CONTROL AND FUEL FEED SYSTEMS

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Summary

A short history of development and principles of construction of automatic control systems for heat engines have been considered. Features of such systems used in diesels, in engines with forced fuel ignition, and in gas turbines have been analysed. Most well-known constructions of fuel-feed systems, designed for the mentioned varieties of heat engines have been presented.

1. Introduction

Fuel feed systems in heat engines are intended for the controlled supply of fuel into the combustion chamber during each working cycle, thus providing in a general case the required fuel dose (cycle feed), the beginning and duration of fuel feed, the characteristics of fuel feed (i.e. distribution of the fed fuel according to the rotation angle of the engine crankshaft), good fuel dispersion and its even distribution within the combustion chamber. For the most effective work, control of the mentioned parameters of fuel feed process must be carried out in accordance with engine working regime and change of its operation conditions. That is why fuel feed systems usually present an integral unit which unites fuel feed apparatus itself and fuel feed control devices (governors).

2. Classification of control systems and short history of their development

Fuel feed control devices, used in heat engines, are intended for maintaining the working regimes of the given engines or their change in accordance with the required algorithm. Purposes of control may be providing constancy of a certain parameter (this task is carried out by stabilization systems), change of this parameter according to the given algorithm in the function of time or some other parameter (program control systems) or in accordance with the algorithm which is known beforehand and determined in the process of control, taking into account the changing external disturbing actions f(t) (tracking systems).

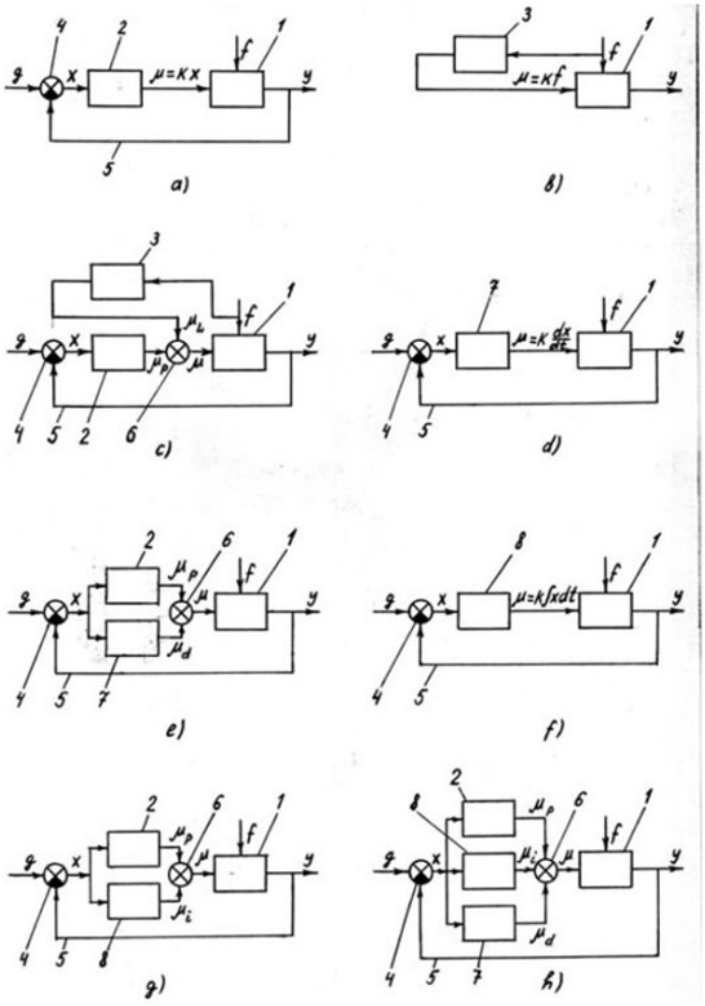

Figure 1. Functional scheme of ACSR with a governor, operating according to deviation (P-governor) (a); with a governor, operating according to disturbance (b); with a combined governor according to deviation and disturbance (c); with D-governor (d); with PD-governor (e); with I-governor (f); with PI-governor (g); with PID-governor (h)

Master action g(t), which determines the required character of output parameter y(t), is fed on the entry of the systems of the first two types (Figure 1,a).

