Розглядається вибір структури і чисельних значень варійованих параметрів електронного блоку керування всережимного регулятора паливоподавання транспортного дизеля з нерегульованим турбонаддувом. Обрані значення варійованих параметрів забезпечують високу точність підтримки необхідного значення кутової швидкості обертання колінчастого валу дизеля. Обрана структура електронного блоку керування забезпечує властивість інваріантності замкненої системи паливоподавання до зовнішніх навантажень, що діють на колінчастий вал

Ключові слова: транспортний дизель, всережимний регулятор паливоподавання, електронний блок, інваріантність системи паливоподавання

Рассматривается выбор структуры и численных значений варьируемых параметров электронного блока управления всережимного регулятора топливоподачи транспортного дизеля с нерегулируемым турбонаддувом. Выбранные значения варьируемых параметров обеспечивают высокую точность поддержания требуемого значения угловой скорости вращения коленчатого вала дизеля. Выбранная структура электронного блока управления обеспечивает свойство инвариантности замкнутой системы топливоподачи к внешним нагрузкам, действующим на коленчатый вал

Ключевые слова: транспортный дизель, всережимный регулятор топливоподачи, электронный блок, инвариантность системы топливоподачи

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STRUCTURAL-PARAMETRICAL SYNTHESIS OF ELECTRONIC CONTROL UNIT OF FUEL FEEDING SYSTEM OF VEHICLE DIESEL ENGINE

T. Aleksandrova
Doctor of Technical Sciences, Associate Professor
Department of system analysis and management*
E-mail: aleksandrova.t.ye@gmail.com

A. Lazarenko
PhD, Assistant
Department of information technologies and systems of wheeled and tracked vehicles named A. Morozov*
E-mail: cool-t177@rambler.ru

*National Technical University «Kharkiv Polytechnic Institute»
Kyrpychova str., 2, Kharkiv, Ukraine, 61002

1. Introduction

Ukrainian tank two-stroke diesel engines with uncontrolled turbosupercharger of series 5TDF and 6TD, mounted on the tanks “Bulat” (T-64 BM), “Bereza” (T-80UD) and “Oplot” (T-84), in unanimous opinion of foreign military experts, is the best tank diesel engines in the world [1]. Diesel engine 5TDF MA with power of 750 hp, mounted on the tank “Bulat” of weight 39 t, provides for the speed of 65 km/h. Diesel engine 6TD-1 with power of 1000 hp, mounted on the tank “Bereza” of weight 44 t, provides for the speed of 70 km/h, while diesel engine 6TD-2 with power of 1200 hp, mounted on the tank “Oplot” of weight 48 t, provides for the speed of 72 km/h. Attempts to use a promising diesel engine 6TD-3 with power of 1500 hp on the tank “Oplot” did not lead to a considerable increase in torque and speed characteristics of the tank. The fact is that at the speeds, which exceed 70 km/h, power losses in the caterpillar propulsor grow sharply. Apparently, this speed should be considered maximum for the tank with traditional construction of the caterpillar propulsor.

Until recently, transport diesels engines of series YMZ-238, produced by Yaroslavl Motor Plant (Russia), were used mainly for lightly armored wheel and caterpillar equipment, as well as for army vehicles KrAZ (Ukraine). The break-up of economic relationships with Russia in the sphere of defense sector of economy raised a question about creating Ukrainian transport diesel engines for the types of indicated armaments. As a result, Ukrainian diesel engine designers in the Kharkov Design Bureau of Engine Technology created diesels engines of series 3TD, namely, 3TD-1, 3TD-2, 3TD-3 and 3TD-4 with power, respectively, of 300 hp, 400 hp, 500 hp and 600 hp. When creating these diesels engines, tank diesel engines 6TD-1 and 6TD-2, which contain 6 pairs of cylinders with oppositely located pistons, were taken as a basis. Diesel engines of series 3TD contain 3 pairs of cylinders and develop half power in comparison with the power of diesel engines of series 6TD. The fuel feed system of diesel engines 3TD in practice is not different from the fuel feed system of diesel engine 6TD, it is hydro-mechanical, besides, all-mode regulator has a non-uniformity degree of 8÷12 %. This means that angular velocity of crankshaft rotation ω_0, set by the driver with the help of control pedal of fuel feed is supported relative to the assigned value with accuracy (0,08÷0,12) ω_0 s^{-1}. For tank diesel engines, this accuracy of the all-mode fuel feed regulator is completely acceptable mainly during tank motion under conditions of impassable road at average speeds of (25÷35) km/h. For transport diesel engines, used in the wheeled lightly armored vehicles and army automobiles, which move at the speed exceeding average speed of tank motion by 2÷3 times, this accuracy of all-mode regulator is clearly insufficient.

In this connection, an increase in operation accuracy of the all-mode fuel feed regulator of transport diesel engine by using electronic control unit for fuel feed is a relevant task. This unit implements a control algorithm, providing for the property of invariance of regulator to the action of continuously changing external disturbances.

2. Literature review and problem statement

The design of all-mode fuel feed regulator for transport diesel engine with the electronic control unit was patented in 1979 [2]. The regulator contained electrical sensors of angular velocity of crankshaft of diesel engine and position of the lath of the fuel pump and position of control of fuel feed pedal. The regulator combined two basic principles of control, the principle of deviation control and the principle of disturbance control, and provided for the invariance property of closed fuel feed system to the action of external disturbances and, therefore, increased static and dynamic accuracy, while the diesel engine, equipped with this regulator, possessed increased fuel efficiency.

Specialists at Kharkov Design Bureau of Engine Technology and from Kharkov Design Bureau of Machine Building named after A. A. Morozov were engaged in the development of industrial models of all-mode fuel feed regulators with electronic control unit for the transport diesel engines of series 5TDF and 6TD, which were used in the national armored tank equipment. Thus, in article [3] it was shown that the use of the all-mode fuel feed regulator with the electronic control unit leads to the reduction in route fuel consumption by the diesel engine 5TDF from 397 l/100 km to 305 l/100 km during motion of tank T-64B at speed 30 km/h, and from 370 l/100 km to 350 l/100 km during motion of the same tank at speed 43 km/h. With the use of electronic control unit in diesel engine 6TD-1, route fuel consumption decreased from 479 l/100 km to 383 l/100 km during motion of tank T-80UD at speed 30 km/h.

In paper [4], a conclusion was drawn that during motion of tank T-80UD with diesel engine 6TD-1, equipped with fuel feed regulator with electronic control unit, route fuel consumption decreased on average by 7 % under severe motion conditions and by 22 % under ordinary conditions.

In article [5], a conclusion was drawn that almost vertical regulatory characteristics, which occur in the use of all-mode regulator with electronic control unit, make it possible to maximally use energy capacities of the diesel engine. Such characteristics make it possible to expand operational rotation frequency due to the stable operation at low angular velocity of crankshaft, to increase mean motion speed of the tank and to decrease route fuel consumption.

In paper [6], authors considered a possibility of building a digital electronic unit of all-mode fuel feed regulator. It was shown that dynamic characteristics of the all-mode regulator essentially depend on the magnitude of period of quantization of digital electronic unit, which is $T = 0.002 \div 0.01$ s for diesel engine 6TD-1.

