POWER MACHINERY

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SELF-TUNING PROCESS OF THE CONTROL LAWS OF THE AVIATION GAS TURBINE ENGINE

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Abstract—*The article is devoted to the selection of parameters and evaluation of the efficiency of an aviation engine based on a system approach, when the engine and power plant are considered as subsystems of a higher-level aircraft complex. To solve the problems of multiparameter optimization, complex mathematical models of the entire system, consisting of the aircraft and control systems, taking into account the properties of the used fuels, are developed. The integration of the aircraft engine and the aircraft is carried out on the basis of the conditions for ensuring mass balance, the volume layout of the starting thrust-mass ratio. In combined power plants, it is possible to consider engines of different types, for example, TPrE with parallel or sequential (tandem) arrangement of circuits, TRBEaf and ramjet and steam hydrogen rocket-turbine engines of several types, the parameters of the working process of which are optimized according to the conditions of a typical program flights The adaptation task can be solved by changing both control programs and parameters of intellectual regulators of individual subsystems, as well as the structure of individual subsystems and connections between them. The higher level determines which strategy and which adaptation algorithm to choose in this situation. The optimal behavior model of the system in the current situation is also determined here. At the next level (the level of the technological complex), a strategy for the integration of the control and planning systems of the gas station, technological equipment and information system is formed, depending on the modes of operation of the gas station and the fulfillment of the tasks set before it. The construction of the ACS GTE model in the VisSim modeling software package was completed, measures were taken to stabilize the system. The transfer functions of the main elements of the electronic automatic control system of the GTE were obtained: a speed sensor, a thermocouple, and a pressure sensor. sensor of the angular position, the actuator mechanism of the nozzle-valve, the movement of the aircraft by the pitch angle.*

Index Term—Control laws; aviation gas turbine engine; self-tuning; transition process; adaptive regulator; flight modes; flight program.

I. INTRODUCTION

When designing an aircraft, the most important tasks may be the choice of the type of engine, parameters of its work process, dimensions, which are determined, as a rule, by the required traction armament, as well as the scheme of layout of the power plant (PP) and its location on the aircraft [1] – [3], which are evaluated primarily by advantages, obtained from their mutual integration.

In order to better adapt the characteristics of the aircraft engine (AE) to the tasks that the aircraft solves in flight, the integration of control systems is necessary. Integrated control systems are particularly effective for the control systems of modern multi-mode aircraft. On the basis of such systems, optimal power plant (PP) control programs are formed using the criteria for evaluating the effectiveness of the aircraft.

As a result, the main task of the automatic control system (ACS) is formed, which boils down to the maximum adaptation of traction and economic characteristics and engine stability reserves to the needs of the aircraft. The optimal control program for AE is a program for changing the controlled parameters of the engine, air intake, and jet nozzle, in which the selected optimality criterion reaches an extreme value. In this case, matching the characteristics of the engine and the aircraft in the take-off zones and at transonic and supersonic flight speeds is achieved by increasing the steepness of the increase in thrust with increasing flight speed at full engine boost modes.

II. PROBLEM STATEMENT

Matching the characteristics of the engine and the aircraft in the take-off zones and at transonic and supersonic flight speeds is achieved by increasing the steepness of the increase in thrust with increasing flight speed in the modes of full engine lift.

For this, combined control programs are used to increase the temperature of the gas in front of the turbine and in the afterburner combustion chamber and "unwind" the engine rotors by the number "Temperature increase" can reach. A typical example is the RD-33 engine control program [1] – [4].

Due to the presence of large excess thrust in high-thrust aircraft, their integration with the aircraft engine can be extended by using the engine as a power source to directly improve the flight characteristics of the aircraft, for example, by taking compressed air from the engine and blowing it on the bearing surfaces of the airframe. Thus, the blowing of thin flat jets of air through the slits in the region of the rear edges of the cantilevered part of the wing (jet flaps) or on the upper surface of the wing in the area of the mechanical flaps allows, due to the influence of supercirculation and downward deviation from the axial direction of the air jets, to increase the lifting force of the wing and, thus, improve the take-off and landing and maneuverability of the aircraft. Studies [4] show that with numbers, the increase in lifting force can reach 20–30%. The implementation of such systems should provide for the optimization of the amount of air pumped out, sampling points and parameters of compressed air transportation systems to the places where it is blown on the aircraft, since the removal of air from the engine improves the aerodynamic characteristics of the aircraft and leads to a decrease in engine thrust. To reduce traction losses during air intake, it may be necessary to adjust the elements of the flow part of the engine. Research [1], [2], [4] – [6] of the engine by Boeing, Pratt & Whitney and Rolls Royce showed that the creation of the Aircraft-aviation engine-fuel system would significantly improve fuel efficiency, reliability and flight safety.