In the stabilization systems controlling input is constant, but in the program control systems it presents a function of time or some other parameter. In the tracking systems, the controlling input g(t) is a random function of time. It is desirable that the output parameter y(t) of the system should accurately replicate the change in master action g(t), i.e. the equality y(t)=g(t) must be provided.

Stabilization systems, the so-called automatic control systems of the regulatory type - ACSR (a variety of automatic control systems - ACS) are most widely spread. The engine usually has several controlled parameters (output parameters y(t) ACS) and control elements, which are affected by the corresponding governors. Automatic governors of rotational speed ω_e of the engine shaft, of injection advance angle θ (or ignition) etc. are widely used.

Here, the engine is the object of control, parameters ω_e, θ are controlled parameters, and the assamblage of the interacting object 1 and governor 2 (Figure 1,a) are the system of automatic control. ACS with one controlled parameter are called one-parametric, but ACS with several controlled parameter - many-parametric. Simultaneous control of several parameters, which are interdependent, is carried out in the systems of interdependent control.

To solve the required control problem, control action on the object control element is organized. Control action μ(t) in ACS is usually a function of the dynamic error x(t), determined as a deviation of the controlled parameter y(t) from its given value g(t), i.e. x(t)=g(t)-y(t). The signal of error x(t) is produced on the element of corison (summarizing element) 4 (Figure 1,a), on which master action g(t) is fed, and through the line 5 of the main negative feedback - controlled parameter y(t) is fed (the cross-hatched sector of the summarizing element 4 means change of the signal sign y(t)).

In this case a closed loop of control is formed, and ACSR becomes closed. Such a principle of ACSR operation is called the principle of control according to the controlled parameter deviation or the principle of Polzunov-Watt.

Governors functioning according to the deviation were developed in connection with the wide use of steam piston engine . The first industrial governor was created in 1765 by the Russian mechanical engineer I.I.Polzunov for his steam engine. It was the governor of water level H in a boiler (Figure 2,a).

When the water level H_{min} is minimum, the passage section of tube 2 and water feed G into the boiler are maximum. As water level H rises, throttle 3 shutts off the passage section of tube 2 under the action of float 1, and water feed stops completely, when the level is maximum H_{max} (G = 0). The difference $\Delta H=H_{max}-H_{min}$ is called the irregularity of work or static error x_{st}, which determines the accuracy of providing constancy of the given value of a controlled parameter and which is a component of dynamic error x(t).