Article [7] presents results of running tests of tank T-80UD with electronic-hydromechanical all-mode fuel feed regulator of diesel engine 6TD-1, which include the following:

1) a decrease in fuel consumption by (7÷27) %;

2) an increase in mean motion speed along straight sections of rough terrain by (10÷12) % and during turning on the rough terrain by 15 %;

3) a decrease in steady frequency of crankshaft rotation from 80 s^{-1} to 40 s^{-1}.

Article [8] presents comparative results of statistical processing of the bench tests of diesel engine 6TD-1 with a standard hydro-mechanical all-mode regulator and the regulator with electronic control unit, which include the following:

1) average speed of tank motion with the use of the all-mode regulator with electronic control unit increases from 26.7 km/h to 27.1 km/h;

2) mean angular velocity of crankshaft decreases from 270.5 s^{-1} to 241.4 s^{-1};

3) loading factor of engine increases from 0.44 to 0.49;

4) average hourly fuel consumption decreases from 106.6 kg/h to 96.1 kg/h.

In article [9], similar data are presented for diesel engine 6TD-2.

In all the above-mentioned studies, values for the varied parameters of electronic control unit were selected experimentally. A problem of parametric synthesis of the standard hydro-mechanical fuel feed regulator of diesel engines of series 5TDF and 6TD was not posed for the following reasons. Although a mathematical model of the disturbed motion of closed fuel feed system of diesel engine 5TDF with hydro-mechanical all-mode regulator was sufficiently adequate to the real object, but in this model there was observed a rather strong dependence of values of the object's parameters on the operation modes of diesel engine, caused, first of all, by a high degree of non-uniformity of hydro-mechanical all-mode regulators. In this connection, it was not possible to select the optimum value of the gain factor of hydro-mechanical regulator for the entire variety of possible operational modes of diesel engine. A small degree of non-uniformity of the all-mode regulator with electronic control unit made it possible to pose a problem about parametric synthesis of the regulator under condition of adequacy of the mathematical model of disturbed motion of closed fuel feed system. This mathematical model was constructed by one of the authors of present article by solving the problem of identification of unknown values of parameters of the fuel feed system of diesel engine 6TD with the help of research stand, created at Kharkov Design Bureau of Machine Building named after A. A. Morozov, and intended for full-scaletests of the elements of motor-transmission compartment of tanks [10, 11].

In paper [12], applying the developed mathematical model, the problem was solved about parametric synthesis of electronic control block of the all-mode fuel feed regulator of diesel engine 6TD-1. The electronic control unit was to meet the requirement of minimum integral quadratic functional, which provides high dynamic accuracy of maintenance of angular velocity of crankshaft, assigned by a driver. At the same time, road tests of the tank with electronic unit of fuel feed control showed that the developed unit was unable to provide the necessary static accuracy of control and led to the conclusion about the need for developing an all-mode fuel feed regulator, which renders the property of invariance to the action of external disturbances to the closed system [13].

At the same time, the absence of adjustable turbine supercharger for diesel engines of series 5TD, 6TD and 3TD leads to an increase in smokiness of exhaust gases and a certain decrease in the traction properties of diesel engine as a result of incomplete fuel combustion in cylinders of the diesel engine. In the foreign models of armored tank equipment, either they use four-cycle diesel engines with adjustable turbine supercharger or gas turbine engines, supplied with the uniform regulator of fuel feed and air supply, which prevents incomplete fuel combustion. In the two-stroke diesel engines with uncontrolled turbine supercharger, the indicated shortcomings are proposed to be removed by using an invariant all-mode fuel feed regulator.

3. The aim and tasks of research

The aim of present work is to solve a problem of parametric synthesis of electronic control unit of the all-mode fuel feed regulator of transport diesel engines of series 5TDF, 6TD and 3TD, which renders the property of invariance toward the action of external disturbances to the closed fuel feed system, which leads to an increase in static and dynamic accuracy of the regulator, a decrease in smokiness of exhaust gases and an increase in the traction characteristics of diesel engine.

To achieve the set aim, the following tasks were to be solved:

– the task of parametric synthesis of all-mode fuel feed regulator, which provides for high dynamic accuracy of control;

– the task of parametric synthesis of all-mode fuel feed regulator, which provides for the property of invariance to the action of external disturbances;

– the task of the synthesis of algorithms, implemented by a digital electronic unit of all-mode fuel feed regulator.

4. Parametric synthesis of all-mode fuel feed regulator, which provides for high dynamic accuracy of control

Fig. 1 shows a schematic of the closed fuel feed system of transport diesel engine with electronic control unit.

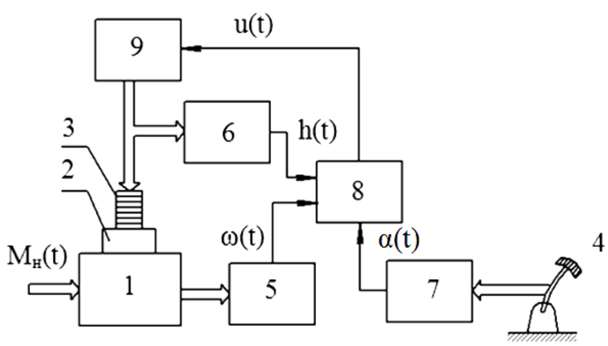

Fig. 1. Schematic of the closed fuel feed system: 1 – diesel engine; 2 – fuel feed system; 3 – lath of fuel pump; 4 – control pedal of fuel feed; 5 – sensor of angular velocity of crankshaft rotation; 6 – sensor of position of fuel pump lath; 7 – sensor of position of pedal of fuel feed control; 8 – electronic control unit; 9 – controlling element; α(t) – position of control pedal of fuel feed; ω(t) – current angular velocity of crankshaft rotation; h(t) – current position of the fuel pump lath; u(t) – controlling signal, formed by electronic unit; $\Delta M_H(t)$ – current load torque on crankshaft

With the help of pedal 4, the driver sets the all-mode regulator by the assigned angular velocity of crankshaft rotation ω_0. All-mode regulator supports the assigned value of angular velocity ω_0 under conditions of continuous change in load torque $M_H(t)$ by changing fuel feed to cylinders of the diesel engine.

A mathematical model of the disturbed motion of the closed fuel feed system is given in article [13] and is written down in the form of a system of differential equations

$$T_d \frac{d\Delta\omega(t)}{dt} + \Delta\omega(t) = k_d \Delta h(t) - k_f \Delta M_H(t); \quad (1)$$

$$T_{1m}^2 \frac{d^2\Delta z(t)}{dt^2} + T_{2m} \frac{d\Delta z(t)}{dt} + \Delta z(t) = \frac{k_m}{c} \Delta u(t); \quad (2)$$

$$T_g \frac{d\Delta h(t)}{dt} + \Delta h(t) = \Delta z(t), \quad (3)$$

where $\Delta\omega(t)$ is the deviation of angular velocity of crankshaft of diesel engine from the assigned value ω_0; $\Delta z(t)$ is the deviation of armature of electromagnet from its position z_0 in the state of established equilibrium; $\Delta h(t)$ is the deviation of lath of fuel pump from position h_0, corresponding to the state of established equilibrium; $\Delta M_H(t)$ is the deviation of external disturbance from its value in the state of established equilibrium.

