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METHOD FOR DETERMINING DYNAMIC CHARACTERISTICS OF FUEL INJECTORS WITH ELECTROMAGNETIC VALVE ACTUATORS

Modern fuel injectors with electromagnetic actuators are critical components of internal combustion engine (ICE) fuel systems, as they determine the accuracy of fuel dosing, combustion efficiency, and the engine’s environmental performance. The dynamic characteristics of injectors, such as response speed, stability of cyclic fuel supply, and compliance with control signals, directly influence engine operation quality. However, over time, these parameters degrade due to wear, contamination, or material degradation, leading to increased emissions of harmful substances, higher fuel consumption, and reduced engine power. The article proposes a diagnostic method for assessing the dynamic characteristics of injectors, which can be used without disassembly or with disassembly. This approach enables early detection of deviations, optimization of maintenance processes, reduction of maintenance labor intensity, and serves as a valuable tool for training specialists in the field of automotive transport (specialty 274 “Automotive Transport”).

Injector testing without removal is performed through a comparative analysis of parameters across all engine injectors. Key diagnostic parameters include: Cyclic fuel supply correction – deviations in the actual volume of fuel injected per cycle compared to the value set by the electronic control unit (ECU). Control signal characteristics – analysis of the shape, amplitude, and duration of pulses sent to the electromagnetic actuator. Injector coil resistance – indicates the condition of electrical components (e.g., open circuits, short circuits). Nozzle opening delay time – the interval between the control signal and the start of nozzle movement during actuator activation, critical for injection synchronization. To evaluate an injector’s condition, all diagnostic parameters must be measured. A deviation in at least one parameter from its nominal value indicates a malfunction or contamination of the tested injector. The article presents a method for determining the dynamic characteristics of fuel injectors with electromagnetic valve actuators.

Key words: microprocessor control systems, electromechanical converter, injector valves, valve solenoid, method of registering valve or armature movement.

INTRODUCTION

The operation of an internal combustion engine (ICE) is based on the conversion of the chemical energy of fuel into mechanical work. The efficiency of this conversion directly affects the engine's performance characteristics, such as fuel economy and exhaust gas emissions. The widespread implementation of microprocessor-based control systems (MPCS) in automotive applications has significantly enhanced ICE performance by optimizing fuel delivery processes, taking into account a wide range of influencing factors.

In modern engines, the delivery of liquid or gaseous fuel into the cylinders is performed mechanically under the control of MPCS, primarily by spraying through valve-type injectors. These injectors are connected to a fuel accumulator where pressure is maintained at a constant level. Preliminary compression of the fuel provides the jet with sufficient mechanical energy to ensure proper spray direction and droplet dispersion—essential for effective mixture formation. At this stage, energy and material exchange occurs in the fuel delivery system through the transfer of a fuel mass that carries chemical energy. The mechanical energy imparted to the fuel jet improves the quality of mixture formation and combustion. Fuel pressure in the accumulator can be adjusted according to engine operating conditions. Additionally, electronic control of injector valves enables precise regulation of injection timing and duration.

MPCS serves as a technical means of establishing informational links for managing energy flows within the fuel system. It collects and processes data from various sensors and utilizes information obtained through mathematical and physical modeling during engine testing and calibration. The controller processes this data—stored in the form of extensive lookup tables—and converts it into control signals directed to the injectors. The information carrier within the system is an electrical signal, and power is supplied from the vehicle's onboard electrical network. The low-power signal generated by the MPCS is amplified in the output driver stage and then sent to the actuator, which includes an electromechanical converter located within the injector. This converter transforms a portion of the electrical energy from the onboard network into mechanical action on the controlled energy flow.

The adoption of MPCS has greatly expanded the potential for implementing complex control algorithms, allowing for the consideration of numerous parameters and more efficient management of energy processes. The amount of electrical energy consumed by the actuator depends on the resistance of the operating medium, as well as the inertia and velocity of the actuator’s moving elements. In many applications, there is a need to achieve both high mechanical force and rapid response time from the electromechanical converter.

Injectors equipped with electromechanical converters that directly actuate the valve (needle) are referred to as electromechanical injectors. In most known designs, valve closure is achieved using a spring, with the needle rigidly connected to the moving part of the actuator. The cyclic fuel delivery in such injectors is determined by the duration of the actuator's activation and the fuel pressure at the injector inlet.