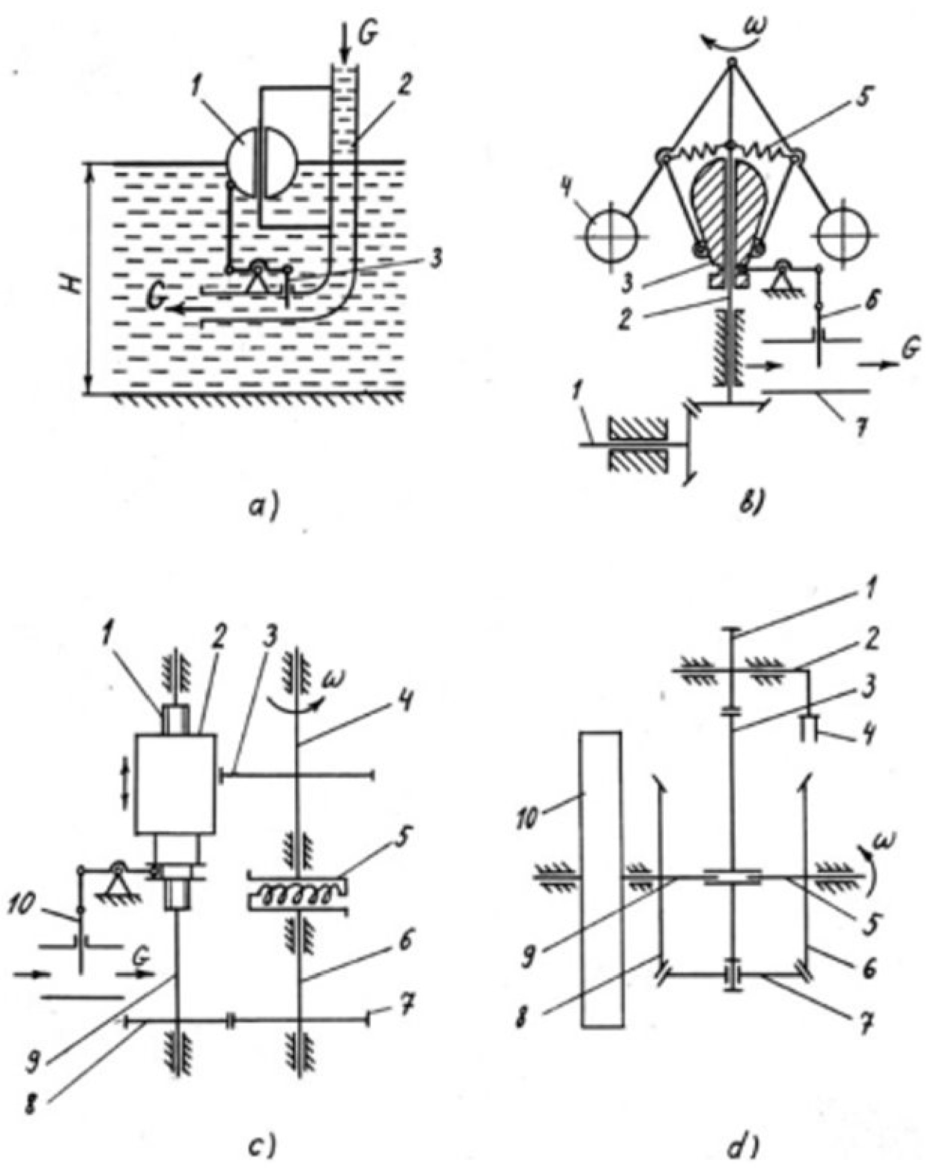

Figure 2. Automatic governors: a - I.I. Polzunov's; b - D. Watt's; c - Ponsele's; d - brothers Seamens'

The centrifugal governor of rotational speed of the steam engine shaft, designed in 1784 by the English mechanical engineer D.Watt, also operates according to deviation (Figure 2,b). When the excess of the given value of rotational speed ω of roller 2, connected to shaft 1 of the steam engine, takes place, weights 4 move apart on a big radius, deform springs 5 and through clutch 3 shift throttle 6, shutting off passage section of stub tube 7. This causes decrease in steam feed G to the steam engine and a reduction of the turning moment M of shaft 1. The difference $\Delta\omega=\omega_{max}-\omega_{min}$, like in the previous case, makes up a static error (irregularity) of control.

ACSR, operating according to the principle of Polsunov-Watt, form the algorithm of control (a dependence between the input and output parameters of the governor). This algorithm is called proportional (P) or static control and is expressed by the dependence

$\mu(t)=kx(t)$, where "k" is the factor of the governor, ACSR, which has a static error x_{st}, caused by the given external action, is called static with respect to this action. If $x_{st}=0$, ACSR is called astatic with respect to this action. The use of P-control does not enable to create an astatic ACSR. That is why other principles of control are also used.

Sometimes the so-called control on disturbing action f(t) - according to the load on the engine (L-control) - is referred to such control principles. When L-control, first suggested by the French scientist Ponsele in 1830, takes place, controlling action $\mu(t)$ is produced by compensation device 3 (L-governor, Figure 1,b), depending on disturbance f(t), and looks like $\mu(t)=kf(t)$, and it is fed on object 1. In this case the principle of compensation of disturbances is realized. As in ACSR, operating on disturbance, the line of the main negative feedback is absent, such ACSR is open.

Control according to disturbance is realized by the governor, in which engine shaft 4 (Figure 2,c) and load shaft 6 are connected by an elastic clutch 5, which fulfils the functions of a sensitive element. Load change causes the relativel turning of shafts 4 and 6. As these shafts are connected to movable gear 2 and to shaft 9 through gears 3,7,8, the turning of shaft 9 relative to gear 2 takes place. As a result, gear 2 shifts along screw 1, and through the system of links and levers moves throttle 10, which changes the feed of working medium G to the engine. Poncele's governor measures directly the change of the engine load, but not the rotational speed of the engine shaft. This enables the creation of an astatic ACSR and to increase its speed, as the change of a speed regime is just the consequence of the load change. But such a governor cannot keep the given speed regime, as the reasons for its change may be not only the load changes. Therefore, control according to disturbance is used only in combination with control according to deviation. In this case ACSR contains P-governor 2 (Figure 1,c), L-governor 3, and produces two controlling pulses - of the shaft rotational speed μ_P and of the engine load μ_L, which are summed up on summarizing element 6: $\mu(t)=k_Px(t)+k_Lf(t)$. The governor becomes two-pulsed, and ACSR becomes combined.

