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THE BASIC ALGORITHM OF THE ALL-SPEED GOVERNOR WITH ELECTRONIC CONTROL AND ITS HARDWARE IMPLEMENTATION

Key words: diesel, fuel delivery system, actuator, microcontroller, electronic governor.

Abstract: The article considers the results of theoretical and experimental studies devoted to the creation of an electronic control system of fuel injection in diesel engines. The method of synthesis of the algorithm for all-speed electronic governor is described. The functional scheme used for the fuel delivery system control based on the microcontroller, the HEINZMANN electric servo actuator, and the BOSCH high pressure fuel pump has been developed and practically implemented. The experimentally obtained static characteristics of the automatic control system under various governor settings are given.

Algorytm sterowania elektronicznego regulatora prędkości wraz z jego implementacją sprzętową

Słowa kluczowe: olej napędowy, układy zasilania, mikrokontroler, regulator prędkości.

Streszczenie: W artykule przedstawiono wyniki badań teoretycznych oraz empirycznych elektronicznego regulatora prędkości układu sterowania wtryskiem paliwa w silniku o zapłonie samoczynnym. Opisano metodę tworzenia algorytmu elektronicznego regulatora dla pełnego zakresu prędkości. Zaprezentowano układ zasilania paliwa zbudowany w oparciu o mikrokontroler, elektryczny siłownik HEINZMANN i wysokociśnieniową pompę paliwową BOSCH, który został wdrożony i przebadany. Otrzymano eksperymentalnie charakterystyki statyczne automatycznego systemu sterowania dla różnych ustawień regulatora prędkości.

Introduction

It is known that significant progress in internal combustion engines (ICE) engineering was achieved through the application of electronic components for the control of engine's units and systems. The electronic control of fuel injection in diesel engines allows one to precisely and differentially adjust the injection process parameters. Only in this way can the the numerous technical requirements put forward be satisfied in modern internal combustion engines [1]. At the same time, it could be argued that mass production of the diesel engine fuel delivery systems with electronic control is still a prerogative just for a several world leading firms. Therefore, it is natural that these manufacturers do not share with any information about the composition, algorithms, and program codes implemented in their products. The same approach is taken by small private companies involved in the re-equipment of fuel delivery systems to make them electronically controlled as well as scientists working in the mentioned area of research.

Only general information on electronic control of fuel delivery system of diesel engines is reported in the publications. It is generally known that the electronic control system of a diesel engine includes a set of sensors in a varying configuration. As a rule, these are a crankshaft rotation speed sensor, the position sensor of the engine controller (both – necessarily), the position sensor of the rack of high pressure fuel pump (HPFP), fuel temperature sensor, boost pressure and ambient temperature sensors, and the sensors of exhaust gases and coolant temperatures. The mentioned electronic control system also includes actuators, such as electromagnets, linear piezo actuators, or stepper motors, and, finally, an electronic control unit (ECU), which connects sensors and actuators through the specially developed algorithm. However, the descriptions of these algorithms of the ECU operation are completely absent. It is only known that ECU processes signals from sensors and, based on the interpolation of the target values that are stored in the memory in tabular form, generates control signals for the actuators [1]. As a rule, these set of tables, their concepts and methods of the control signal generation are commercial secrets (know-how) of the producers.

1. Literature review

Some publications on the synthesis of ICE control algorithms are known. Thus, in the article[2], there is information on the implementation of the algorithms for electronic control of diesel engines. However, the description of the algorithms is absent. In addition, the peculiarities of the locomotive diesel operation do not allow implementing this control algorithm in the engine of the ground transportation. The same problem is related to the marine engine control algorithms application, which is discussed in [3]. The works of V. Furman and A. Bogaevsky were also devoted to the development of electronic control systems for diesel locomotive engines [4, 5, and others].

Recently, many scientific papers are devoted to the electronic control of the test benches [6, 7]. The purpose of them is to reproduce the transient test cycles of the ICE to determine their environmental performance. However, implemented algorithms are used in managing a completely different object, indirectly related to the engine.