At a constant position of pedal 4 $\alpha(t)=\alpha_0$, corresponding to the assigned angular velocity ω_0, controlling signal $\Delta u(t)$ is created in the form

$$\Delta u(t) = k_\omega \Delta\omega(t) + k_h \Delta h(t), \quad (4)$$

where k_ω and k_h are the varied parameters of electronic unit of all-mode regulator.

In equations (1)–(3), T_d designates a time constant of diesel engine, T_{1m} and T_{2m} are the time constants of controlling electromagnet, T_g is the time constant of fuel hydraulic servomotor, k_d and k_f are the gain factors of diesel engine; k_m is the gain factor of electromagnet; c is stiffness coefficient of the fixing spring of electromagnet.

Let us substitute relationship (4) into the right part of equation (2) and solve system (1)–(3) relative to higher derivatives. As a result, we obtain a mathematical model of disturbed motion of the closed fuel feed system

$$\frac{d\Delta\omega(t)}{dt} = -\frac{1}{T_d}\Delta\omega(t) + \frac{k_d}{T_d}\Delta h(t) - \frac{k_f}{T_d}\Delta M_H(t);$$

$$\frac{d^2\Delta z(t)}{dt^2} = -\frac{T_{2m}}{T_{1m}^2}\frac{d\Delta z(t)}{dt} - \frac{1}{T_{1m}^2}\Delta z(t) + \frac{k_m}{cT_{1m}^2}\left[k_\omega \Delta\omega(t) + k_h \Delta h(t)\right];$$

$$\frac{d\Delta h(t)}{dt} = -\frac{1}{T_g}\Delta h(t) + \frac{1}{T_g}\Delta z(t). \quad (5)$$

Let us introduce into examination a vector of state of the closed system of fuel feed

$$X(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \end{bmatrix} = \begin{bmatrix} \Delta\omega(t) \\ \Delta z(t) \\ \frac{d\Delta z(t)}{dt} \\ \Delta h(t) \end{bmatrix}$$

and write down system (5) in the normal Cauchy form:

$$\dot{x}_1(t) = -\frac{1}{T_d}x_1(t) + \frac{k_d}{T_d}x_4(t) - \frac{k_f}{T_d}\Delta M_H(t);$$

$$\dot{x}_2(t) = x_3(t);$$

$$\dot{x}_3(t) = -\frac{T_{2m}}{T_{1m}^2}x_2(t) - \frac{1}{T_{1m}^2}x_3(t) + $$
$$+\frac{k_m}{cT_{1m}^2}k_\omega x_1(t) + \frac{k_m}{cT_{1m}^2}k_h x_4(t);$$

$$\dot{x}_4(t) = -\frac{1}{T_g}x_4(t) + \frac{1}{T_g}x_2(t). \quad (6)$$

Let us write down system (6) in the vector-matrix form

$$\dot{X}(t) = A(k_\omega, k_h)X(t) + BF(t),$$

where $A(k_\omega, k_h)$ is natural matrix of system (7); B is the matrix of control; F(t) is the vector of external disturbances. Matrices $A(k_\omega, k_h)$, B and vector F(t) take the following form

$$A(k_\omega,k_h) = \begin{bmatrix} -\frac{1}{T_d} & 0 & 0 & \frac{k_d}{T_d} \\ 0 & 0 & 1 & 0 \\ \frac{k_m k_\omega}{cT_{1m}^2} & -\frac{1}{T_{1m}^2} & -\frac{T_{2m}}{T_{1m}^2} & \frac{k_m k_h}{cT_{1m}^2} \\ 0 & \frac{1}{T_g} & 0 & -\frac{1}{T_g} \end{bmatrix};$$

$$B = \begin{bmatrix} -\frac{k_f}{T_d} \\ 0 \\ 0 \\ 0 \end{bmatrix}; \quad F(t) = \Delta M_H(t).$$

Then characteristic equation of the closed fuel feed system is written down as

$$\det\left[A(k_\omega,k_h) - Es\right] = T_d T_g T_{1m}^2 s^4 +$$
$$+T_m\left(T_g T_{2m} + T_{1m}^2\right)s^3 + T_d\left(T_g + T_{2m}\right)s^2 +$$
$$+T_d\left(1 - \frac{k_m}{c}k_h\right)s + \left(1 - \frac{k_m}{c}k_h\right) - \frac{k_m k_d}{c}k_\omega = 0. \quad (7)$$

In the plane of varied parameters (k_ω, k_h), we shall build the lines of equal stability level; for this purpose, we shall replace $s=\alpha+j\omega$ [14] in characteristic equation (7). Assigned by the magnitude $\alpha\leq 0$ and by changing value of ω from zero to infinity, in plane (k_ω, k_h) we obtain the line of equal stability level, which limits region G_α. Inside region G_α, stability margin of the system, by which we understand a distance from an imaginary axis of plane of roots of characteristic equation (7) to the nearest valid root or the nearest pair of complex-conjugate roots, not less than $\alpha<0$. At certain $\alpha=\alpha^*<0$, region G_α degenerates into a point or the line of maximum stability margin.

Substituting $s=\alpha+j\omega$ into equation (7), we obtain

$$T_d T_g T_{1m}^2\left\{\left[\left(\alpha^2-\omega^2\right)^2 - 4\alpha^2\omega^2\right] + j4\alpha\omega\left(\alpha^2-\omega^2\right)\right\} +$$
$$+T_d\left(T_g T_{2m} + T_{1m}^2\right)\left[\left(\alpha^3 - 3\alpha\omega^2\right) + j\left(3\alpha^2\omega - \omega^3\right)\right] +$$
$$+T_d\left(T_g + T_{2m}\right)\left[(\alpha^2-\omega^2) + j2\alpha\omega\right] +$$
$$+T_d\left(1 - \frac{k_m}{c}k_h\right)(\alpha + j\omega) +$$
$$+\left(1 - \frac{k_m}{c}k_h\right) - \frac{k_m k_d}{c}k_\omega = 0. \quad (8)$$

Complex magnitude is equal to zero in case when its real and imaginary parts are equal to zero, therefore, from relationship (8), we obtain:

$$T_d T_g T_{1m}^2\left[(\alpha^2-\omega^2)^2 - 4\alpha^2\omega^2\right] +$$
$$+T_d\left(T_g T_{2m} + T_{1m}^2\right)\left(\alpha^3 - 3\alpha\omega^2\right) +$$
$$+T_d\left(T_g + T_{2m}\right)\left(\alpha^2 - \omega^2\right) +$$
$$+\left(T_d\alpha + 1\right)\left(1 - \frac{k_m}{c}k_h\right) - \frac{k_m k_d}{c}k_\omega = 0; \quad (9)$$

$$T_d T_g T_{1m}^2 4\alpha\left(\alpha^2-\omega^2\right) + T_d\left(T_g T_{2m} + T_{1m}^2\right)\left(3\alpha^2 - \omega^2\right) +$$
$$+T_d\left(T_g + T_{2m}\right)2\alpha + T_d\left(1 - \frac{k_m}{c}k_h\right) = 0. \quad (10)$$