According to the differential (D) principle of control the algorithm of control is determined as $\mu(t)=kdx/dt$ (Figure 1,d), i.e. the controlling action $\mu(t)$, which is formed by the D-governor 7, must be proportional not to the signal of error x(t), but to its derivative dx/dt. Such a governor, first suggested by brothers Seamens (Germany) in 1845, contains the differential gearing, one of gears 6 (Figure 2,d) of which is mounted on shaft 5 of the engine. Rotation of gear 6 through differential gear 7 drives gear 8, shaft 9 of the governor and flywheel 10, which tends to keep the rotation with a constant speed. When the engine load is changed, the angular acceleration on shaft 5 and gear 6 appears, but gear 8 with flywheel 10 keeps the previous rotational speed due to their sluggishness. That is why, quadrant 3 turns relative to the axis of rotation of shafts 5,9, and through gear 1, controlling roller 2 and link 4 acts on the controlling element - rack or throttle (not shown in Figure 2,d).

This governor, which is a differentiating device, and is called an accelerometer, responds to the speed of change of the controlled parameter - to the angular acceleration of the engine shaft. The pulse of the angular acceleration may increase the speed of ACSR, as at the moment of load change it is more considerable than the pulse of deviation of the shaft rotational speed. But the governor, responding only to the change of the angular acceleration, cannot keep the given speed regime as it does not respond to the changes of the controlled parameter. Therefore, the D-governor 7 (Figure 1,e) is used only in combination with the P-governor 2. Such a combined governor, producing two controlling pulses - according to rotational speed μ_P and according to shaft acceleration μ_D, is called a proportional-differential (P-D-governor) and forms the controlling action, and looks like $\mu(t)=k_P x(t)+k_D dx/dt$.

The drawback of P- and D-governors is the static error x_{st}. The forming of the integral (I) algorithm of control like $\mu(t)=k_I\int x(t)dt$, where $\mu(t)$ depends linearly on the accumulated time error of control x(t), enables the increase of the accuracy of ACSR operation in steady-state regimes. Integration of the signal x(t) is carried out by I-governor 8 (Figure 1,f), which enables to create an astatic ACSR, i.e. to provide $x_{st}=0$. But this governor, which is an integrating device, increases ACSR tendency to waves. Therefore, to provide the required quality of ACSR operation, I-governor 8 (Figure 1,g) is used only in combination with P-governor 2. Such combined proportional-plus-integral (PI) governors form algorithm of control like $\mu(t)=k_P x(t)+k_I\int x(t)dt$. Due to the presence of the integral component μ_I, PI-governors do not have a static error. The required qualitative indices of ACSR operation in unsteady-state regimes are provided by the proportional component μ_P of the algorithm of control.

Dynamic qualities of ACSR with PI-governor are made better, when introducing the differential component μ_D to the algorithm of control. This causes the forming of proportional-integral-differential (PID) algorithm - $\mu(t)=k_P x(t)+k_I\int x(t)dt+k_D dx/dt$. This algorithm is produced by PID-governor, which contains P,I,D-governors (positions 2,7,8 in Figure 1,h). Such functioning of ACSR provides considerable improvement of static and dynamic properties of ACSR. Besides the considered algorithms of control nonlinear algorithms, for example relay ones, are used.

The first governors fulfilled direct control (governors of direct action), where the sensitive element directly acted on the controlling element of the object. But direct control is possible only in objects of low power in which no big efforts are needed for moving the controlling elements. In powerful objects the power, generated by the sensitive element, may be not sufficient for moving the controlling element. In this case an additional source of power, which strengthens the controlling action, is necessary. The governor, containing an additional source of power - an actuator, is called the governor of indirect action. Hydraulic actuators - servomotors - are almost exceptionally used as amplifying elements 3 (Figure 3), mounted between the sensitive element 2 and the object of control 1.

In 1873 the French engineer J.Farko first realized indirect control by introducing an actuator - hydraulic servomotor with rigid feedback - into the control circuit. In 1884 a governor of indirect action with additional relay feedback, which operated only at the presence of error x(t), was designed. The relay feedback was then changed by the constant proportional-plus-integral feedback.