The electromechanical converter functions as the interface between the electrical control system and the mechanical valve of the injector. Its operation is based on the principle of converting electrical energy into mechanical energy. According to their operating principles, electromechanical converters are categorized as electromagnetic, electrodynamic, magnetostrictive, and piezoelectric. Electromagnetic and electrodynamic converters rely on the interaction of externally generated magnetic fields, while magnetostrictive

and piezoelectric types utilize the intrinsic physical properties of materials and their crystalline structures, which respond to magnetic or electric fields.

LITERATURE REVIEW AND PROBLEM STATEMENT

Modern research highlights the significant impact of microprocessor-based control systems on improving the efficiency of internal combustion engines (ICE). As shown in [1], the use of predictive control enables real-time adaptation of fuel supply parameters, enhancing fuel economy and reducing harmful emissions. Other studies [2, 3] examine the structure of ignition and fuel injection control systems, focusing on the precision of fuel volume and injection timing regulation. Special attention is given to injectors with electromechanical drives, where the pulse duration and fuel pressure directly determine the injection cycle. The authors of [4, 5] emphasize that the performance of an injector largely depends on the design of the electromechanical transducer, particularly its inertial characteristics and energy consumption, which are critical under high-speed operation.

One of the most well-known electromechanical transducers – due to its efficiency, simplicity, and long history – is the electromagnetic transducer, which utilizes the electromagnetic interaction forces of magnetic fields generated by the electromagnet coil within the ferromagnetic cores of the stationary magnetic circuit and the moving armature.

The high efficiency of electromagnetic devices is due to the presence of ferromagnetic materials in the magnetic system with a significantly higher relative magnetic permeability than that of air. The influence of ferromagnetic masses reduces the magnetic resistance of the environment surrounding the energized coil, thereby increasing the magnetic flux. A characteristic feature of electromagnetic interaction forces is their independence from the direction of the magnetic flux and thus the current direction in the control coil. Consequently, electromagnetic energy transducers have a unidirectional characteristic, meaning they operate only in one direction.

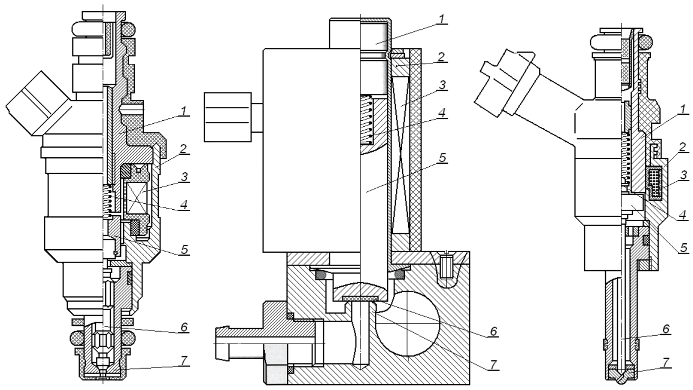
This type of injector, featuring an electromagnetic drive, has become widespread in spark-ignition engines. Below are the designs of injectors used for delivering gasoline, compressed natural gas (CNG), and liquefied petroleum gas (LPG).

Figure 1a shows the design of a Bosch injector, which is widely used in distributed gasoline injection systems in intake manifolds.

Injectors used by the Volkswagen Group for gasoline injection into the combustion chamber (Fig. 1c) differ from the previous ones by their elongated nozzle tip, adapted for harsher temperature conditions, as well as by the shape of the magnetic circuit and the number of turns in the electromagnet coil. This is because direct gasoline injection is time-constrained, requiring a faster-acting electromechanical transducer.

Injectors for delivering LPG or CNG (Fig. 1b) significantly differ from the previous two designs in terms of the shape of the electromagnet components, valve construction, and the direct placement of the injectors on the fuel rail.