Relationships (9) and (10) are the system of two algebraic equations with two unknowns k_ω and k_h. Let us solve system (9) and (10) relative to the unknowns k_ω and k_h

$$k_\omega = \frac{c}{k_m k_d}\left\{\begin{array}{l} -\left(T_g + T_{2m}\right)2\alpha - \\ -\left(T_g T_{2m} + T_{1m}^2\right)\left(3\alpha^2 - \omega^2\right) - \\ -T_g T_{1m}^2 4\alpha\left(\alpha^2 - \omega^2\right) - \\ -T_d\left(T_g + T_{2m}\right)\times\left(\alpha^2 + \omega^2\right) - \\ -T_d\left(T_g T_{2m} + T_{1m}^2\right)\left(2\alpha 3 + 4\alpha\omega^2\right) + \\ +T_d T_g T_{1m}^2\left[\left(\alpha^2-\omega^2\right)^2 - 4\alpha^4\right] \end{array}\right\}; \quad (11)$$

$$k_h = \frac{c}{k_m}\left[\begin{array}{l} 1 + \left(T_g + T_{2m}\right)2\alpha + \\ +\left(T_g T_{2m} + T_{1m}^2\right)\left(3\alpha^2 - \omega^2\right) + \\ +T_g T_{1m}^2 4\alpha\left(\alpha^2 - \omega^2\right) \end{array}\right]. \quad (12)$$

If in relationships (11) and (12) we assume $\alpha=0$, then as a result we obtain the relationships, which describe the limit of stability region of the closed fuel feed system:

$$k_\omega =$$
$$= \frac{c}{k_m k_d}\left\{\left[T_g T_{2m} + T_{1m}^2 - T_d\left(T_g + T_{2m}\right)\right]\omega^2 + T_d T_g T_{1m}^2\omega^4\right\}; \quad (13)$$

$$k_h = \frac{c}{k_m}\left[1 - \left(T_g T_{2m} + T_{1m}^2\right)\omega^2\right]. \quad (14)$$

In Fig. 2, the limit of stability region of the closed fuel feed system, built with the help of relationships (13) and

(14), is shaded in accordance with the rule of shading [13] so that shading is directed inside the stability region.

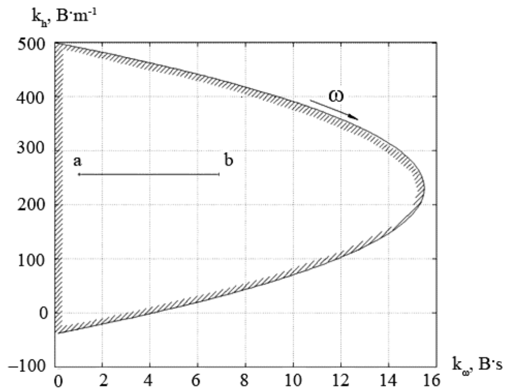

Fig. 2. Stability region and region of maximum stability margin of the closed fuel feed system

Fig. 2 also shows the section of straight line ab parallel to axis k_ω and lagging behind it by distance $k_h^* = 259.28$ V·m^{-1}, to which the lines of equal stability level at $\alpha^*=-44.183$ are contracted, in this case, magnitude α^* represents the maximum stability margin of the fuel feed system. At point a, the value of varied parameter k_ω is $k_{\omega a}=1.4$ V·s, while at point b, the value of the same parameter is $k_{\omega b}=6.8$ V·s.

Values of parameters of the closed fuel feed system, when constructing the stability region and the region of maximum stability margin, were taken to be equal to: $T_d=0.3$ s; $T_{1m}^2=0{,}15\cdot10^{-4}$ s^2; $T_{1m}=1.51\cdot10^{-4}$ s; $T_{2m}=0.6\cdot10^{-2}$ s; s=100 N·m^{-1}; km=0.2 N·V^{-1}; $k_d=-10^3$ m^{-1}·s^{-1}.

Stability margin of the automatic control system is closely connected with another indicator – speed of response, which implies the time of attenuation of transient processes in the closed system. These indicators for linear systems of automatic control are connected by the following empirical dependence

$$t_n = \frac{3}{|\alpha^*|}.$$

The larger is the stability margin of system α^*, the higher is its speed of response.

It was indicated above, that the regulatory characteristics of all-mode regulator with electronic control unit were close to vertical. This circumstance is the reason for the fact that even a small change in angular velocity of crankshaft $\Delta\omega(t)$ leads to a significant change in the displacement of the fuel pump lath. However, the magnitude of displacement of lath is limited and does not exceed magnitude $h^*=12.5$ mm. Consideration of this limitation leads to the fact that the mathematical model of disturbed motion of the closed fuel feed system becomes nonlinear and takes the form

$$\dot{x}_1(t) = -\frac{1}{T_d}x_1(t) + \frac{k_d}{T_d}x_5(t) - \frac{k_f}{T_d}\Delta M_H(t);$$

$$\dot{x}_2(t) = x_3(t);$$

$$\dot{x}_3(t) = \frac{k_m}{cT_{1m}^2}k_\omega x_1(t) - \frac{1}{T_{1m}^2}x_2(t) - \frac{T_{2m}}{T_{1m}^2}x_3(t) + \frac{k_m}{cT_{1m}^2}k_h x_5(t);$$

$$\dot{x}_4(t) = \frac{1}{T_g}x_2(t) - \frac{1}{T_g}x_5(t).$$

$$x_5(t) = \begin{cases} x_4(t) & \text{at } |x_4(t)| \le h^*; \\ h^*\operatorname{sign}x_4(t) & \text{at } |x_4(t)| > h^*. \end{cases} \qquad (15)$$

Fig. 3 shows solutions for system (15) at initial conditions $x_1(0)=10$ s^{-1}; $x_2(0)=x_3(0)=x_4(0)=0$ and at the values of varied parameters k_ω and k_h corresponding to points *a* and *b* in Fig. 2.

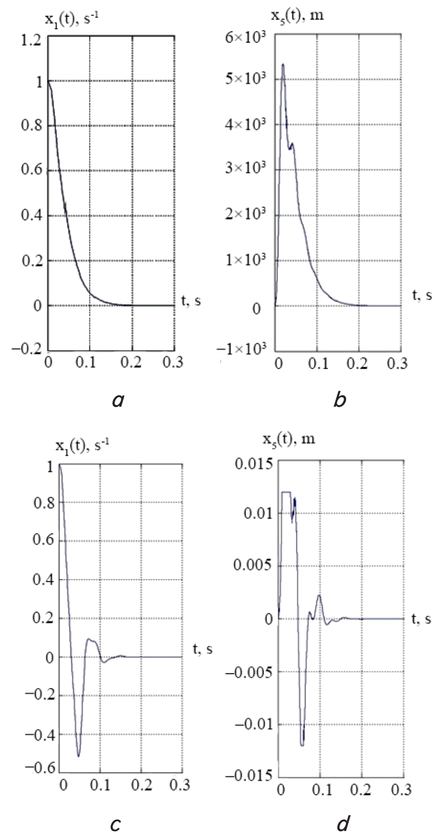

Fig. 3. Processes in the closed fuel feed system: *a, b* – correspond to point *a* in Fig. 2; *c, d* – correspond to point *b* in Fig. 2

Analysis of Fig. 3 allows us to draw a conclusion that speed of response of the nonlinear closed system (15) at maximum stability margin does not exceed $t_n=0.2$ s at points *a* and *b*. The processes, which correspond to point *a*, are of aperiodic character, while the processes, which correspond to point *b*, are of oscillatory nature with the lath of fuel pump entering limitation $\|x_5(t)=h^*|$. This indicates a decrease in fuel efficiency of the diesel engine at displacing its operating point from position *a* to position *b*. Thus, the values of the varied parameters of electronic unit of stabilizer, which provide for high dynamic accuracy of the closed fuel feed system, are: $k_\omega^*=1.4$ V·s; $k_h^*=259.28$ V·m^{-1}.

