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CONTROL PROGRAMS OF THE AVIATION GAS TURBINE ENGINE IN THE MODES OF ACCELERATION, GAS RESET, START-UP. OPTIMIZATION AND ESTIMATION OF THE QUALITY OF CONTROL PROGRAMS

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Abstract*—The article is devoted to the formation of requirements for the accuracy of regulation of an aviation gas turbine engine, one of which is the maintenance of engine thrust at a given operating mode, regardless of the engine condition, within the gas temperature margin. Its value should not be significantly affected by turning on or off additional power and air consumers, as well as various regulatory influences on the part of the automatic control system (turning on or turning off the bypass in the compressor and blowing the housings, partial restriction of the supply of cooled air, changing the position of the guiding devices). Fulfilling the requirements for the accuracy of regulation is important for ensuring the reliability and safety of the operation of the power plant and the convenience of controlling the aircraft. In order to reduce operating costs, it is necessary that during operation, a minimum number of additional settings of the ACS in the acceleration mode, gas reset and start-up mode are required. The control program is implemented in the form of a automatic control system (ACS), which is a closed circuit of the main feedback. There is also a flexible local feedback loop in the circuit, which is designed to stabilize the ACS, which contributes to the fact that the ACS is quite stable. The presence of feedback in the ACS indicates that the system may be unstable, so the analysis of the ACS should include an assessment of its stability and, if necessary, the selection of measures and means for its stabilization. Changing the input signal at the first moment of time leads to a corresponding increase in deviation, since the links in front of the object and the object itself have inertia and therefore the rotation frequency cannot change instantly. The change in deviation, being an amplified amplifier, thyristor converter and generator, taking into account their inertia, leads to a gradual change in the control value, the voltage on the anchor, which smoothly changes the frequency of rotation of the shaft so that the tracking error, that is, the deviation, is directed to zero. Voltage feedback stabilizes the ACS and increases its speed. This is how tracking is done. The implementation of wireless technologies in the ACS of the gas station has been studied, which will allow to reduce the mass and dimensions of the nodes due to the reduction of the number of connectors and cables, increase the reliability and accuracy of the adjustment of the ACS, reduce maintenance costs and increase fire safety.*

Index Term—Control programs; aviation gas turbine engine; acceleration; gas reset; start-up; transition process; quality; mass reduction; wireless.

I. INTRODUCTION

Monitoring of limitations when choosing regulation programs. The engine idle time depends on a number of factors: the inertia of the rotating masses of the engine (proportional to the moment of inertia of the rotor relative to the axis of rotation), the reserves of the gas dynamic stability (GDS) of the compressor, the permissible increase in gas temperature, external conditions, etc., which must be taken into account when choosing programs for controlling these modes. Given the given structural parameters and characteristics of the engine units, the intake time is determined by the programs for adjusting the low gas (LG) and intake modes, in accordance with the features of which the influence of external conditions is manifested, as well as the dynamic characteristics of the intake regulator and parameter limiters.

The possibilities of obtaining the required time of reception when choosing adjustment programs are limited by the stability of the work process and the strength of the structure, which limit the permissible increase in fuel consumption. Restrictions according to GDS usually act at the beginning and in the middle part of the acceptance process, and in terms of strength at its end [1] – [9].

II. PROBLEM STATEMENT

An increase T_g^* in the acceleration process is accompanied by an increase in the $\pi_c^* / G_{an.}$ ratio and a decrease in the compressor's GDS reserves, that is, the line of mode regulator (LMR) at the acceleratiom is located above the line of stable modes. This limits the possibility of increasing fuel consumption under the condition of maintaining the required value ΔK_y. The allowable consumption ΔK_y of the compressor reserve at the acceleration usually does not exceed 8...10% [2] – [5].

As a result, the aim of the research is to develop the latest control programs of aviation gas turbine engines that will help to keep ΔK_y in necessary range during the operation of engine and aircraft in the mode of acceleration, gas reset, start-up. Also, must researched their optimization and quality estimation.

III. CONTROL IN THE GAS ACCELERATION AND GAS RESET MODES

Due to the strength of the turbine blades, the temperature T_g^* must be limited. Due to the fact that in modes with a reduced rotation frequency ($n < n_{\max}$), the circular speeds and stresses from centrifugal forces in the blades are less, as well as due to the inertia of the process of heating the turbine blades, small short-term excesses of the gas temperature of the value $T_{g\max}^*$. The amount and time of permissible temperature overshoot (re-adjustment) depend on the thermal resistance of the material of the blades and the efficiency of the cooling system, but in all cases the negative effect of overshoot should be kept in mind on the resource of the engine. Under the condition of preservation of mechanical strength, the permissible deviations of the rotation frequency at the acceleration mode are also limited.

The control program in the acceleration mode (Fig. 1) will allow this process to be carried out in the shortest possible time, if in the frequency range from n_{LG} to $n_{\max}$ it provides excess fuel, admissible under the conditions of maintaining the necessary reserves of stability and strength in accordance with the listed restrictions. In practice, the received reception time is usually more than the minimum possible as a result of both the non-optimality of control programs when external conditions change, and errors in their implementation, which include static and dynamic errors of regulators. Heat dissipation in the engine structure also leads to an increase in the acceleration time.

If the program $T_{G\max}^* = \text{const}$ is implemented during engine regulation, then the acceleration control program must first of all ensure the preservation of the necessary reserves of compressor stability in this process. Since it is impossible to directly measure the reserves of stability of the compressor, applications are used to control the acceleration capacity, which take them into account in an indirect way. The requirements for the process of acceleration when the external conditions change can be most fully fulfilled when fuel is dosed in accordance with programs that allow ensure the similarity of transient modes in the engine. This condition is satisfied by maintaining the set values of the parameter complexes, which contain the ratio G_T / p_c^* that characterizes the coefficient of excess air and the gas temperature. By the value of this ratio, it is possible to determine the position of the limits of the surge of the compressor and the region of stable operation of the combustion chamber. Reception management programs built on the basis of parameter complexes of this type can take the form [8]:

$$G_T / p_c^* = f(n, T_{in}^*),\quad G_T / (p_c^* n) = \text{const},$$

$$G_T / (p_c^* n) = f(n_n),\quad G_T / p_c^* = f(\pi_c^*)\ \text{e.t.c.}$$

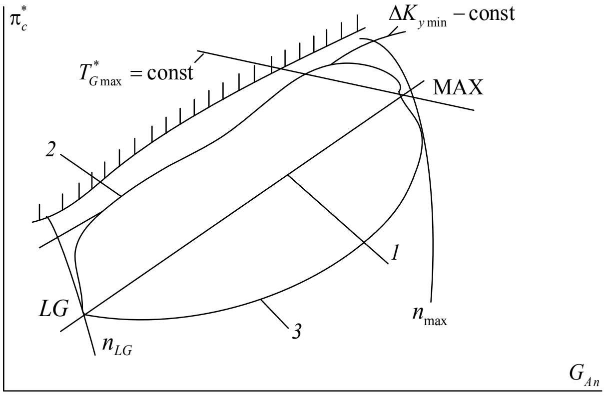


Fig. 1. Processes of acceleration and reset in the plane of the characteristics of the compressor: *1* is the line of stable modes of operation; *2* is the process of acceleration; *3* is the reset process [6], [7]