However, a common feature of all the above injector types is the presence of electromechanical transducer elements: a ferromagnetic magnetic circuit encompassing the coil and a movable armature. That is, they are all direct-action electromechanical devices with an electromagnetic drive.



a) b) c)

1 – inner magnetic circuit; 2 – outer magnetic circuit; 3 – electromagnet coil; 4 – spring; 5 – electromagnet armature; 6 – injector valve (needle); 7 – valve seat (sealing surface)

Fig. 1. Designs of injectors for gasoline and gas delivery

The main advantage of electromagnetic fuel injectors (EMFIs) lies in their structural simplicity, while a significant drawback is the delay in the needle valve opening due to the operation of the electromechanical transducer.

OBJECTIVE AND PROBLEM STATEMENT

The objective of this study is to reduce the labor intensity and increase the informativeness of diagnostics for electromagnetic injectors in distributed injection systems of gasoline and gas-powered passenger vehicles under operating conditions, by using a developed method for measuring the injector valve's open state duration τ_{inj}. (method for recording the movement of the valve or armature).

RESEARCH RESULTS

In almost all systems, the basis of the injector control algorithm is the model for determining the cyclic supply:

$$G_{cf} = g_{st} \cdot \tau_d, \quad (1)$$

where g_{st}– static nozzle performance, τ_k– duration of the control pulse supplied to the injector. Under static nozzle performance g_{st} understand its ability to pass the amount of fuel G_f with a constantly open valve for a certain period of time τ_d.

From Fig. 2 it is seen that the valve motion diagram has a shape close to a trapezoid. According to formula (1), the cyclic flow is defined as the area of a rectangle with height g_{st} and width τ_d

Error in determining the cyclic feed:

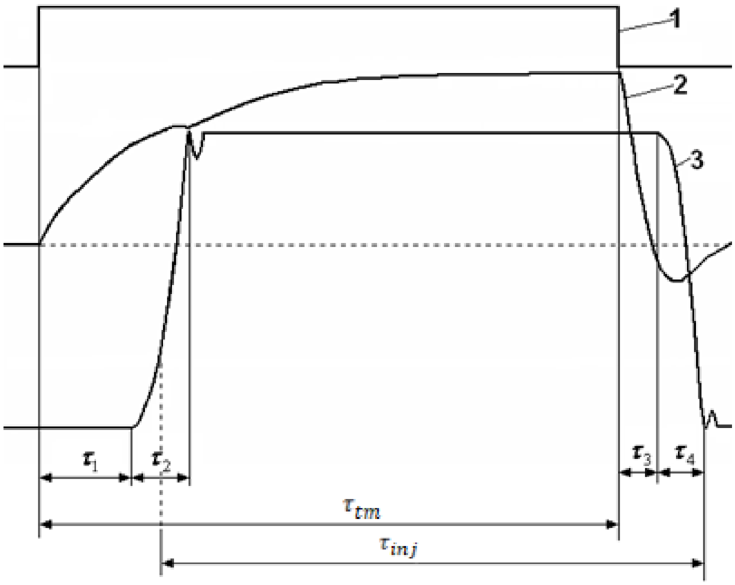
$$\frac{\Delta G_{cf}}{G_{cf}} = \frac{\Delta g_{st}}{g_{st}} + \frac{\Delta \tau_d}{\tau_d}, \quad (2)$$

where $\frac{\Delta G_{cfn}}{G_{cf}}$, $\frac{\Delta g_{st}}{g_{st}}$ та $\frac{\Delta \tau_d}{\tau_d}$ – relative errors of cyclic delivery, static nozzle performance and control pulse duration.

The following is obvious: firstly, g_{st} differs in different injectors due to technological inaccuracies and changes in operation due to contamination; secondly, as can be seen from Fig. 2, the duration of the open state of the injector valve τ_{inj} differs from the duration of the electric control pulse τ_d supplied to the injector electromagnet winding by the amount of valve flight delay during lift-off and landing:

$$\tau_{inj} = \tau_d - (\tau_1 + 0{,}5\tau_2) + (\tau_3 + \tau_4). \quad (3)$$

In the formula (3) τ_1 – time spent overcoming spring resistance and fuel pressure; τ_2 – time spent overcoming the resistance force of the spring, the friction force, the inertia of the valve and the armature of the electromagnet during direct flight; τ_3 – the time during which the accumulated force of the electromagnet will decrease so much that the force of the spring and fuel pressure will exceed it and the return movement of the armature will begin; τ_4 – time spent overcoming friction, valve inertia and solenoid armature during landing.