5. Parametric synthesis of the all-mode fuel feed regulator, providing invariance of the system to the action of external disturbances

Differential equation (1) describes dynamics of the control object – transport diesel engine, while differential equations (2) and (3), along with relationship (4), describe dynamics of the all-mode fuel feed regulator. We convert the equations of mathematical model (1)–(4) according to Laplace:

$$\left(T_d s+1\right)\Omega(s)=k_d H(s)-k_f L\left\{\Delta M_H(t)\right\};$$

$$\left(T_{1m}^2 s^2+T_{2m}s+1\right)Z(s)=\frac{k_m}{c}\left[k_\omega \Omega(s)+k_h H(s)\right];$$

$$\left(T_g s+1\right)H(s)=Z(s),$$

where through Ω(s), H(s) and Z(s) we designate the Laplace transforms of the corresponding time functions Ω(s)=L{Δω(t)}; H(s)=L{Δh(t)}; Z(s)=L{Δz(t)}.

Then a transfer function of the control object and automatic regulator may be represented in the form:

$$W_0(s)=\frac{\Omega(s)}{H(s)}=\frac{k_d}{T_d s+1}; \tag{16}$$

$$W_a(s)=\frac{H(s)}{\Omega(s)}=\frac{k_m k_\omega}{c\left[\left(T_{1m}^2 s^2+T_{2m}s+1\right)\left(T_g+1\right)-\frac{k_m}{c}k_h\right]}. \tag{17}$$

Transfer function of the disconnected system is equal to the product of transfer function (16) and (17)

$$W_p(s)=\frac{k_m k_\omega k_d}{c\left[\left(T_{1m}^2 s^2+T_{2m}s+1\right)\left(T_g+1\right)-\frac{k_m}{c}k_h\right]\left(T_d s+1\right)}. \tag{18}$$

The denominator of transfer function (18) is represented in the normal form according to decreasing degrees s. As a result, we have

$$W_p(s)=$$

$$=\frac{\frac{k_m}{c}k_\omega k_d}{T_d T_g T_{1m}^2 s^4+T_d\left(T_{1m}^2+T_g T_{2m}\right)s^3+T_d\left(T_g+T_{2m}\right)s^2+T_d\left(1-\frac{k_m}{c}k_h\right)s+\left(1-\frac{k_m}{c}k_h\right)}. \tag{19}$$

An analysis of relationship (19) makes it possible to draw a conclusion that the closed fuel feed system of transport diesel engine, examined in the previous chapter, demonstrates astaticism of zero order [15]. Hence it follows that the system possesses a rather low static accuracy.

If we assume that the gain factor of electronic unit k_h satisfies the condition

$$1-\frac{k_m}{c}k_h=0, \tag{20}$$

then transfer function of disconnected system (19) takes the form

$$W_p(s)=$$

$$=\frac{\frac{k_m}{c}k_\omega k_d}{s^2\left[T_d T_g T_{1m}^2 s^2+T_d(T_{1m}^2+T_g T_{2m})s+T_d(T_g+T_{2m})\right]}. \tag{21}$$

It follows from relationship (21) that if condition (20) is satisfied, the closed fuel feed system has astaticism of second order, which provides for the invariance of system to the action of external disturbances and substantially decreases static error of system [16, 17].

On the other hand, if condition (20) is satisfied, it leads to the fact that the coefficient at s in the characteristic equation of closed system (7) becomes zero, which indicates the loss of stability of the closed system. Consequently, there is a contradiction between the property of invariance of the closed control system to the action of external disturbances and the property of its stability, which is usually removed through a compromise when selecting varied parameters of the regulator [18, 19].

Let us select the law of control, realized by electronic unit in the following form [13]

$$\Delta u(t)=k_\omega \Delta\omega(t)+k_h \Delta h(t)+k_{\dot h}\Delta\dot h(t). \tag{22}$$

Then characteristic equation of the closed fuel feed system is written down as

$$T_d T_g T_{1m}^2 s^4+T_d\left(T_{1m}^2+T_g T_{2m}\right)s^3+$$
$$+T_d\left(T_g+T_{2m}-\frac{k_m}{c}k_{\dot h}\right)s^2+$$
$$+\left[T_d\left(1-\frac{k_m}{c}k_h\right)-\frac{k_m}{c}k_{\dot h}\right]s+$$
$$+\left(1-\frac{k_m}{c}k_h\right)-\frac{k_m k_d}{c}k_\omega=0. \tag{23}$$

If in characteristic equation (23) we assume $k_{\dot h}=0$, then equation (23) degenerates into equation (7).

Taking into account condition (20), equation (23) takes the following form

$$T_d T_g T_{1m}^2 s^4+$$
$$+T_d\left(T_{1m}^2+T_g T_{2m}\right)s^3+$$
$$+T_d\left(T_g+T_{2m}-\frac{k_m}{c}k_{\dot h}\right)s^2-$$
$$-\frac{k_m}{c}k_{\dot h}s-\frac{k_m k_d}{c}k_\omega=0. \tag{24}$$

Analysis of characteristic equation (24) leads to the conclusion that at certain specific values of varied parameters k_ω and $k_{\dot h}$ the invariant system of fuel feed control at value of the varied parameter

$$k_h=\frac{c}{k_m} \tag{25}$$

is stable. Let us build the boundary of stability region of the closed invariant fuel feed system in the plane of varied parameters (k_ω, $k_{\dot h}$), for which in equation (24) we replace s=α+jω, highlight real and imaginary parts and make them equal to zero. As a result, we shall obtain the following relationships for constructing the boundary of stability region

$$k_\omega=-\frac{c}{k_m k_d}\times$$
$$\times T_d\left\{\left[T_g+T_{2m}+\left[T_d\left(T_g T_{2m}+T_{1m}^2\right)+T_{1m}^2 T_g\right]\right]\omega^2\right\}\omega^2;$$

$$k_{\dot{h}} = -\frac{c}{k_m} T_d \left(T_d T_{2m} + T_{1m}^2 \right) \omega^2. \quad (26)$$

The boundary of stability region of the closed invariant fuel feed system, built with the help of relationships (26), is given in Fig. 4 (the shading is directed inside stability region).