The disadvantage of these programs is the impossibility when choosing them to accurately take into account such factors as the change in the fuel combustion completeness ratio, heat removal in the engine structure, etc., which as a result does not allow to meet the requirements for the acceleration time when the operating conditions change. This makes it possible to develop control programs that use a set of parameters that includes rotor acceleration [8]:

$$\frac{dn}{dt} : (dn/dt)(1/p_c^*) = \text{const},$$

$$(dn/dt)(1/p_c^*) = f(n_n)\quad \text{e.t.c.}$$

But in this case, the restrictions on GDS reserves are less accurately taken into account. Therefore, modern ACSs use both types of programs at the same time, and programs of the first type are entrusted with the task of protecting against violations of GDS.

The program of controlling the elements of its flow part significantly affects the process of engine acceleration. Increasing the compressor ΔK_y in the area of reduced rotation frequencies and in the LG mode by adjusting the compressor and opening the nozzle allows you to increase the allowable excess fuel here and reduce the acceleration time [3], [5].

Adjusting the compressor and nozzle in the acceleration process in order to reduce its duration is aimed at increasing the power of the turbine, which leads to an increase in the acceleration of the rotor. For this purpose, the guidance devices (GD) of the compressor must be adjusted to increase air flow G_{air}, i.e. to open, when increasing the rotation frequency. Expedient anticipatory disclosure in comparison with that required for stable engine operation modes, which can be implemented by using derivative signals in control algorithms $dn / dt, dp_c^* / dt$.

Preservation of the nozzle with the acceleration opening allows it to have an increased value π_G^*. But in order to obtain the minimum time of acceleration for thrust, it is advisable to reduce the area of the nozzle in this process so as to reach the required covered position when the rotation frequency approaches the value $n_{\max}$.

It should be noted that the selection of control programs for the elements of the flow part of the engine and fuel dosing at acceleration are interrelated. When resetting the rotation frequency G_T, the ratio π_c^* / G_{air} and T_G^* also decreases. As a result, LMR passes below established modes. Therefore, there is no restriction on the stability of the compressor in this process. In this case, it may be caused by the instability of the combustion chamber when the mixture is depleted (lean failure), which is most likely at reduced pressures in the engine tract. Limiting the minimum fuel consumption G_T serves as protection against such a breakdown. Other factors limiting the speed of reset are the danger of inadmissible stresses in heated structural elements during rapid cooling, and in supersonic flight modes the possibility of surge of the air manifold.

Control when resetting the rotation frequency, which allows you to take into account existing restrictions, can be performed by applying fuel consumption reduction programs similar to acceleration control programs, for example, which use a set of parameters G_T / p_c^*.

IV. CONTROL IN START-UP MODE

The ability to start quickly and reliably is one of the most important characteristics of the engine. Control in the start-up mode should ensure that the engine enters the LG mode in a given time while meeting the GDS and strength limitations. The start-up time $t_{\text{st-up}}$ is normalized in depending on the purpose of the aircraft on which the engine is installed. As a rule, the value $t_{\text{st-up}}$ is about an order of magnitude greater than the acceleration time [1] – [9].

In starting conditions, one of the rotors is spun up with the help of a starter to start the gas turbine engine, since the autonomous operation of the engine is possible only at a rotation frequency at which the torque developed by the turbine becomes greater than the resistance moment. The start-up time $t_{\text{st-up}}$ depends on a number of factors, the main ones being the moment of inertia of the rotor (decreasing the moment of inertia is reduction $t_{\text{st-up}}$), starter power (increasing power is decreasing $t_{\text{st-up}}$), starter disconnection time, rotation frequency in the LG mode (n_{cLG}), GDS reserves of the compressor and combustion chamber, permissible increase T_G^*.

The gas turbine start-up process can be imagined in three stages: 1) rotor spin-up by the starter without supplying fuel to the engine (cold start-up) to the frequency n_{c1} at which fuel is supplied to the combustion chamber and ignited; 2) simultaneous operation of the starter and turbine up to the frequency n_{c2} when the stator is disconnected; 3) operation of the engine without a starter, spin-up of the rotor by the turbine with an increase in the frequency of rotation to n_{cLG}. The characteristic values of rotation frequencies at the boundaries of the stages are: $n_{c1} = (0.1...0.2)n_{c\max}$, $n_{c2} = (0.3...0.45)n_{c\max}$, $n_{cLG} = (0.65...0.7)n_{c\max}$. The duration of the first and second stages is 70 ... 90% of the start-up time.

When choosing a control program for start-up, it is taken into account that the main limitation of fuel consumption is determined by the GDS reserves of the compressor, the reduction of which begins after reaching the frequency n_{c1} when the fuel is ignited and increases T_G^*. At the end of the third stage, the fuel supply decreases when switching to the LG mode. At this stage, and sometimes at the second, the maximum permissible value $T_{G\max}^*$ may be reached and fuel consumption G_T should be reduced.

Autorotation mode is the starting point for launching in flight, in which the launch can be carried out without turning on the starter by supplying fuel and turning on the ignition. The main limitation of launching in flight is related to the stable operation of the combustion chamber, with a negative impact on the conditions ignition and steady burning provide a decrease in pressure and temperature levels, an increase in the flow rate at the entrance to the combustion chamber. As a result, the range of flight modes in which launch is possible is limited by speed and altitude. The start-up time increases with increasing altitude due to a decrease in the excess power of the turbine and an increase in the rotation frequency in the LG mode.

Taking into account the considered regularities, modern engine control programs in the start-up mode can be represented by functional dependencies of this type. When $n_c \le n_{c1}$ fuel is ignited

$$G_T = f\left(p_{in}^*, T_{in}^*, t_T\right),$$

where t_T is the fuel temperature.

For control after ignition of the fuel, the approach to the selection of control programs is similar to that considered for the acceleration mode $G_T / p_c^* = f(n, T_{in}^*)$ or $n_{\text{air}} / p_{in}^* = f\left(n, T_{in}^*\right)$ using the first program to protect against GDS violation. The surge protection functions of the compressor can, in addition, be performed by the anti-surge protection system, and a program $T_{G\max}^* = f(T_{in}^*)$ can be additionally applied to limit T_G^*.