1 – control signal; 2 – current strength in the electromagnet coil; 3 – motion diagram of the electromagnet armature (injector valve)

Fig. 2. Oscillogram of processes in the electromagnetic actuator of the injector valve

Formula (3) can also be presented in another form:

$$\tau_{inj} = \tau_d - \Delta\tau_{dis}. \quad (4)$$

where $\Delta\tau_{dis}$– takes into account the discrepancy between the control pulse τ_d and the real injection time τ_{inj} and is determined from the formula:

$$\Delta\tau_{dis} = (\tau_1 + 0{,}5\tau_2) - (\tau_3 + \tau_4). \quad (5)$$

Sometimes it is more convenient to use the correction factor k_τ,, which takes into account the delay in the operation of the injectors. It can be determined from the formula:

$$k_\tau = 1 - \frac{\Delta\tau_{dis}}{\tau_d}. \quad (6)$$

The condition for the start of movement of the electromagnet armature is the excess of the electromagnet force over the resistance forces acting in the opposite direction:

$$F_p \geq F_{np} + F_{mp} + F_n, \quad (7)$$

where F_p – electromagnet force, F_f – spring force, F_{fr} – friction force, F_{fp} – force from fuel pressure.

The magnitude of the force of the electromagnetic drive is determined by the formula:

$$F_p = [\frac{U}{R_c} \cdot (1 - e^{-\frac{\tau}{T}})]^2 \cdot \omega^2 \cdot \mu_0 \cdot S \cdot \frac{1}{2\delta^2}, \quad (8)$$

where U – coil voltage; R_c – coil resistance; ω – number of turns in the coil; μ_0 – absolute magnetic permeability of vacuum; S – cross-sectional area of the magnetic core; δ – magnetic gap in a magnetic circuit; τ – current time; T – the time constant of the electromagnet coil, which is determined from the formula:

$$T = \frac{L}{R_c}, \quad (9)$$

where L – coil inductance.

As shown by formulas (2), (3), (4), (5) and (6), the time components that cause the displacement of τ_{inj} relative to τ_d in this process involve certain factors that partially depend on the manufacturing technology and can also change over time and depending on operating conditions. The gaps between the pre-tension pairs become dirty, the surfaces in the contact points of the spring and the injector valve wear out, the gap between them and, accordingly, the spring force changes; due to the aging of the materials, shrinkage occurs and the spring stiffness, supply voltage, resistance and inductance of the electromagnet coil change.

When equipping the engine with injectors, it is necessary to ensure that the kit contains injectors in which the time intervals $\tau_1 \ldots \tau_4$ differ by no more than 5%. This is especially true when converting a gasoline engine to operate on gas fuel, because the characteristics of gas injectors are significantly different from gasoline ones.

To establish the difference between injectors by the characteristic τ_{inj}, several methods can be used:

– the method of spilling in dynamic mode;

– the method of registering the movement of the valve or armature;

– the method of registering the movement of the fuel jet.

Each of the above methods has its own disadvantages and advantages.

For example, the spill method is universal for nozzles of any design used for liquid fuel injection. It is difficult to measure the amount of gas supplied separately by each nozzle. In addition, the specified method allows you to detect only the difference in the amount of fuel supplied between nozzles and is not able to find out the difference in all delay time intervals from τ_1 to τ_4.

The method of registering the movement of the valve or armature allows you to obtain in detail all the delay time intervals τ_1, τ_2, τ_3, τ_4. But it can be applied only to those nozzles whose design allows the registration of the movement of the valve or armature.

The method of registering the movement of the fuel jet can be applied only to liquid fuel injection nozzles.

The paper proposes a method of registering the movement of the valve or armature, which can be applied to the nozzles shown in Fig. 1 a and 1 b.

The experiments were carried out on a laboratory model containing a serial gasoline injection nozzle as an object for determining dynamic characteristics, a control pulse generator and a set of converters and amplifiers that allow recording in the acquisition system the processes that occur in the electromagnetic actuator of the valve injector. The model consists of a power source and a monoblock containing an injector equipped with a current sensor and an optoelectronic valve displacement sensor, amplifiers for these sensors, a pulse generator with pulse frequency and duration regulators, a detachable connector for connecting the data acquisition system. This makes it possible to obtain an oscillogram of the processes (Fig. 2) that occur in the electromagnetic actuator, which cannot be implemented directly on the engine. The duration of all phases of the injector valve movement is determined from the oscillogram.