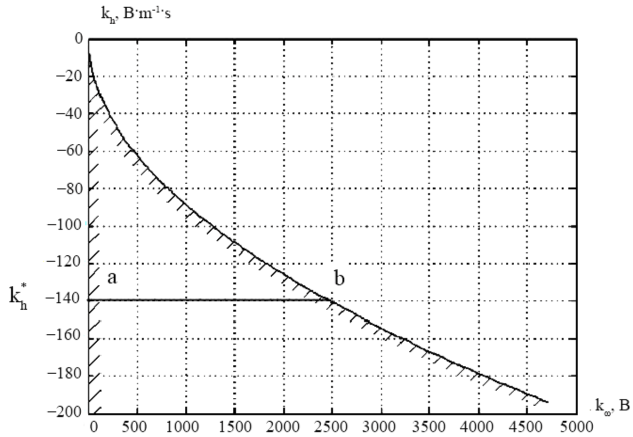

Fig. 4. Stability region of the closed fuel feed system

Inside the stability region, we shall select an arbitrary value of varied parameter $k_{\dot{h}} = k_{\dot{h}}^*$. In this case, possible values of parameter k_ω are located in section (a, b). In this section, we shall select the value of parameter $k_\omega = k_\omega^*$, providing for the maximum stability margin of the closed fuel feed system. For this purpose, we shall assume $k_{\dot{h}} = k_{\dot{h}}^*$ in characteristic equation (24) and express varied parameter k_ω as:

$$k_\omega = -\frac{c}{k_m k_d} \left[\begin{array}{l} -\frac{k_m}{c} k_{\dot{h}}^* s + T_d \left(T_g + T_{2m} - \frac{k_m}{c} k_{\dot{h}}^* \right) s^2 + \\ + T_d \left(T_g + T_{2m} + T_{1m}^2 \right) s^3 + T_d T_g T_{1m}^2 s^4 \end{array} \right]. \quad (27)$$

In the right part of relationship (27), we shall introduce designations:

$$a_1 = -\frac{k_m}{c} k_{\dot{h}}^*; \quad a_2 = T_d \left(T_g + T_{2m} - \frac{k_m}{c} k_{\dot{h}}^* \right);$$

$$a_3 = T_d \left(T_g + T_{2m} + T_{1m}^2 \right); \quad a_4 = T_d T_g T_{1m}^2.$$

As a result, we have

$$k_\omega = \frac{c}{k_m k_d} \left(a_1 s + a_2 s^2 + a_3 s^3 + a_4 s^4 \right). \quad (28)$$

In (28), we assume s=α+jω, and we will highlight the real and imaginary parts in the obtained relationship:

$$\mathrm{Re}\, k_\omega = \\ = \frac{c}{k_m k_d} \left\{ \alpha a_1 + \left(\alpha^2 - \omega^2 \right) a_2 + a_3 \left(\alpha^3 - 3\alpha\omega^2 \right) + a_4 \left[\left(\alpha^2 - \omega^2 \right)^2 - 4\alpha^2 \omega^2 \right] \right\}; \quad (29)$$

$$\mathrm{Im}\, k_\omega = \\ = \frac{c}{k_m k_d} \left\{ a_1 \omega + a_2 2\alpha\omega + a_3 \left(3\alpha^2 \omega - \omega^3 \right) + a_4 4\alpha\omega \left(\alpha^2 - \omega^2 \right) \right\}. \quad (30)$$

Fig. 5 shows the boundary of stability region and lines of the equal stability level of the closed fuel feed system, built in the plane of complex parameter k_ω [20] with the help of relationships (29) and (30) at changing ω from zero to infinity at different values α<0.

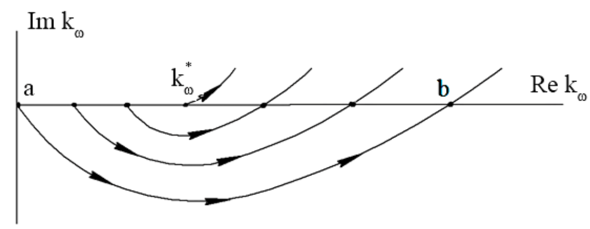

Fig. 5. Lines of equal stability level in the plane of comprehensive parameter k_ω

Each of the lines of equal stability level limits section ab along the real axis. At certain α=α*<0, section ab contracts to point k_ω^*, which is the point of maximum stability margin of the closed system.

Table 1 contains values of varied parameters of the electronic unit of invariant all-mode fuel feed regulator and corresponding values of stability margin of the closed fuel feed system α*.

Table 1

Values of varied parameters of electronic unit

k_h^*, V·m^{-1}	500	500	500	500	500	500	500	500
$k_{\dot{h}}^*$, V·m^{-1}·s	–10	–20	–30	–50	–100	–200	–500	–1000
k_ω^*, V·m	0,0064	0,0143	0,0228	0,0394	0,0815	0,1665	0,4165	0,833
α^*	–1,274	–1,43	–1,515	–1,572	–1,613	–1,67	–1,67	–1,67

An analysis of Table 1 allows us to make a conclusion that the maximum value of magnitude of stability margin of the closed system is equal to α*=–1.67 and is attained at $k_{\dot{h}}^* = -200$ V·m^{-1}·s and $k_\omega^* = 0.1665$ V·s. Further increase in absolute magnitude of varied parameter $k_{\dot{h}}^*$ and, as a result, of parameter k_ω^* does not lead to an increase in stability margin of the closed system.

Let us substitute relationship (22) into right part of differential equation (2). As a result, a normal form of mathematical model of disturbed motion of the closed fuel feed system takes the form:

$$\dot{x}_1(t) = -\frac{1}{T_d} x_1(t) + \frac{k_d}{T_d} x_4(t) + \frac{k_f}{T_d} \Delta M_H(t);$$

$$\dot{x}_2(t) = x_3(t);$$

$$\dot{x}_3(t) = \frac{k_m k_\omega}{c T_{1m}^2} x_1(t) - \frac{1}{T_{1m}^2} \left(1 - \frac{k_m k_{\dot{h}}}{c T_g} \right) x_2(t) - \\ - \frac{T_{2m}}{T_{1m}^2} x_3(t) + \frac{1}{T_{1m}^2} \left(\frac{k_m k_h}{c} - \frac{k_m k_{\dot{h}}}{c T_g} \right) x_4(t);$$

$$\dot{x}_4(t) = -\frac{1}{T_g} x_4(t) + \frac{1}{T_g} x_2(t). \quad (31)$$

The closed fuel feed system is invariant to the action of external disturbance $\Delta M_H(t)$, if the value of varied parameter k_h satisfies condition (20). Taking into account this condition, as well as taking into account a limitation of the magnitude in displacement of the fuel pump lath, mathematical model (31) is written down as

$$\begin{aligned}
&\dot{x}_1(t) = -\frac{1}{T_d}x_1(t) + \frac{k_d}{T_d}x_5(t) + \frac{k_f}{T_d}\Delta M_H(t);\\
&\dot{x}_2(t) = x_3(t);\\
&\dot{x}_3(t) = \frac{k_m k_\omega}{cT_{1m}^2}x_1(t) - \frac{1}{T_{1m}^2}\left(1-\frac{k_m k_{\dot{h}}}{cT_g}\right)x_2(t) -\\
&-\frac{T_{2m}}{T_{1m}^2}x_3(t) + \frac{1}{T_{1m}^2}\left(1-\frac{k_m k_{\dot{h}}}{cT_g}\right)x_5(t);\\
&\dot{x}_4(t) = \frac{1}{T_g}x_2(t) - \frac{1}{T_g}x_5(t);\\
&x_5(t) = \begin{cases} x_4(t) & \text{at} \quad |x_4(t)| \le h^*;\\ h^* \operatorname{sign} x_4(t) & \text{at} \quad |x_4(t)| > h^*. \end{cases}
\end{aligned} \tag{32}$$

Let a change in load torque on crankshaft of the diesel engine take the form, represented in Fig. 6.