V. GAS TURBINE ENGINES CONTROL PROGRAM OPTIMIZATION

On the defined engine operation mode the optimization task is reduced to finding the parameters of the PI-controller: the time constant and the gain factor.

The transfer function of the PI controller has the form:

$$W(s) = k_s \frac{sT_s + 1}{sT_s},$$

k_s is gain factor of the PI controller; T_s is the time constant of the PI controller.

In order to determine the time constant of the regulator, you should take the lower logarithmic amplitude frequency characteristics (LAFCh), for which the requirements for reserves in terms of phase and amplitude are met, and draw tangents to it with slopes of 0 db/dec and –20 db/dec.

In order to increase the accuracy of the determinations, the LACh can be constructed in a range of two decades (for setting the limits of the range, Fig. 2). The value of the coefficient $k_p = 0.5$ is a good initial approximation if the requirements for the phase and amplitude margins are met. Of course, the gain of the P-regulator, equal to 0.275, should be taken into account in the gain of the PI-regulator. As a result, we choose the value of the k_p coefficient equal to $k_p = 0.275 \cdot 0.5 = 0.165$.

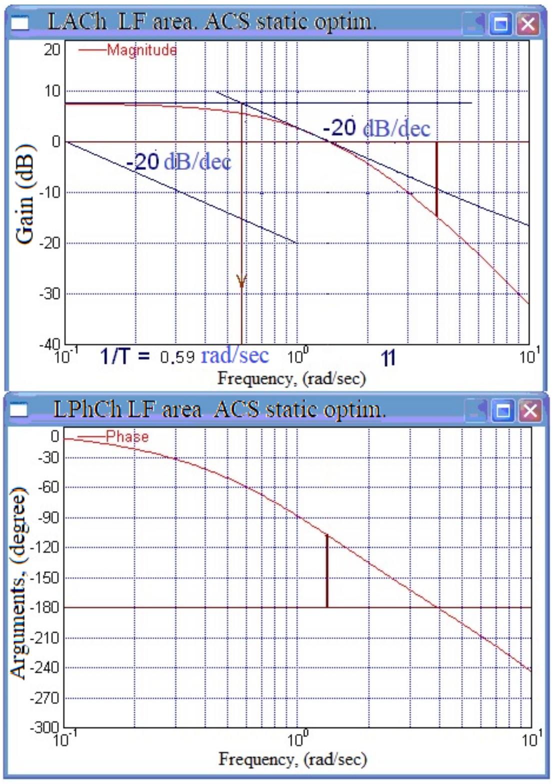
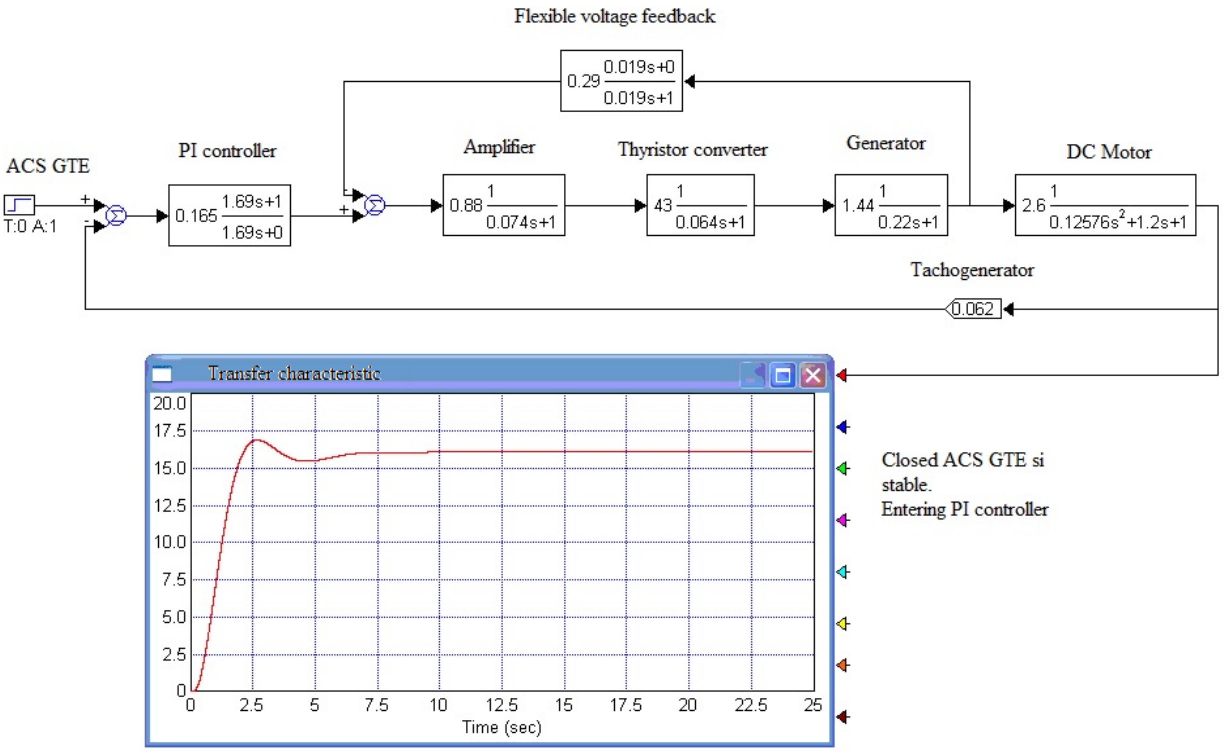


Fig. 2. Determination of the constant time of the PI controller according to the LACh of the system for which the requirements for stability reserves in terms of phase and amplitude are met. The frequency of the point of intersection of the tangents with a slope of 0 dB/dec and -20 dB/dec is the reciprocal of the desired time constant of the PI controller. $1/T = 0.59$ rad/s, $T = 1.69$ s

A. Entering the PI controller into the control loop (Fig. 3)

The control and re-control time and can be seen on the enlarged window of the transient characteristic (Fig. 4).