Part of the well-known open publications on electronic control of diesels describe the control algorithms just for separate systems: the fuel rail of the common rail system [8], air supply system [9], mountain brake system [10], EGR system [11], electromagnet diagnostics system of HPFP [12], etc. All the above-mentioned solutions are not directly related to the speed control system of the engine.

Works [13, 14] cannot be fully described as electronic control solutions, since they refer to the remote transmission of "manual" control of the input lever of a mechanical controller. However, the transmission occurs with the help of an electromagnetic-pneumatic actuator controlled by a microcontroller.

Works from G.M. Kukharenko and A.N. Marchuk [15, 16] are devoted to the development of a fuel supply control algorithm for a particular mode of the engine operation, namely for the start mode.

The work [17] could be considered as the closest to the current research as to its major task and offered concept. However, the authors of this research used a stepper motor as an actuator, which is known to have a low response time that would have a negative impact on the dynamic characteristics of the control system. In addition, the control algorithm is based on the interpolation of the controller's static characteristics stored in the controller memory in tabular form. This would add an additional load to the controller's central processor and leads to an increase in the intrinsic time (inertia) of the electronic governor.

Based on the current analysis that was described above, there is a relevant scientific and technical task on creation of effective (in terms of high operation speed) system of electronic control for diesel engine fuel supply. The opened program algorithm could be realized in this system. This is the purpose of present article.

2. Theoretical part. Synthesis of the static characteristics of electronic governor using an analogue method

Let us consider the work of the all-speed governor with a variable tightening of the spring, the scheme of which is shown in Fig. 1. The corresponding algorithmic structural scheme, which is based on the electronic replacement of physical information processes (linear movements of units or operating forces) is shown in Fig. 2. Thus, the travel of the clutch of the sensing element under the action of the inertia forces of the rotating masses can be represented as a certain algorithm of rotational speed measurements, and the force of the spring tightening could be accepted as an algorithm used for processing the external control action. From this point of view, the governor lever can be represented as a certain calculator whose equilibrium position uniquely determines the value of the output signal Hp_0.

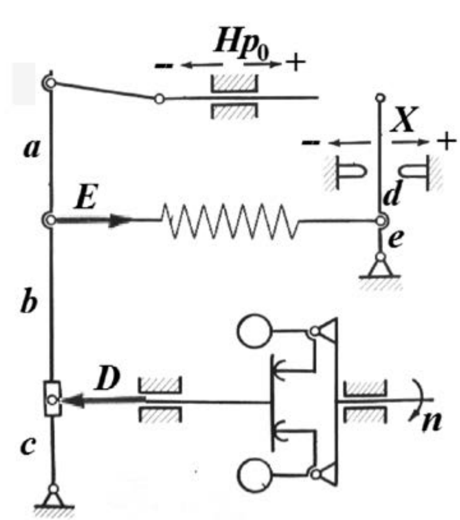

Fig. 1. All-speed governor with the variable spring tightening – the schematic diagram

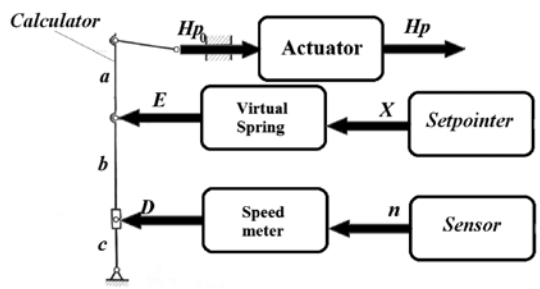

Fig. 2. The schematic diagram of the all-speed governor with electronic control

Then the static equilibrium condition of the all-speed governor with variable spring tightening can be described mathematically as follows

$$E \cdot (b+c) = D \cdot c \tag{1}$$

where E is the conditioned restoring force, which is the governor spring tightening force. This force is composed of the force of preliminary tightening of the spring (E_0) and its current deformations related to the movement of the control lever (X) and HPFP rack (Hp_0):

$$E = E_0 + C \cdot \overline{X} \cdot (X_{\max} - X_{\min}) \frac{e}{d+e} - C \cdot \overline{Hp}_0 \cdot (Hp_{\max} - Hp_{\min}) \frac{b+c}{a+b+c} \tag{2}$$

where C – virtual coefficient of spring stiffness in N/m. The bar denotes relative values.