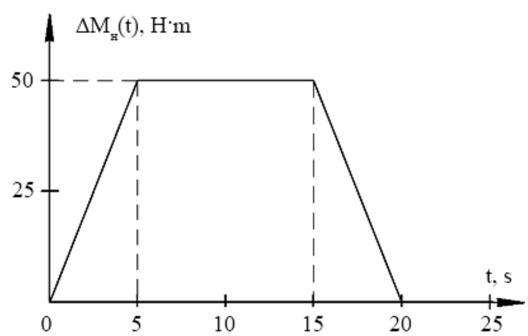

Fig. 6. Change in load torque $\Delta M_H(t)$

Function $\Delta M_H(t)$ is described by relationship F

$$\Delta M_H(t) = \begin{cases} 10t & \text{at} \quad 0 \le t < 5;\\ 50 & \text{at} \quad 5 \le t < 15;\\ 50 - 10(t-15) & \text{at} \quad 15 \le t < 20;\\ 0 & \text{at} \quad t \ge 20. \end{cases} \tag{33}$$

The processes of working out external disturbance (33) are the solutions for the closed system (32), (33) at values of the varied parameters of electronic unit of fuel feed regulator k_ω^*=0.1665 V·s; k_h^*=500 V·m^{-1}; $k_{\dot{h}}^* = -200$ V·m^{-1}·s. They are presented in Fig. 7.

An analysis of these processes allows us to make the following conclusions:

1) if load torque on the crankshaft of engine changes over time, in the examined system there occur dynamic errors, the magnitude of which is proportional to the rate of change in load torque;

2) if the value of disturbing moment is constant, then the magnitude of static error in the examined system tends to zero, that is, the system is invariant to the action of static external disturbances.

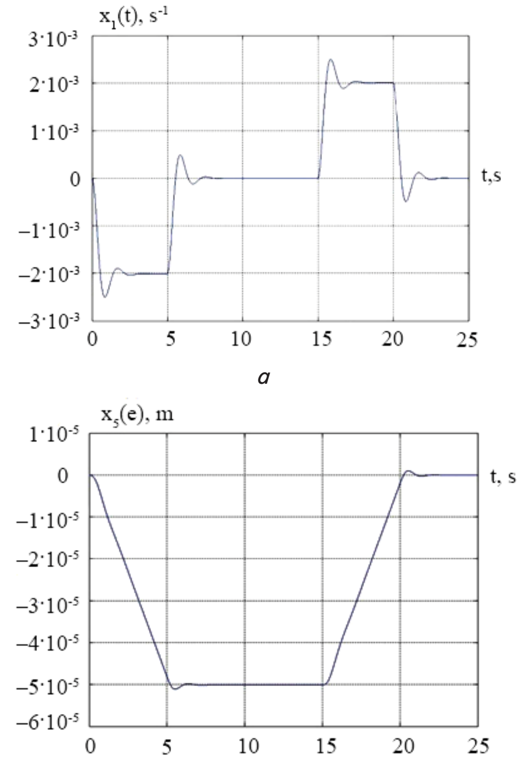

Fig. 7. Processes of working out external disturbances: *a* — process of changing angular velocity of crankshaft; *b* — process of changing a position of lath of fuel pump

6. Algorithms, realized by a digital electronic unit of the all-mode fuel feed regulator

High quality in the control processes for the systems and aggregates of self-propelled wheel and caterpillar vehicles is achieved by the use of digital electronic units, including fuel feed systems of transport diesels engines [21]. A schematic of the digital electronic unit of fuel feed control of transport diesel engine is represented in Fig. 8, where the following designations are accepted: CAC is the converter "analog-to-code"; FB are the digital Butterworth low-frequency filters; FL is the digital Lanczos low-frequency filter; SM is the switch of operation modes of the diesel engine; R is the relay; W is the winding of relay; K1, K2 are the contacts of relay; CCA is the converter "code-to-analog".

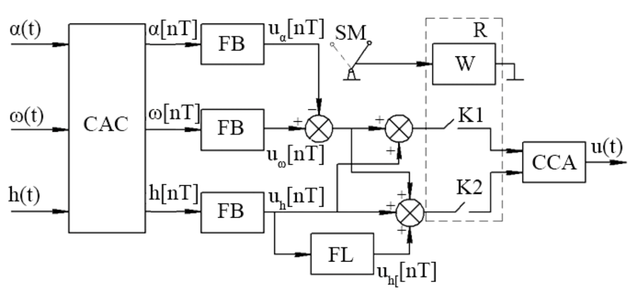

Fig. 8. Digital electronic control unit

The results, obtained above, lead to a conclusion that during motion of the vehicle along the rough terrain and under tough road conditions, when a significant loading change within a short time interval occurs, it is expedient to use the all-mode regulator with high dynamic accuracy of control, the electronic unit of which implements the law of control (4). When moving along the routes with high-quality road surface, but with frequent ascends and descents, it is expedient to use the all-mode regulator, which renders the property of invariance to the action of slowly changing external disturbances to the closed system of fuel feed, as well as low static error of control. Transition from one mode to another is accomplished by a driver with the help of switch of modes SW that controls operation of relay R with the normally closed contact K1 and by the normally disconnected contact K2. Butterworth filters FB perform the filtration of high-frequency interferences of grid functions α[nT], ω[nT] and h[nT], where T is the period of quantization of digital electronic unit.

Butterworth filters of second order have a discrete transfer function, written down in the form [22, 23]

$$W_b(z)=\frac{a_0+a_1z^{-1}+a_0z^{-2}}{b_0+b_1z^{-1}+b_2z^{-2}}. \qquad (34)$$

Lanczos filters are used for evaluating grid function $u_{\dot{h}}[nT]$ based on grid function $u_h[nT]$. A discrete transfer function of the Lanczos filter of second order is written down as [24]

$$W_b(z)=c_0+c_1z^{-1}-c_1z^{-3}-c_0z^{-4}. \qquad (35)$$

Parameters of digital filters (34) and (35) are [18]:

a_0=0.08073; a_1=0.16147;

b_0=1.48256; b_1=–1.83854; b_2=0.67789;

c_0=5; c_1=2.5.