Closed ACS GTE si stable.
Entering PI controller

Fig. 3. Automatic control system with a PI controller

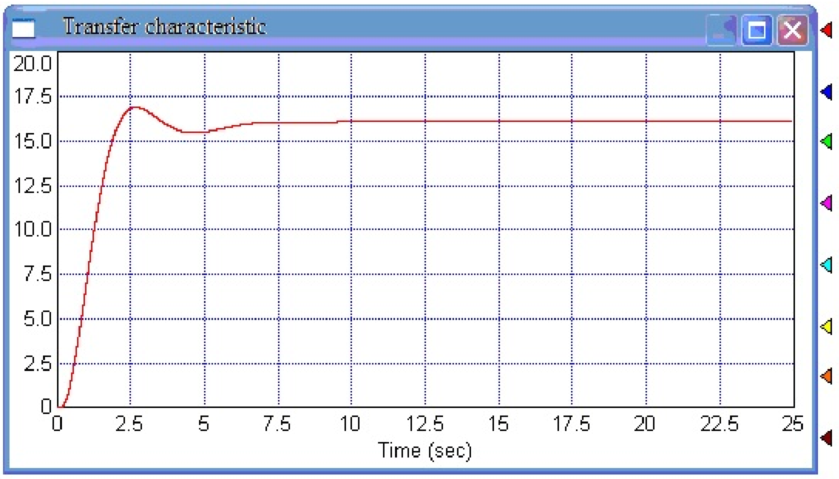


Fig. 4. Transient characteristic of ACS with a PI controller

The re-control is slightly higher than 5%. The set value of the control error is zero. In general, ACS has a good quality

B. Specified of PI controller parameters

Since the method of determining the parameters of the PI controller used for correction is approximate, the quality of the ACS can be improved by specifying the values of the regulator's gain coefficient and its time constant within a few tens of percent. By trial and error, it can be established that changing the time constant worsens the transient characteristic, and reducing the gain allows you to reduce the overregulation, make it less than 5%, which has a positive effect on the regulation time.

Thus, as a result of structural and parametric optimization, the following ACS scheme was obtained (Fig. 5). For ease of comparison, the transition function of the DC motor is given and enlarged by 4 times.

Let's show the transition function on a larger scale (Fig. 6). Some reductions in the gain of the PI controller made it possible to reduce overregulation, as a result of which the transition function of the ACS reached 10% is the interest corridor no longer leaves it. Formally, this made it possible to reduce the adjustment time. Note that the motor under the control of the ACS begins to change the frequency more smoothly compared to when a stepped armature voltage is directly applied to it, and the adjustment time of the ACS is practically the same as for the DC Motor in autonomous mode.

In conclusion, we will show the LAFCh and LPhFCh of the open circuit of the optimized ACS (Figs 7 and 8). LAFCh grows infinitely linearly with decreasing frequency. Stability reserves in both phase and amplitude are good. The transient characteristic of the open circuit increases linearly with time, which explains the presence of an integrator in the circuit, which is an input component to the PI controller.