The following algorithm for conducting tests is proposed in the work:

1 Prepare the data acquisition system for operation: check the presence of grounding, turn on the power to the computer system unit, start the Power Graf program, select the number of channels for registration – 4, set the sampling frequency to 50 kHz in the "Frequency" window.

Assign names to the channels: 1 – control pulse, V; 2 – current strength, A; 3 – coil voltage, V; 4 – armature displacement, mm.

2 Turn on the power to the laboratory layout unit. Using the pulse frequency and duration regulators located on the layout, set the frequency and duration of the control pulses τ_d.

3 Record the processes in the nozzle by clicking the "Start" button in the Power Graf program menu. After 1 s, click the same button again.

4 Save a fragment of the test process to an individual file. The file name includes the student's last name, as well as information about the frequency and duration of the control pulse τ_d on the injector.

5 Perform data processing by determining the duration of the phases of movement of the electromagnet armature together with the injector needle: τ_1, τ_2, τ_3, τ_4, as shown in Fig. 2.

6 According to formula (3), determine the duration of the open state of the injector sprayer τ_{inj}, the discrepancy of the control pulse τ_d to the real injection time $\Delta\tau_{dis}$ according to formula (5), and the delay coefficient k_τ according to formula (6).

CONCLUSIONS

Phased injection provides equal conditions for mixture formation in all cylinders. But due to the technological spread of the injector characteristics, there is uneven fuel supply. If the set of injectors for the engine is selected with small deviations μf (for example 3%), and the delay time is approximately the same, then the unevenness of the supply of gasoline to the cylinders of the new engine is ensured within approximately the same limits.

Changing the static and dynamic characteristics of the injectors during operation significantly affects the unevenness of the fuel supply. Changing the cross-section of the spray holes affects the overall performance of the injectors. The difference in the delay of the injector valves by 0.1 ms leads to an increase in unevenness in low-flow modes by 2 ... 2.5 times.

The described method for determining the energy performance of a vehicle can be used for work on determining fuel consumption on vehicles equipped with distributed fuel injection systems, as well as for determining or clarifying the basic norms of consumption for transport work, taking into account the operating conditions. elements of the fuel injection system.

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***Горбік Ю.В.* Метод визначення динамічних характеристик паливних форсунок з електромагнітними приводами клапанів**

Сучасні паливні форсунки з електромагнітними приводами є критичними компонентами систем живлення двигунів внутрішнього згоряння (ДВЗ), від яких залежить точність дозування палива, ефективність згоряння суміші та екологічні показники двигуна. Динамічні характеристики форсунок, такі як швидкість спрацьовування, стабільність циклової подачі та відповідність керуючим сигналам, безпосередньо впливають на якість роботи двигуна. Проте з часом їхні параметри погіршуються через знос, забруднення або деградацію матеріалів, що призводить до збільшення викидів шкідливих речовин, зростання витрати палива та зниження потужності. У статті запропоновано метод діагностики динамічних характеристик форсунок який можливо використовувати без їх демонтажу, або з демонтажем, що дозволяє виявляти відхилення на ранніх етапах та оптимізувати процеси технічного обслуговування, а також зменшити трудомісткість технічного обслуговування. Також запропоновану методику доцільно використовувати у навчальному процесі для підготовки фахівців спеціальності 274 «Автомобільний транспорт».

Перевірка форсунок здійснюється шляхом порівняльного аналізу показників усіх форсунок двигуна. До цих параметрів відносяться корекція циклової подачі пального, характеристики керуючого сигналу, опір форсунки, час затримки відкриття голки форсунки при спрацьовуванні електромеханічного перетворювача. Для визначення стану форсунки необхідно встановити значення всіх діагностичних параметрів. Відхилення хоча б одного з них від номінального значення свідчить про несправність або забруднення перевірюваної форсунки. Запропоновано метод визначення динамічних характеристик паливних форсунок з електромагнітними приводами клапанів.

Ключові слова: мікропроцесорні системи керування, електромеханічний перетворювач, клапані форсунки, соленоїд клапанів, метод реєстрації руху клапана або якоря.

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