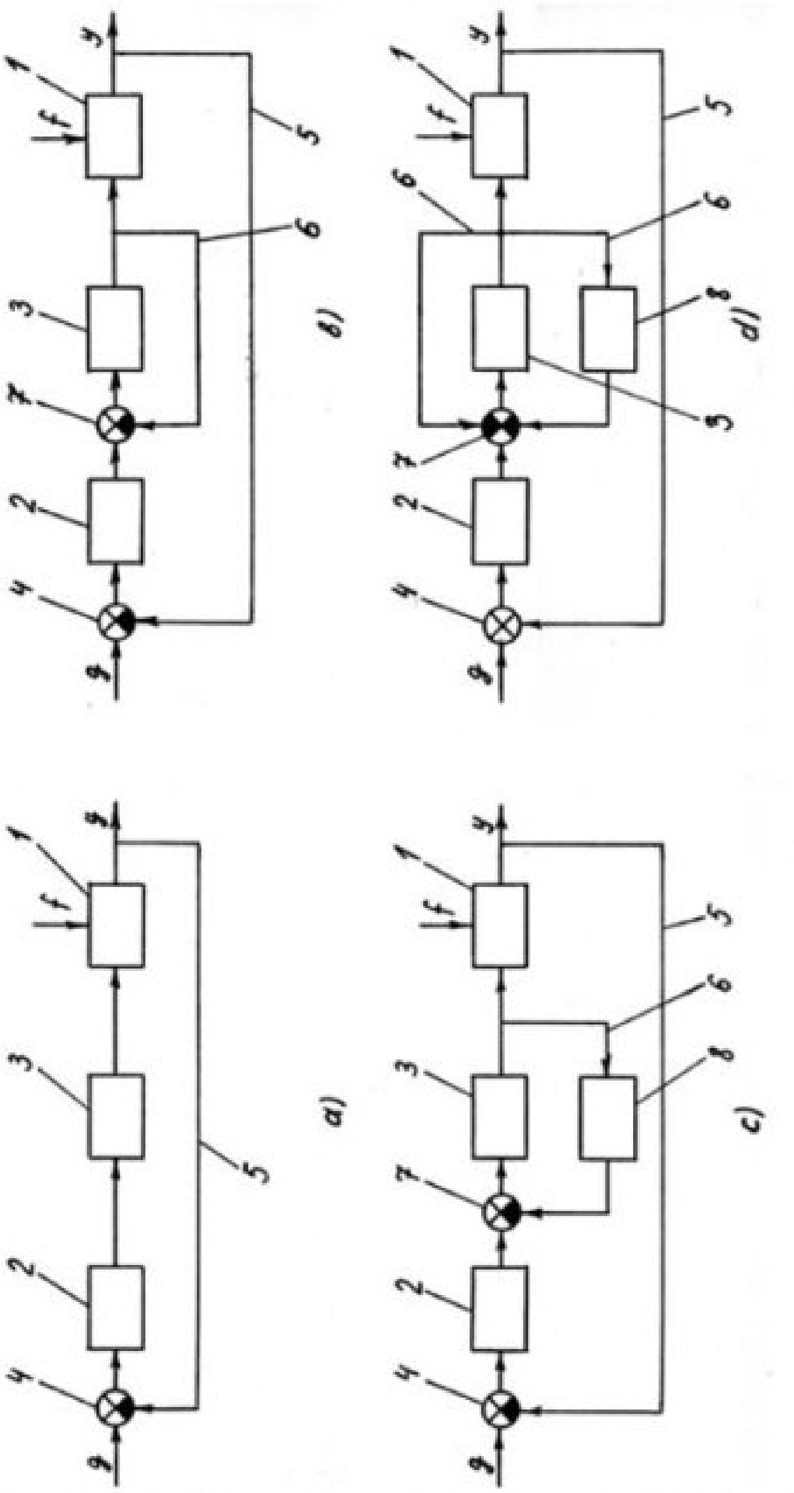

Figure 3. Functional scheme of ACSR with the governors of indirect action with hydraulic actuators: a - without feedback; b - with rigid kinematic feedback; c - with flexible (proportional-plus-integral) kinematic feedback; d - with combined feedback

Included into the structure of the governor of indirect action, the servomotor has valve 3 (Figure 4,a), which is moved by clutch 2 of centrifugally- sensitive element 1.