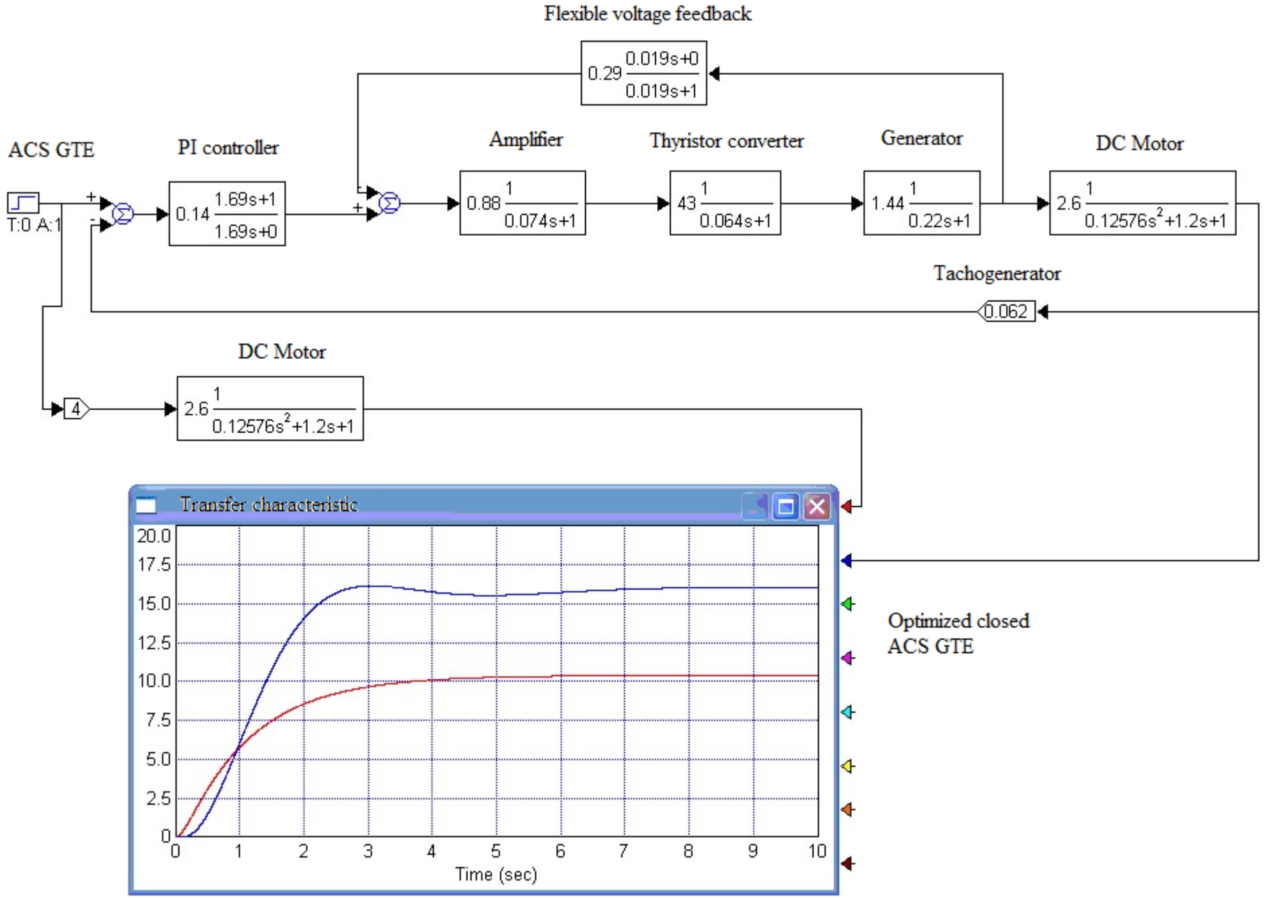


Fig. 5. The optimized ACS model and its transition function

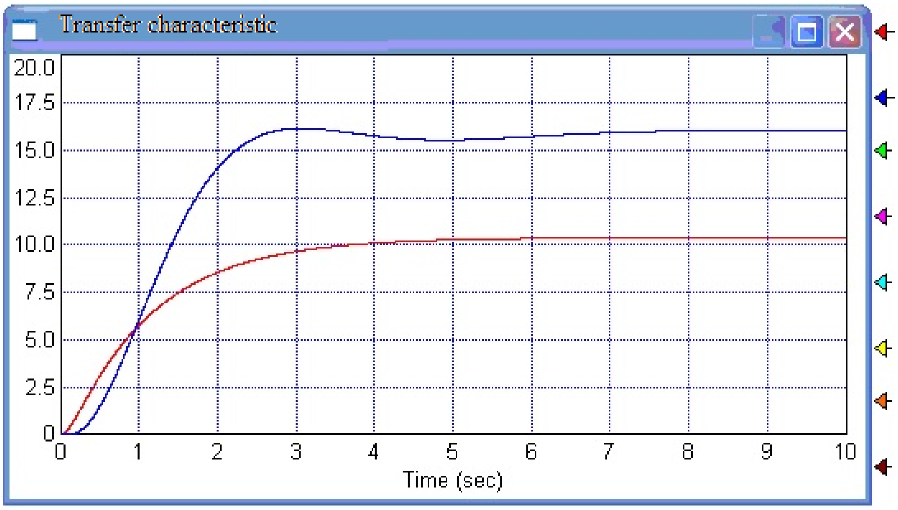


Fig. 6. Transient functions of the ACS and its control object – DC Motor (values increased by 4 times)

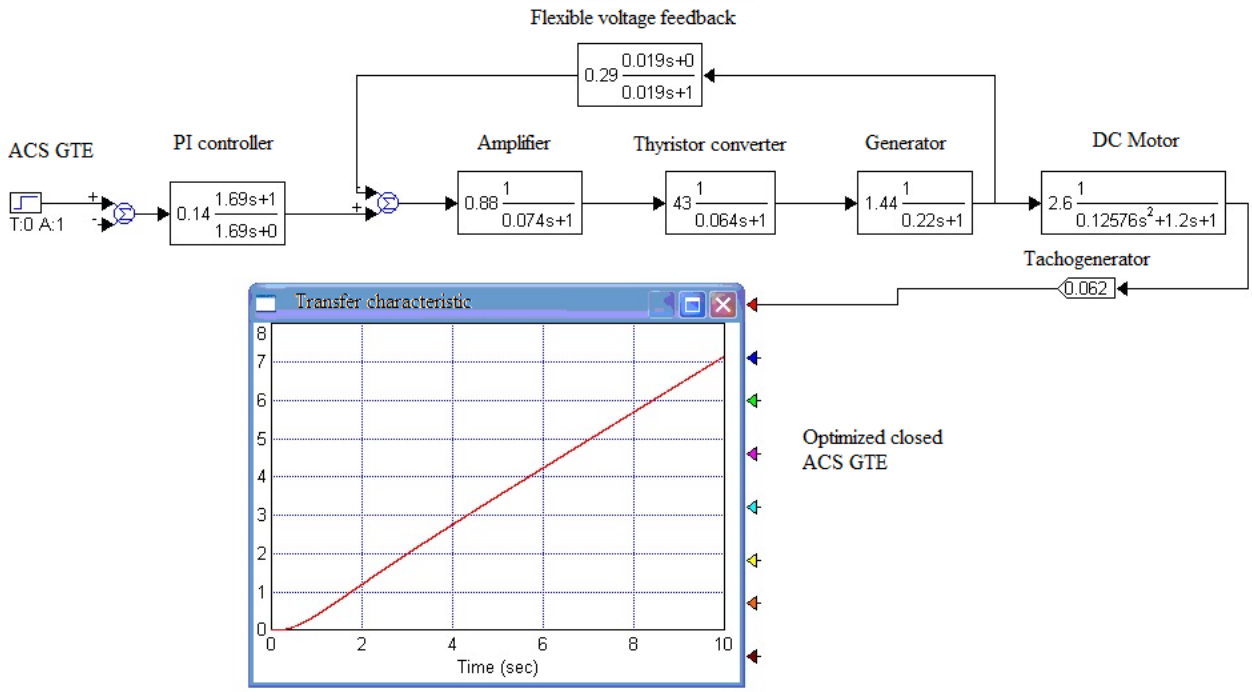


Fig. 7. The optimized ACS gas turbine engine (GTE) model and its transition function

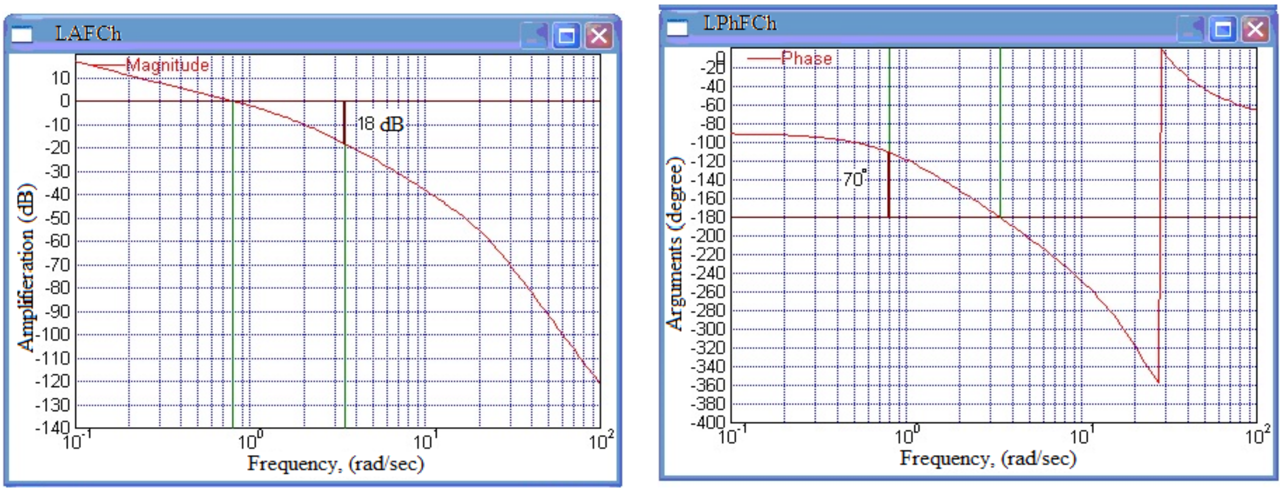


Fig. 8. The LAFCh and LPhFCh of the open circuit of the optimized ACS

VI. ESTIMATION OF THE QUALITY OF ACS

The concept of the quality of a linear ACS combines the accuracy of its tracking of the reference signal and the suppression of disturbances, as well as the speed of operation.

The quality of ACS is evaluated by direct and (or) indirect indicators of transient and stable modes.

Indirect indicators are reserves of ACS stability in terms of phase and amplitude and the order of astatism. For static systems, the gain of the circuit should also be specified. There are many other indirect indicators of quality.

Direct quality indicators are divided into transient mode indicators, this is the adjustment time t_s and readjustment $\sigma\%$, and steady mode indicators: error coefficients for position c_0, speed c_1 and acceleration c_2.

