased due to the engine crankshaft rotation frequency increase. It is different for different injectors and corresponds to a certain value. The shorter injection time interval the lower injector operation efficiency is. Any deviations from the nominal values prove the injector wear:

- dirty gaps between precision pairs;
- worn-out surfaces in contact areas of a spring and an injector valve;
- shrinkage factor and spring rigidity loss;
- deviations in supply voltage, resistance and inductance of electromagnetic coil.

Conclusions. A laboratory stand for both fuel characteristics and supply modes assessment and electrical parameters of electromagnetic injectors of car petrol engine distributed injection system estimation as well has been developed. Some components of ICE operation electronic control systems, namely Multec-S injection system, have been used as the stand basis. This fact has simplified the stand design and reduced its cost comparing with the conventional industrial stands with similar functions. This stand is a demonstrative one which is increasing the education processes efficiency in laboratory research. Besides, the stand can be used for parameters assessment and diagnostics (defect identification) of separate functional components (sensors, injectors) of the car injection system.

Mathematical modeling of electromagnetic injectors efficiency dependence on the change of main parameters of fuel injection system functioning: crankshaft rotation frequency, fuel pressure in the distributing rail and injectors operation time has been carried out based on the obtained multifactor experimental data. The above-mentioned mathematical modeling has been done using well-known techniques of regression analysis which made possible the assessment of the most efficient operation modes of a multifactor system.

Fuel supply deviations (approximately 50%) by some injectors in different operation modes, namely at certain rotation frequency of the engine crankshaft have been found due to the results of the above-mentioned research. This fact has proved the importance of the error cause identification and the system improvement.

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УДК 629.3.018.2

ЕКСПЕРИМЕНТАЛЬНІ ТА АНАЛІТИЧНІ ДОСЛІДЖЕННЯ СИСТЕМИ КЕРУВАННЯ ЕЛЕКТРОМАГНІТНИМИ ФОРСУНКАМИ БЕНЗИНОВОГО ДВИГУНА

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Резюме. *Розроблено лабораторний стенд для дослідження й діагностики функціональних елементів системи подавання пального й для покращення ефективності навчального процесу при лабораторних дослідженнях. Конструкція стенда містить елементи електронних систем керування роботою двигуна внутрішнього згоряння та дає змогу діагностувати роботу системи керування двигуном із використанням зовнішніх діагностичних модулів. Вартість стенда є кошторисно нижчою у порівнянні з професійним обладнанням відомих виробників подібного обладнання. Дизайн лабораторного стенда є ілюстративним і може бути використаний для загального оцінювання якості обраної системи керування ДВЗ. Із використанням вказаного стенда виконано оцінювання параметрів, які характеризують ефективність упорскування пального окремими форсунками двигуна за кількох режимів роботи. Режими роботи, що відповідають різній швидкості обертання колінчастого вала моделювали, використовуючи вбудований блок електронного управління та модулятор імпульсів електромагнітних форсунок. Виконано експериментальні дослідження та отримано основні характеристики подачі пального електромагнітними форсунками досліджуваного двигуна для деяких режимів його роботи. На основі даних експериментальних досліджень проведено математичне моделювання продуктивності електромагнітних форсунок від зміни основних параметрів функціонування системи впорскування пального: частоти обертання колінчастого вала, тиску пального у розподільній рампі та часу роботи форсунок. Метою аналітичного моделювання є оцінювання та визначення оптимальних режимів роботи багатофакторної системи. Моделювання виконано з використанням відомих методик регресійного аналізу.*

Ключові слова: *лабораторний стенд, система впорскування пального, електромагнітні форсунки, комплексна система керування двигуном, регресійний аналіз.*

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