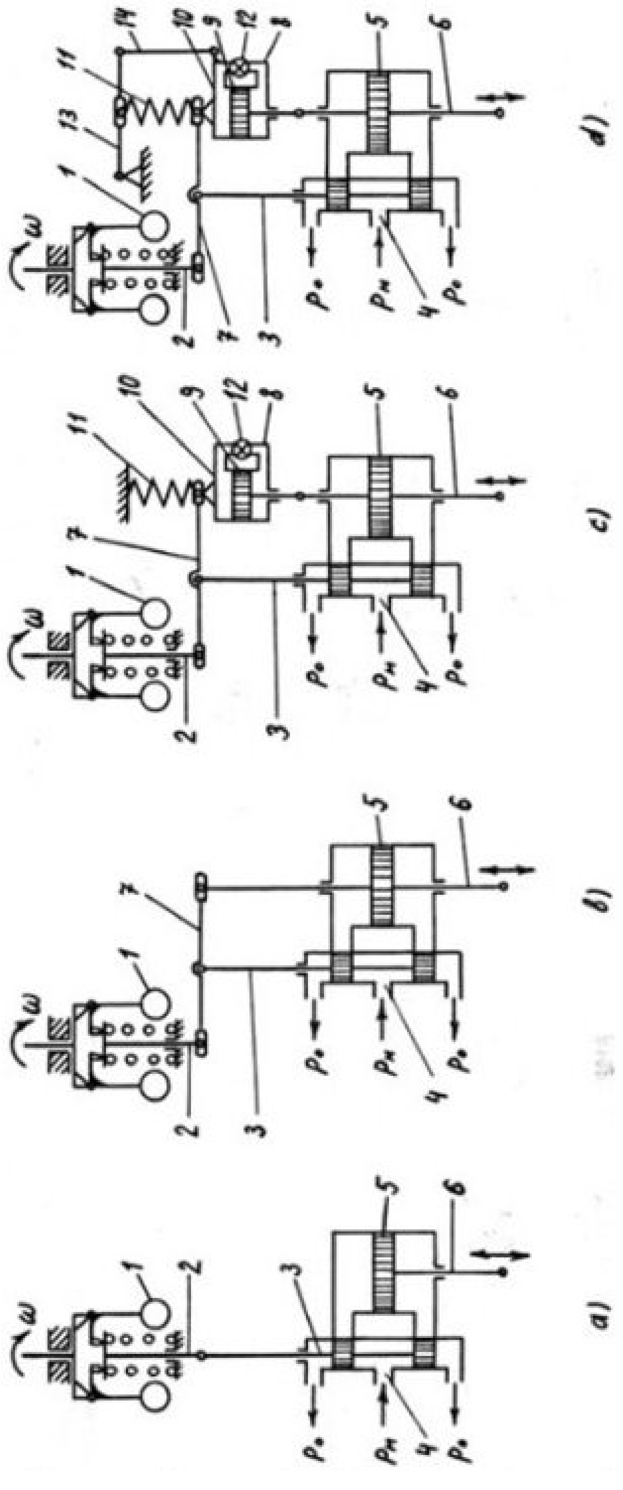

Figure 4. Governors of indirect action with hydraulic actuators; a - without feedback; b - with rigid kinematic feedback; c - with flexible (proportional-plus-integral) kinematic feedback; d - with combined feedback

The valve controls high pressure oil supply through passage 4 into the cylinder of servopiston 5. It is the pressure difference in the cylinder chambers, that creates a force, transmitted by servopiston 5 and rod 6 to the engine controlling element.

The presence of the servomotor in ACSR, which is an integrating device, may cause waves of the controlled parameter. Therefore, servomotors without feedback (Figure 3,a) are not used in practice. For ACSR stabilization, local feedbacks of various types are introduced into it. They apply hydraulic actuator 3.

When the rigid feedback is being realized, the output signal of hydraulic actuator 3 (Figure 3,b) is being fed back on its input - on summarizing element 7 through feedback line 6. For this purpose, lever 7 (Figure 4,b), which connects the shifts of valve 3 and servopiston 5, is introduced into the governor construction. This enables to stabilize ASCR, but static error x_{st} is kept like in scheme of direct control (Figure 1,a).