Quality indicators of the transition mode are determined by the transition characteristics of the ACS. For ACS defined by $t_p = 2.36$ s and $\sigma = 2\%$ (this is the relative excess of the first maximum of the transient function over its constant value).

Error coefficients characterize the accuracy of ACS operation in steady state. For good-quality static ACS, the value of c0 should be within 0.01–0.1, for astatic ACS, $c_0 = 0$. Coefficients c_1 and c_2 characterize the rate of change of the target signal, at which the tracking error is small. In other words, these coefficients characterize the speed of the ACS in a stable mode of operation, and therefore their values are not directly regulated.

Since the optimized ACS is astatic, its error coefficient $c_0 = 0$. To determine the error coefficient at the speed c_1, you need to connect a generator of a linearly increasing signal to the input of the ACS. The constant value of the error signal is equal to the value of c_1 (Fig. 9).

To check the quality of the ACS both in the tracking mode and in the stabilization mode, it is necessary to simultaneously apply a step action and a step disturbance (Fig. 10). Various delays should be added to these actions for clarity of the transient characteristic.

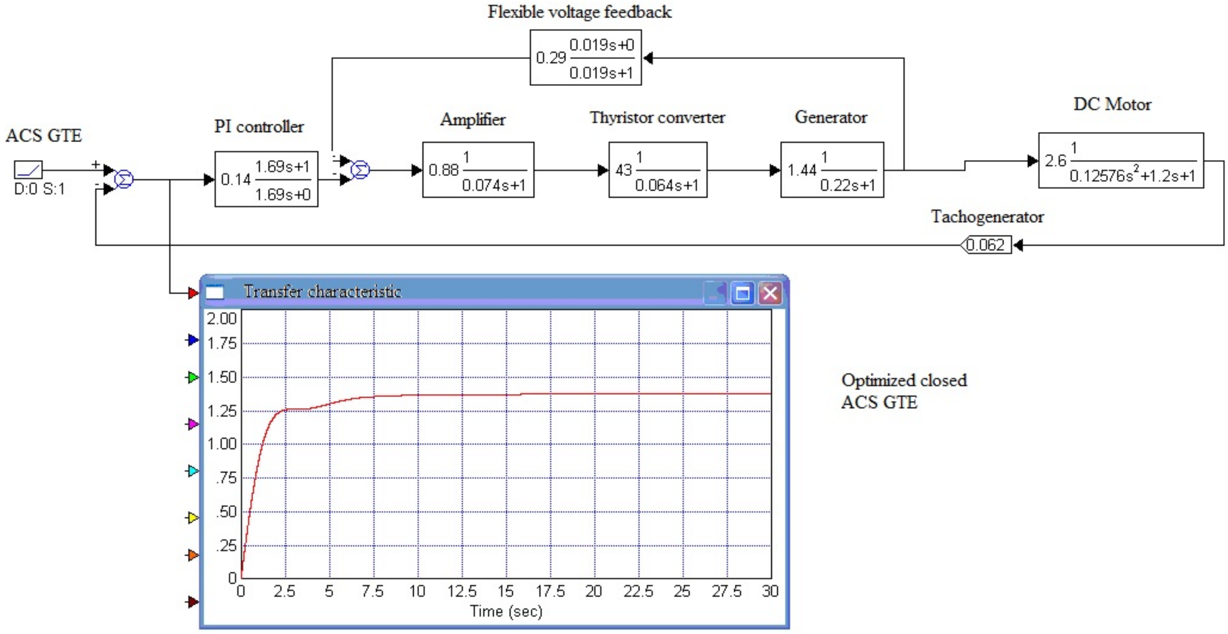


Fig. 9. The diagram for determining the error coefficient based on the speed of astatic ACS

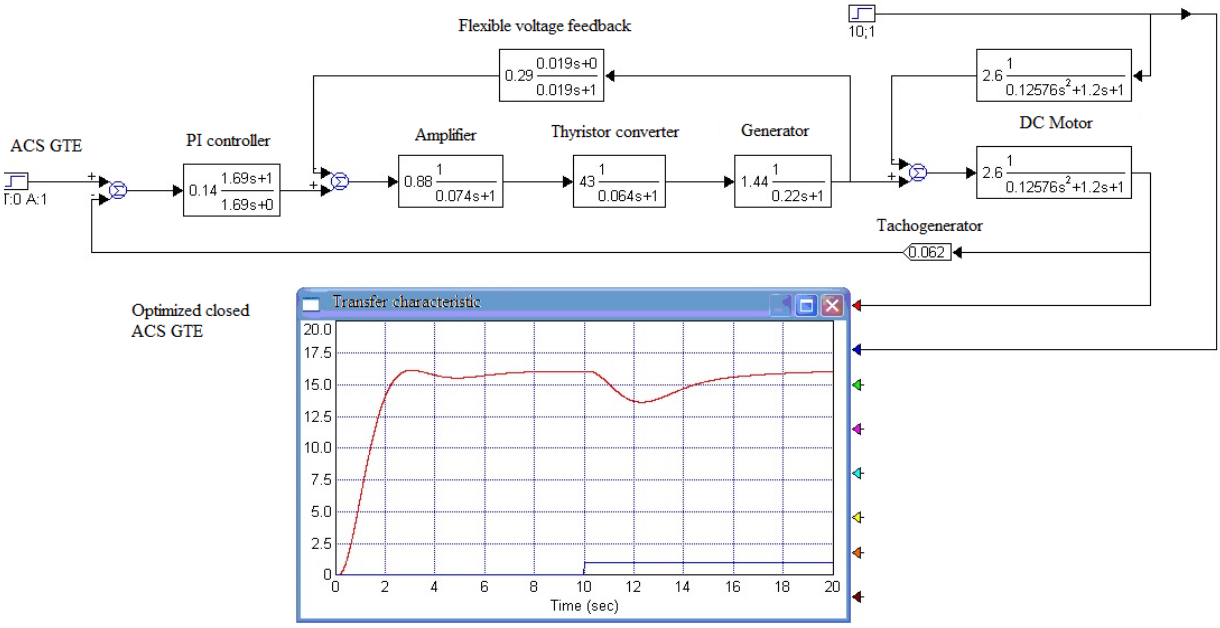


Fig. 10. Cumulative effect on ACS GTE of a step assignment and perturbation

Since the task specified requirements for the quality of disturbance compensation, we will consider the obtained quality to be satisfactory. Otherwise, it will be necessary to adjust the scheme either by increasing the gain of the loop, or by increasing the astatism of the ACS according to the disturbance, or by introducing a compensating device.