The conditional support force $D = f(\omega)$ is, in fact, a rotational speed meter. If the supposition is correct, it obeys a linear dependence, then:

$$D = K \cdot \overline{\omega} \cdot (\omega_{\max} - \omega_{\min}) = K \frac{\pi}{30} \overline{n} \cdot (n_{\max} - n_{\min}) \tag{3}$$

where the constant coefficient of proportionality K has the dimension of N/s^{-1} (it is an analogue of the inertial coefficient of the mechanical governor shown in [18]).

If we substitute Equations (2) and (3) into Equation (1), we obtain the following:

$$\left[E_0 + C \cdot \overline{X} \cdot (X_{\max} - X_{\min}) \frac{e}{d+e} - C \cdot \overline{Hp}_0 \cdot (Hp_{\max} - Hp_{\min}) \frac{b+c}{a+b+c} \right] (b+c) =$$
$$= K \frac{\pi}{30} \overline{n} \cdot (n_{\max} - n_{\min}) \cdot c,$$

and open the brackets on its left:

$$E_0 \cdot (b+c) + C \cdot (X_{\max} - X_{\min}) \frac{e(b+c)}{d+e} \cdot \overline{X} - C \cdot (Hp_{\max} - Hp_{\min}) \frac{(b+c)^2}{a+b+c} \cdot \overline{Hp}_0 =$$
$$= K \frac{\pi}{30} \overline{n} \cdot (n_{\max} - n_{\min}) \cdot c.$$

Then divide the obtained expression by a factor, $C \cdot (Hp_{\max} - Hp_{\min}) \frac{(b+c)^2}{a+b+c}$:

$$\frac{E_0}{C(Hp_{\max} - Hp_{\min})} \cdot \frac{a+b+c}{b+c} + \frac{X_{\max} - X_{\min}}{Hp_{\max} - Hp_{\min}} \cdot \frac{e(a+b+c)}{(d+e)(b+c)} \cdot \overline{X} - \overline{Hp}_0 =$$
$$= \frac{\pi}{30} \cdot \frac{K(n_{\max} - n_{\min})}{C(Hp_{\max} - Hp_{\min})} \cdot \frac{c(a+b+c)}{(b+c)^2} \overline{n}.$$

Then we can denote the constants in the resulting expression as follows:

$$\frac{E_0}{C(Hp_{\max} - Hp_{\min})} \cdot \frac{a+b+c}{b+c} = A_1,$$
$$\frac{X_{\max} - X_{\min}}{Hp_{\max} - Hp_{\min}} \cdot \frac{e(a+b+c)}{(d+e)(b+c)} = A,$$
$$\frac{\pi}{30} \frac{K(n_{\max} - n_{\min})}{C(Hp_{\max} - Hp_{\min})} \cdot \frac{c(a+b+c)}{(b+c)^2} = B.$$

Then, there is the equation of the governor with electronic control of the following form:

$$A_1 + A \cdot \overline{X} - \overline{Hp}_0 = B \cdot \overline{n}$$

where

$$\overline{Hp}_0 = A_1 + A \cdot \overline{X} - B \cdot \overline{n} \tag{4}$$

This is the algorithm of the proposed electronic governor. The relationship between the values of Hp_0 and the physical position of the rack of HPFP Hp is described in detail in [19].

In addition, from Equation (4), it is possible to obtain the static characteristics of the governor in the form of $\overline{Hp}_0 = f\left(\overline{X}, \overline{n}\right)$, and by choosing the coefficients A_1, A, and B – to set the required form of the static characteristics.