Hydraulic actuators applied by the flexible feedback, in line 6 (Figure 3,c) of which, proportional-plus-integral device 8 is placed, do not have this disadvantage. Such device is hydraulic element 8 (Figure 4,c), piston 9 of which is connected to servopiston 5, and body 10 - to lever 7. The piston forms 2 oil chambers in body 10. Between these chambers constrictor 12 is placed. Spring 11 with constant preliminary deformation stops the action of feedback in static regimes and zero error x_{st}. The rigid and flexible feedback may be realized not only as kinematic, but also as force feedback, acting on the governor spring.

Sometimes (e.g. when parallel operation of diesel-generators occurs), it is necessary to provide a small, but not zero error x_{st}. In this case the combined feedback (Figure 3,d) with two parallel lines - rigid and flexible feedback - is used. Such feedback is realized by varying preliminary deformation of spring 11, the suspension point of which is placed on lever 13, connected to body 10 of hydraulic element through link 14.

ACSR of direct action in Figure 1,a and of indirect action in Figure 3,a have one main negative feedback 5 and summarizing element 4 (forming one control closed loop) and are one-looped. Hydraulic actuator 3 (Figure 3,b,c,d) apply of local feedback 6 transforms ACSR of indirect action into many-looped.

A new stage of ACS improvement is connected with the development of electrical engineering and electronics. One of the first was the rotational speed electromagnetic governor of the shaft of the steam engine, constructed in 1854 by the Russian mechanical engineer K.I.Konstantinov. The usage of electronic elements gives more opportunities to form difficult algorithms of control with introducing actions according to higher derivatives, integrals and introducing different functions.

The first electronic governors controlled the object parameters according to a strict program. The control program in ACS, created on the basis of a microcomputer may change. In such ACS parameters of object 1 (Figure 5,a) are measured by sensors 3,4,5, which convert the results of measurements into electrical signals, entering electronic unit 6 of governor 2.