VII. MODELING OF RECEPTION AND TRANSMISSION OF THE GTE WIRELESS NETWORK TRACT

In Figures 11–14 present a diagrams of the distributed structure of the ACS GTE using wireless sensor networks [9], which will allow to reduce the number of radial communication lines due to the transition to multiplex channels of information exchange, simplify the search for faults, localization of failures and restructuring of the structure, integration of hardware and software of the aircraft and engine, reduce the probability of destruction of the entire system and, thus, increase its survivability.

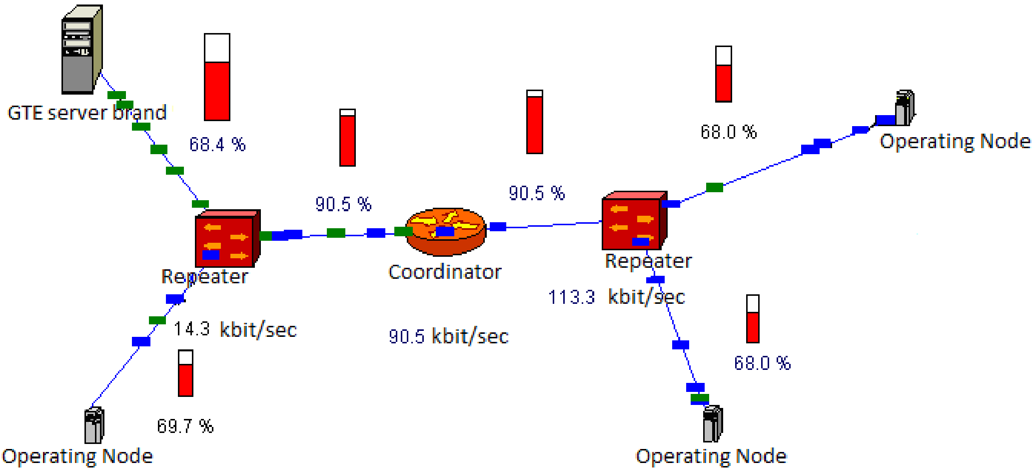


Fig. 11. "Star" topology. The maximum network load is about 88%

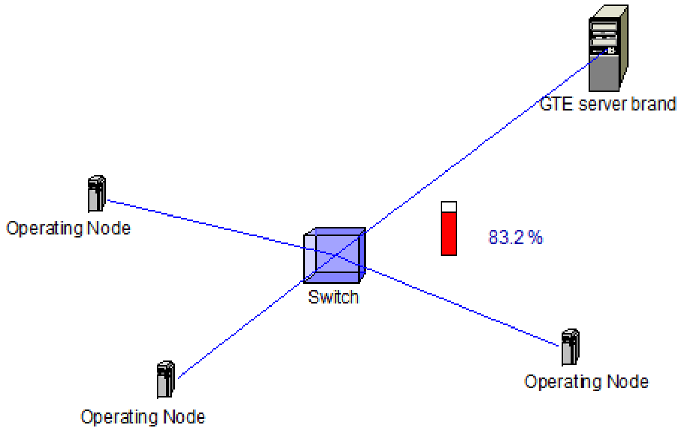


Fig. 12. Topology "bus at a point". The maximum network load is about 83%

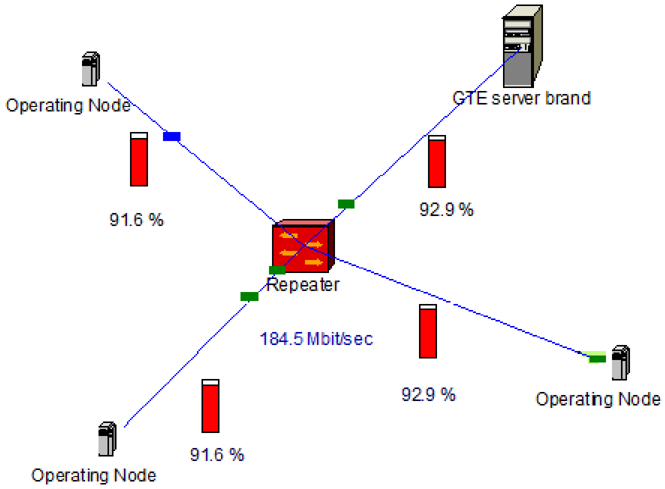


Fig. 13. "Star" topology. The maximum network load is about 92%

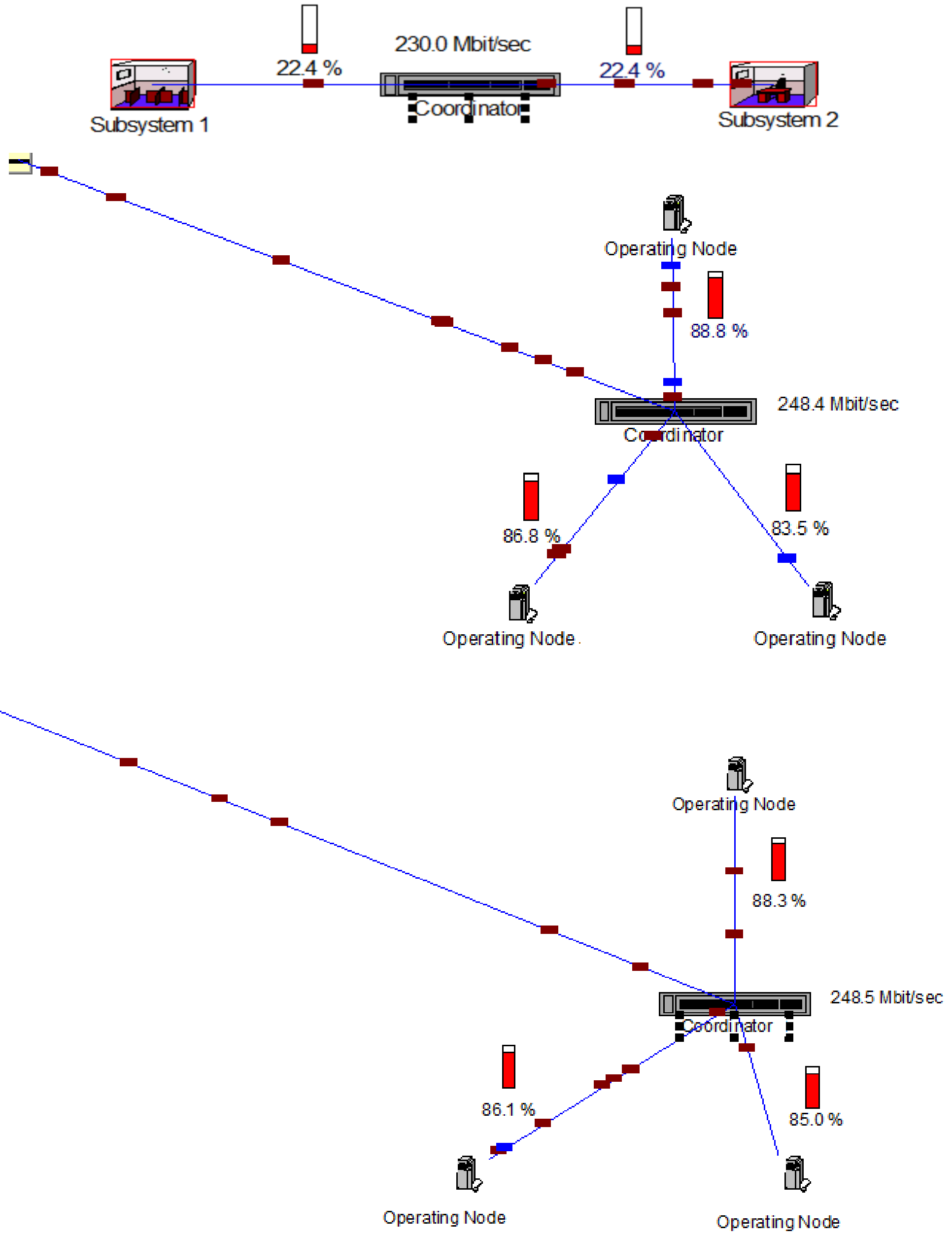


Fig. 14. Snowflake topology. The maximum network load is about 87% in subsystems and 23% between subsystems

A wireless network model based on the star topology in the NetCracker software was created to investigate the organization (adaptive processing of requests) of an aviation engine automatic control system (Figs 11 – 14). 3 IEEE 802.15.4 ACS GTE nodes were used as network hosts. Special software is selected for the server to support SQL server host traffic. A repeater and a PAN coordinator are used to connect workstations and servers. The maximum load of the network is about 88%.

VIII. CONCLUSIONS

The control programs of the aviation gas turbine engine in the acceleration, gas reset, and start-up modes were studied, as well as the optimization and evaluation of the quality of the control program. In order to maintain the specified amount of thrust of the engine during the entire period of its operation, it is necessary to have a sufficient reserve for the parameter (it can reach several tens of degrees), which should be taken into account at the stages of choosing the design parameters of the engine.

Various adjustment parameters are used in the control programs of steady engine operation modes: high-pressure rotor rotation frequency; low-pressure rotor speed (General Electric, CFM, PW6000 engines). The RB211-22B engines of the Rolls-Royce company and a number of engines of the SE "Ivchenko-Progress" use regulation by the value of.

In modern foreign two-circuit engines for mainline aircraft, the degree of pressure increase in the engine or EPR (Engine Pressure Ratio) is widely used as a control parameter, which meets the listed requirements for engines with separate circuits (JT9D-7R4, PW2000, PW4000) and with a common output device (RB211-524G/H, RB211-535, V2500, BR700).

Combined traditional and new methods of information processing in various ways to design a wireless stochastic information system for the control of an aviation gas turbine engine. These methods were applied to data collected from the request source node to the GTE control unit and initial self-tuning tests to verify the effectiveness of the integrated methods.

The proposed sequence tasks of the GTE information system are able to collect and process information from remote nodes of the subsystem in the energy signal with very high accuracy. The accuracy of the proposed GTE control unit was confirmed by tests conducted on a computer-simulated signal.

For the design of the information system of the engine, it is important to make the right choice of solutions used to build a telecommunications system (network technologies), which ensures information interaction between system elements and users. Here it is necessary to determine the network structure, the network software used, protocols of different levels, network equipment.