3. Experimental work. Determination of the static characteristics of the electronic governor on a motorless test bench

The schematic diagram of the diesel engine management system that was developed by the authors is shown in Fig. 3. As it can be seen from the figure, the external and internal influencing factors for the system are as follows: X – the current position of the engine controller, n – the current crankshaft rotation speed, Hp the position of the HPFP rack, and f – the relative magnitude of the PWM signal stuffing. The actuator's controller is a part of the engine's ECU.

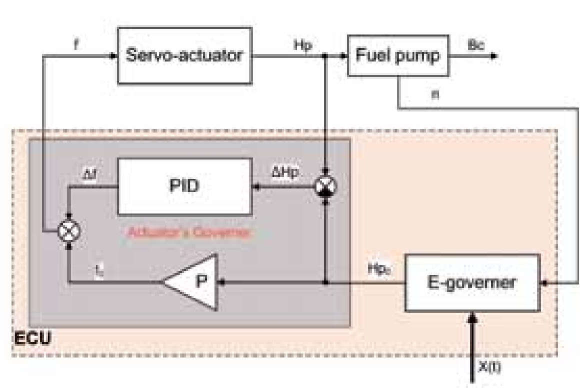

Fig. 3. The schematic diagram of the diesel engine management system

As the actuator in the drive of the HPFP rack, a HEINZMANN servo actuator model StG 6-02V was used. The design of the actuator is based on a DC motor driven by a PWM signal. It has a toothed gearbox and a non-contact reverse positional connection. This actuator provides an output torque of 6 N·m and a range of the angle of rotation of the output shaft is 36° [20]. The algorithm developed for control of the actuator's output link positioning is given in the paper [19].

Other components included in the management system, in addition to the actuator, are the following: microcontroller Atmel SAM3X8E ARM Cortex-M3 with a clock frequency of 84 MHz, 96 MB of RAM and 512K bytes programmable memory with a 488 Hz output frequency of 12-bit PWM signal; power supply unit 330 W; and, an integral bridge driver of electric motor with output current up to 43 A.

The BOSCH PES 4P 100A 320RV fuel delivery pump, which provides a fuel injection pressure up to 80 MPa at the maximum fuel delivery rate of 170 mm^3, is used as a controlled fuel injection pump. Initially, the HPFP was equipped with an all-speed mechanical governor of the RQV type. The static characteristics of the pump were determined by the authors experimentally, and it is shown in Fig. 4. It is important to note that obtained results completely correspond to the reference data given in [1].

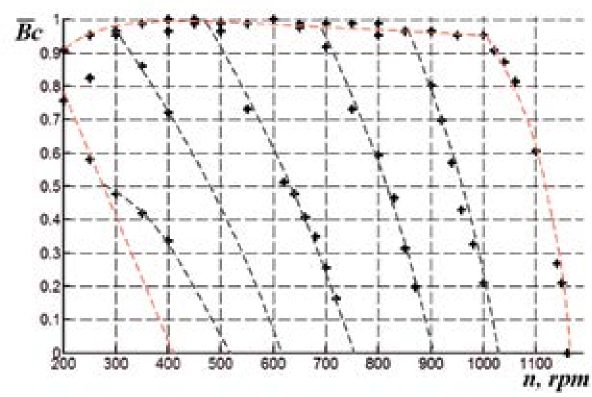

Fig. 4. Static characteristics of BOSCH PES 4P high pressure fuel pump equipped with standard mechanical governor of RQV type

The appearance of an experimental setup that includes an electronic governor with an actuator and attached to the HPFP is shown in Fig. 5. The system is mounted on a KI921M motorless test bench used for the examination of fuel systems, which allows adjustment and recording the static characteristics of the diesel's HPFP.