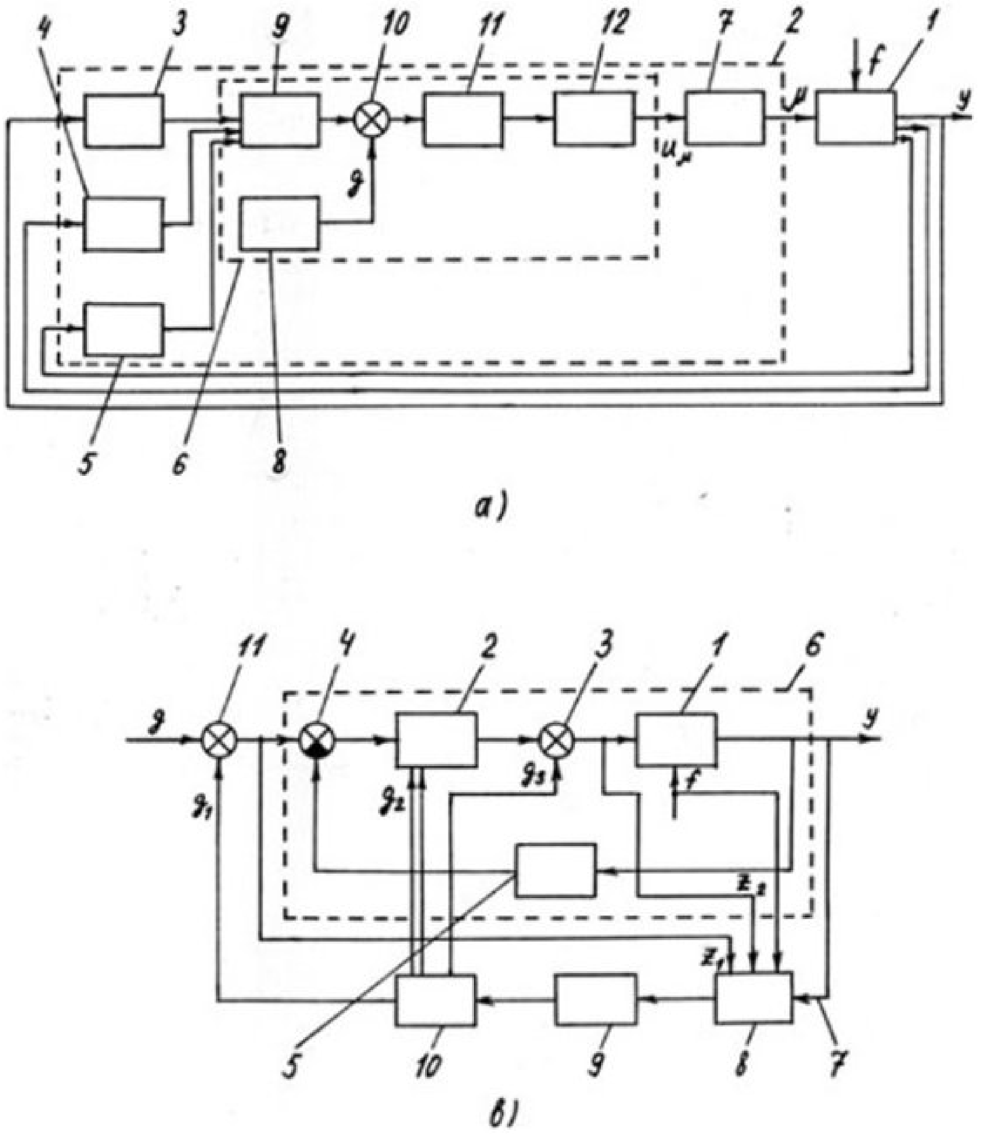

Figure 5. Functional scheme of a microprocessor (a) and adaptive ACS (b)

Unit 6 forms the controlling signal U_μ, which depends on the difference between the real value of the controlled magnitude y and its given value g. Signal U_μ is fed on actuator 7, exerting action μ on the controlling element of object 1. The required algorithm of change of controlled parameter y is formed by the program set-point device 8.

The electronic unit is constructed on the basis of analog (indiscrete) or discrete elements. In the second case ACS are divided into indiscrete (object 1, sensors 3,4,5, actuator 7) and discrete parts - governor, including the program set-point device 8, analog-to-digital converter (ADC) 9, element of coMParison 10, microprocessor 11, digital-to-analog converter (DAC) 12. In the discrete part of the ACS quantization is produced - conversion of an indiscrete signal into a discrete one. According to this type of signal, ACS are divided into indiscrete (in which the signal, converted from one element to another, is indiscrete) and discrete ones. The discrete ACS are divided into sampled (in which a signal is sampled), relay (in which a signal is quantized) and digital (in which a signal is digitized) ones. The microprocessor ACS refer to digital ones.

Advantages of electronic governors are most pronounced in adaptive ACS, capable to change their structure, parameters or algorithms of control on the basis of the current information about the object and external factors in the process of oneration. Adaptive ACS are distinguished according to the way of control: in self-adapting ACS parameters of the control device are changed, in self-organizing ACS - their structure is changed. Self-learning ACS, improving algorithms of their operation on the basis of analysis of control experience, have most opportunities. In adaptive ACS the control program is usually connected with the complex indeces of the guality of work, which provides keeping the extremal value of this index. Finding of the optimum regime, corresponding to the extremum of the quality index, may be carried out by an automatic search (search and extremal ACS) or by a searchless way (searchless or analytical ACS).

Adaptive ACS, besides the main control loop 6 (Figure 5,b), including object of control 1, governor 2 with a variable structure, summarizing element 3, element of comparison 4 and the line of the main negative feedback 5, have a self-adapting loop. This loop has analyzer 8, which determines ACS parameters (y, z_1, z_2) and disturbing action f, synthesizer 9, which forms settings, parameters and the governor structure, and actuator 10. It exerts an action on the variable part of governor, changing its parameters (signal g_2), or feeds additional master signal g_1 on summarizing element 11. Test signals g_3 may be formed for organizing ACS search waves. The presence of an additional self-adapting loop makes ACS many-looped, and its structure - multi-step. Governor 2, which is on the lowest step of the control hierarchy, is used for fulfilling commands of the self-serving loop, which is on a higher hierarchy step.

Peculiarities of ACS creating for heat engines of various types are caused by the differences of their static and dynamic features, and also by the design of their fuel feed systems.

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Biographical Sketch

Markov Vladimir Anatolyevich (borne in 1958) graduated from Bauman Moscow Higher Technical School in 1981 (speciality "Piston and Combined Engines"). Doctor of Engineering Sciences, professor of "Thermal Physics" Department of the Bauman Moscow State Technical University. Author of more than 100 publications in the field of fuel feed and automatic control of internal combustion engines