As a result, the aim of the research is to develop the latest methods of self-tuning regulator of control laws of aviation gas turbine engines that will help to develop the optimal control (law) program of aircraft flight.

III. CONSTRUCTION, LAUNCH AND ANALYSIS OF THE CONTROL PROGRAM OF THE AVIATION ENGINE

Main transfer functions of control law can be defined from the engine operation mode of defined aircraft flight.

The main elements of electronic ACS gas turbine engine (GTE) [6], [7]:

Frequency rotation sensor: $W(s) = k_n$.

Thermocouple:

$$W(s) = \frac{[\tau_2 - k(\tau_2 - \tau_1)]s + 1}{\tau_1\tau_2 s^2 + (\tau_1 + \tau_2)s + 1} k_T, \quad \frac{\tau_2}{\tau_1} = 1...20.$$

Pressure sensor:

$$W(s) = \frac{K_1}{\tau_1^2 s^2 + 2\tau_1\xi s + 1},$$

$$K_1 K_2 = K_p,\ \tau_1 = 0.01 \text{ s},\ \tau_2 = 0.01\text{s}.$$

Wireless sine cosine transformers (WSCT) angular position sensor:

$$W_1(s) = k_{\cos\theta}, \quad W_2(s) = k_{\sin\theta}.$$

Executive mechanism of the nozzle-damper:

$$W(s) = \frac{K_B}{\tau^2 s^2 + 2\xi\tau s + 1}, \quad \tau = 0.03 \text{ s}.$$

For the take off mode, the GTE transfer function will look like this:

$$W_{GTE}(s) = \frac{5}{6s + 1}.$$

For the low gas mode, the transfer function will have the form:

$$W_{\mathrm{GTE}}(s) = \frac{2.5}{3.5s + 1}.$$

For the cruising mode of flight, the GTE transfer function (by the frequency of rotation of the turbocharger):

$$W_{GTE}(s) = \frac{3.5}{4s + 1}.$$

The transfer function of a single-cycle gas turbine power plant based on the gas temperature behind the turbine can be obtained using the transfer function:

$$W_{GTE}(s) = 0.35\frac{0.829s + 1}{0.56s + 1}.$$

For the maximum mode of operation, the transfer function of the object of a single-phase gas turbine according to the frequency of rotation of the rotor can be obtained:

$$W_{GTE}(s) = \frac{0.45}{0.56s + 1}.$$

Transfer function according to the frequency of rotation of the high-pressure rotor for a two-shaft GTE:

$$W_{GTE}(s)=0.866\frac{0.206s+1}{0.133s^2+0.94s+1}$$

$$=0.866\frac{0.206s+1}{(0.766s+1)(0.174s+1)}.$$

For the maximum mode of operation, the transfer function of a two-shaft GTE according to the gas temperature behind the turbine:

$$W_{GTE}(s)=0.333\frac{0.064s^2+0.667s+1}{0.133s^2+0.94s+1}$$

$$=0.333\frac{0.064s^2+0.667s+1}{(0.766s+1)(0.174s+1)}.$$

Transfer function of aircraft by pitch angle

$$W_{\vartheta\delta}(s)=\frac{\vartheta(s)}{\delta_{\text{в}}(s)}=\frac{b_e(s+a_{22})}{(s^2+2\xi_0\omega_0 s+\omega_0^2)s},\ \vartheta.$$

Let's get the model of automated control system (ACS) (Fig. 1).

IV. ESTIMATION OF STABILITY AND STABILIZATION OF THE OPEN ACS. PARAMETRIC OPTIMIZATION OF ACS

Let's open the main feedback circuit, connect it to the oscilloscope and start the simulation (Fig. 2).