Based on the static characteristics of the RQV all-speed mechanical governor (shown in Fig. 4) as well as to repeat these characteristics in the electronic governor, it was assumed that the velocity meter has a parabolic dependence, i.e. $D = f\left(\omega^2\right)$. Then the basic equation of the algorithm used in the governor takes the form of

$$\overline{Hp}_0 = A_1 + A \cdot \overline{X} - B \cdot \overline{n} \tag{5}$$

Fig. 5. The experimental setup mounted on motorless test bench

Using the special analytical technique, the values of the constants in the equation were chosen as $A_1 = 0.217$, $A = 3.17$, $B = 2.41$.

Moreover, additional equations that govern the work of the maximum speed control actuator, idle speed control actuator, as well as the positive and negative correctors have been implemented in the electronic governor's algorithm. Their parameters are consistent with the parameters of a 100-kW power output diesel engine. The electronic governor is supposed to be installed on this engine; therefore, the required adaptability (provided by the positive corrector), the limitation of smoke (negative correction), and the minimum and maximum idling speeds ought to be ensured. It is important to note that, in the region of the boundary injection rates, the characteristics obtained using the electronic governor is somewhat different from the corresponding settings of the mechanical governor.

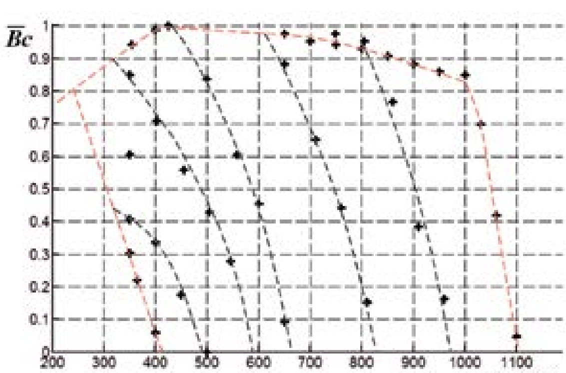

Fig. 6. Static characteristics of BOSCH PES 4P high pressure fuel pump equipped with all-speed electronic governor (similar to RQV type)

Experimentally obtained static regulatory characteristics of the system using the electronic governor are shown in Fig. 6. A comparison of data in Fig. 4 and Fig. 6 shows that the electronic governor system developed by the authors can provide identical static characteristics of a commercial (standard) mechanical governor.

In addition, using the flexibility in adjusting the algorithm of the electronic governor, it is possible simply to reconfigure the same device as a two-mode controller. For example, using the following equation:

$$\overline{Hp}_0 = A_1 + A \cdot \overline{X} - B \cdot \overline{n}$$

with coefficients, $A_1 = 0.365$, $A = 0.668$, $B = 0.0776$, the static regulatory characteristics get the form shown in Fig. 7 (experimental data obtained by the authors). This setting almost coincides with the work of the BOSCH, type RQ mechanical governor [1].

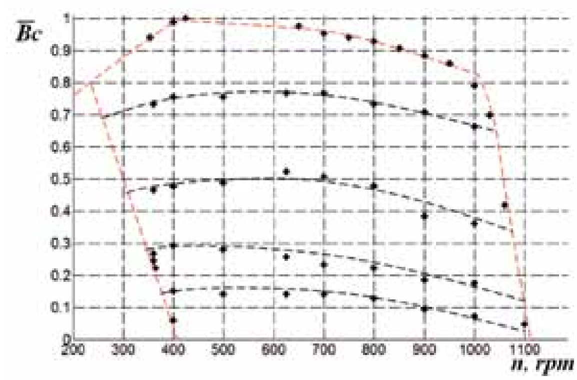

Fig. 7. Static characteristics of BOSCH PES 4P high pressure fuel pump equipped with two-speed electronic governor (similar to RQ type)

Conclusions

Thus, in the present work, the authors have developed and verified experimentally a flexible algorithm of the diesel engine speed governor with electronic control. The offered algorithm allows one to repeat easily the characteristics of the mechanical governor create any required regulatory characteristics of the engine, including the possibility of universalization through combining in one device two, three, or more governors designed for different purposes.

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