Solving these problems will reduce the load on communication channels, reduce network traffic, speed up the delivery of transmitted messages, and increase the reliability of connections.

It is also possible to highlight the main problems that are solved for the design of systems:

1) organization of interaction using host-server technology;

2) the organization of the system's communication service using network technologies – the creation of a calculation network of the information system;

3) formation and organization of the functioning of the integrated system of databases of the information system.

Solving these problems allows us to formulate the requirements for the application and system software, which was considered as an interaction between the service device and the sources of the request hosts by implementing a network model of the GTE control unit that receives and transmits the GTE channel with a load of 88%, 83%, 92%, 87%.

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С. С. Товкач. Програми керування авіаційного газотурбінного двигуна на режимах прискорення, скидання газу, режиму запуску. Оптимізація та оцінка якості програм керування

Статтю присвячено формуванню вимог точності регулювання авіаційного газотурбінного двигуна, однією з яких є підтримка тяги двигуна на заданому режимі роботи незалежно від стану двигуна в межах запасу за температурою газу. На її значення не повинно суттєво впливати включення або відключення додаткових споживачів потужності і повітря, а також різні регулюючі впливи зі сторони САК (включення – виключення перепуску в компресорі і обдування корпусів, часткове обмеження подачі охолоджуваного повітря, зміна положення направляючих апаратів). Виконання вимог до точності регулювання є важливим для забезпечення надійності і безпеки роботи силової установки та зручності керування літаком. Для зниження експлуатаційних витрат необхідно, щоб в процесі експлуатації вимагалась мінімальна кількість додаткових налаштувань САК на режимі прискорення, скидання газу та режимі запуску. Програма регулювання реалізована у вигляді САК, яка є замкненим контуром головного зворотного зв'язку. В контурі є і гнучкий місцевій зворотній зв'язок, який призначеній для стабілізації САК, сприяє тому, щоб САК була досить стійкою. Наявність зворотних зв'язків в САК свідчить про те, що система може бути і нестійкою, тому аналіз САК повинний включати оцінку її стійкості і, при необхідності, вибір заходів і засобів для її стабілізації. Зміна вхідного сигналу в перший момент часу приводить до відповідного зростання відхилення, оскільки ланки перед об'єктом і сам об'єкт мають інерційність і тому частота обертання не може змінитися миттєво. Зміна відхилення, будучи посилена підсилювачем, перетворювачем тиристора і генератором, з врахуванням їх інерційності приводить до поступової зміни керуючої величини – напруги на якорі, яка плавно змінює частоту обертання валу так, що помилка стеження, тобто відхилення, спрямовується до нуля. Зворотний зв'язок за напругою стабілізує САК і підвищує її швидкодію. Таким чином здійснюється стеження. Досліджено впровадження безпровідних технологій в САК ГТД, що дозволить зменшити масу і габарити вузлів за рахунок зменшення кількості роз'ємів і кабелів, підвищити надійність та точність регулювання САК, знизити витрати на технічне обслуговування і підвищити пожежну безпеку.

Ключові слова: програми керування; авіаційний газотурбінний двигун; прискорення; скидання газу; запуск; перехідний процес; якість; зменшення маси; безпровідний.

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