In the mode of improved dynamic accuracy, the digital electronic unit of the all-mode fuel feed regulator in accordance with relationships (4) and (34) realizes the following control algorithms

$$\Delta u[nT]=k_\omega\Delta u_\omega[nT]+k_h\Delta u_h[nT];$$

$$\Delta u_\omega[nT]=\frac{a_0}{b_0}\Delta\omega[nT]+\frac{a_1}{b_0}\Delta\omega[(n-1)T]+\frac{a_0}{b_0}\Delta\omega[(n-2)T]-\frac{b_1}{b_0}\Delta u_\omega[(n-1)T]-\frac{b_2}{b_0}\Delta u_\omega[(n-2)T];$$

$$\Delta u_h[nT]=\frac{a_0}{b_0}\Delta h[nT]+\frac{a_1}{b_0}\Delta h[(n-1)T]+\frac{a_0}{b_0}\Delta h[(n-2)T]-\frac{b_1}{b_0}\Delta u_h[(n-1)T]-\frac{b_2}{b_0}\Delta u_h[(n-2)T]. \qquad (36)$$

In the mode of increased static accuracy, in which the property of invariance of the closed fuel feed system to the action of slowly changing disturbances is provided, the electronic unit, in accordance with relationships (22), (34) and (35), implements the following control algorithms:

$$\Delta u[nT]=k_\omega\Delta u_\omega[nT]+k_h\Delta u_h[nT]+k_{\dot{h}}\Delta u_{\dot{h}}[nT];$$

$$\Delta u_\omega[nT]=\frac{a_0}{b_0}\Delta\omega[nT]+\frac{a_1}{b_0}\Delta\omega[(n-1)T]+\frac{a_0}{b_0}\Delta\omega[(n-2)T]-\frac{b_1}{b_0}\Delta u_\omega[(n-1)T]-\frac{b_2}{b_0}\Delta u_\omega[(n-2)T];$$

$$\Delta u_h[nT]=\frac{a_0}{b_0}\Delta h[nT]+\frac{a_1}{b_0}\Delta h[(n-1)T]+\frac{a_0}{b_0}\Delta h[(n-2)T]-\frac{b_1}{b_0}\Delta u_h[(n-1)T]-\frac{b_2}{b_0}\Delta u_h[(n-2)T];$$

$$\Delta u_{\dot{h}}[nT]=c_0\Delta u_h[nT]+c_1\Delta u_h[(n-1)T]-c_1\Delta u_h[(n-3)T]-c_0\Delta u_h[(n-4)T]. \qquad (37)$$

The described all-mode fuel feed regulator with the digital electronic control unit for the tank diesel engine 6TD-2 was created as a component of the tank information-control system (TICS) at Lvov Scientific Research Radio-Technical Institute (Ukraine) with direct participation of authors of present article. Tests of the regulator demonstrated that fuel efficiency of the diesel engine increases within the same limits as when using the regulator, depicted in Fig. 1 and described in articles [3–9]. However, the accuracy of maintaining tank motion speed, assigned by the driver, grows by 2÷3 times when using the digital regulator, which enables the motion of tank column en route with a higher speed and at lower safety range between moving objects of armored vehicles. The tests also showed that the use of Butterworth and Lanczos filters of second order in algorithms (36) and (37) is sufficient enough to provide for the required accuracy of regulator at the magnitude of quantization period T=0.002 s [25].

7. Discussion of results of solving the problem on structural-parametric synthesis of the electronic control unit of fuel feed system of the transport diesel engine

The conclusion was made as a result of conducted studies that in the fuel feed system of the transport diesel engine, it is expedient to use a two-channel electronic control unit. Selecting an appropriate channel of the electronic control unit is done by the driver depending on road conditions. This scheme of electronic unit makes it possible to minimize both dynamic errors, which appear during motion of vehicle in the rough terrain, when there is a significant change in load within a short time interval, and the static errors, which appear when moving along the routes with high-quality road surface but with lengthy ascends and descents. Thus, the proposed fuel feed system is in a certain sense universal. It should be used, first of all, in vehicles of high cross-country capability, in particular, in the wheeled and tracked vehicles with military purpose. Thus, specialists at Kharkov Design

Bureau of Machine Building named after A. A. Morozov are planning, after completion of road tests, to use the diesel engine of series 3TD with the digital electronic block of fuel feed in the wheel armored transporter BTR-4 instead of the diesel engine “DEUTZ” (Germany).

A replacement of the diesel engine “DEUTZ” with the diesel engine 3TD, made in Ukraine, will make it possible to substantially reduce production cost of the indicated armored transporter.

8. Conclusions

1. The channel, providing high dynamic accuracy of fuel feed control, contains a sensor of angular velocity of crankshaft rotation of the diesel engine, as well as the sensors of position of fuel pump lath and the pedal of fuel feed control, the outputs of which are connected to inputs of the electronic unit, which implements linear combination of the input signals of sensors.

2. The channel, providing for invariance of the fuel feed system to the action of external disturbances, realizes a control algorithm, which uses, in addition to the output signals of the above-indicated sensors, information about the velocity of displacement of the fuel pump lath of the diesel engine.

3. High accuracy and interference protection of the closed fuel feed system may be achieved by using a digital electronic control unit with the implementation of digital Butterworth and Lanczos low-frequency filters.

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ESTIMATION OF HEAT FIELD AND TEMPERATURE MODELS OF ERRORS IN FIBER-OPTIC GYROSCOPES USED IN AEROSPACE SYSTEMS

D. Breslavsky
Doctor of Technical Sciences, Professor, Head of Department*
E-mail: brdm@kpi.kharkov.ua

V. Uspensky
Doctor of Technical Sciences, Associate Professor*
E-mail: uspensky61@gmail.com

A. Kozlyuk
Postgraduate student*
E-mail: alenakozlyk@gmail.com

S. Pashchenko
Postgraduate student*
E-mail: sergeypaschenkospu@gmail.com

O. Tatarinova
PhD, Associate Professor*
E-mail: ok.tatarinova@gmail.com

Yu. Kuznyetsov
PhD, Associate Professor, head of laboratory
Theoretical Laboratory
PJSC «HARTRON»
Akademika Proskury str., 1, Kharkiv, Ukraine, 61070
E-mail: kuznyetsovy@gmail.com

*Department of Computer Modeling of Processes and Systems
National Technical University "Kharkiv Polytechnic Institute"
Kyrpychova str., 2, Kharkiv, Ukraine, 61002

Розроблено та досліджено чисельно-аналітичні моделі теплового нестаціонарного процесу та пов'язаної з ним похибки вимірювань волоконно-оптичних гіроскопів (ВОГ). З урахуванням значень температури, отриманих шляхом моделювання, а також результатів калібрування конкретних ВОГ, побудовано прогнози величин похибок вимірювань. Проведено порівняння результатів моделювання з експериментальними даними. Наведено рекомендації з розвитку результатів та їхнього практичного використання

Ключові слова: гіроскоп, скінченноелементна модель, нестаціонарна теплопровідність, інструментальні похибки,температурна модель, калібрування

Разработаны и исследованы численно–аналитические модели теплового нестационарного процесса и связанной с ним погрешности измерений волоконно-оптических гироскопов (ВОГ). С учетом значений температуры, полученных путем моделирования, а также результатов калибровки конкретных ВОГ, выполнен прогноз величин погрешностей измерений. Проведено сравнение результатов моделирования с экспериментальными данными. Приведены рекомендации по развитию результатов и их практическому использованию

Ключевые слова: гироскоп, конечноэлементная модель, нестационарная теплопроводность, инструментальные ошибки, температурная модель, калибровка

1. Introduction

Fiber-optic gyroscopes (FOG) have been widely used recently in the control and navigation of aerospace systems [1]. Ensuring accuracy of measurement of external influences on instruments is an important technical problem. One of the main factors influencing FOG readings is the environment temperature variation. For the instruments installed aboard flying vehicles, this temperature can vary within a wide range. For example, temperature fluctuations can range