The figure shows that the open ACS is unstable. To ensure the fulfillment of the necessary condition for the practical use of the Nyquist criterion, the open ACS must be stabilized.

It is not difficult to see that the loss of stability of an open-ended ACS occurs due to the presence of local feedback (systems consisting of stable links and feedback can lose stability). It is interesting to note that this connection was introduced in order to ensure sufficient stability and quality of the resulting ACS. This indicates that the parameters of the voltage feedback loop are set incorrectly and may require correction.

V. STABILIZATION OF THE CIRCUIT BY REDUCING THE GAIN OF THE AMPLIFIER

Stabilization of ACS requires some practical experience (Fig. 3), on the basis of which it is possible to determine in which links the parameter changes should be made. In this case, it is possible to stabilize the open circuit by changing the parameters of two elements: the amplifier and the voltage feedback loop (VF). First, we will simply try to reduce (increase) the gain of the amplifier until the open circuit is brought to a state close to the limit between stable and unstable modes.

Now it is possible to stabilize the open ACS, providing at least a minimum, two-fold (that is, 6 dB) margin of stability of the local feedback circuit. To do this, we will reduce the gain of the amplifier by half (Fig. 4).

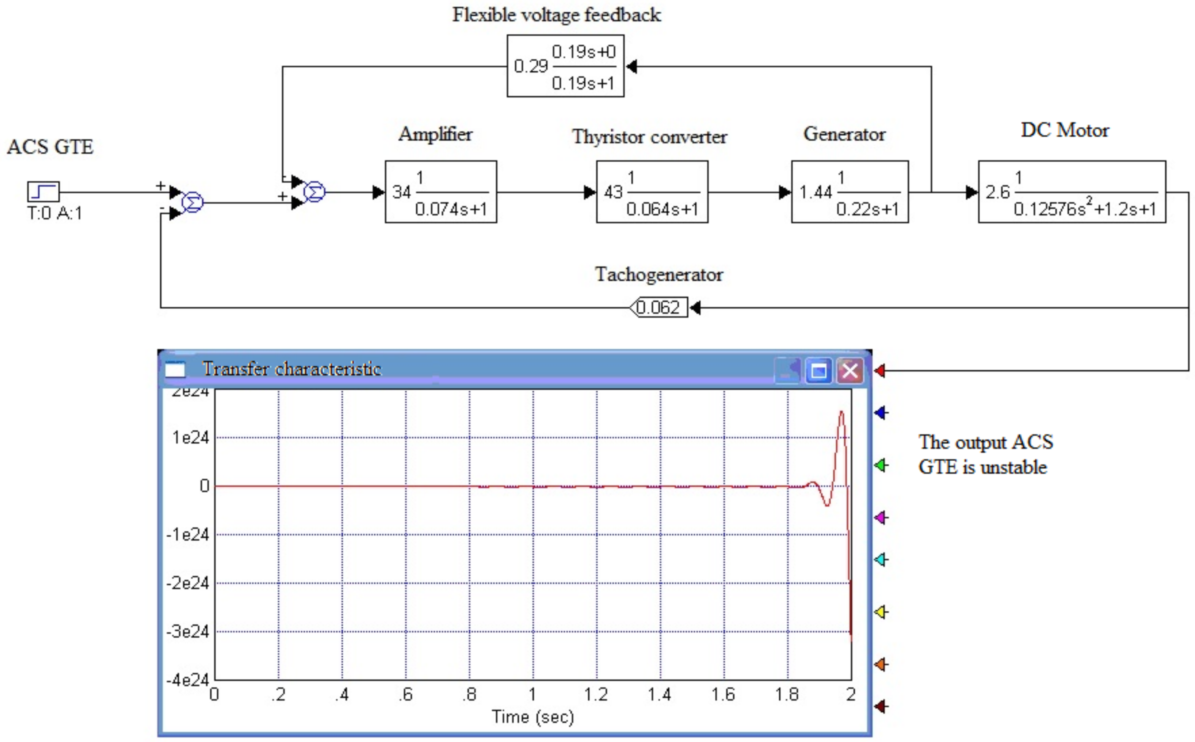


Fig. 1. Model of the original ACS GTE. The transient characteristic of the original ACS is an oscillatory process with an amplitude that increases with time. The output ACS is unstable

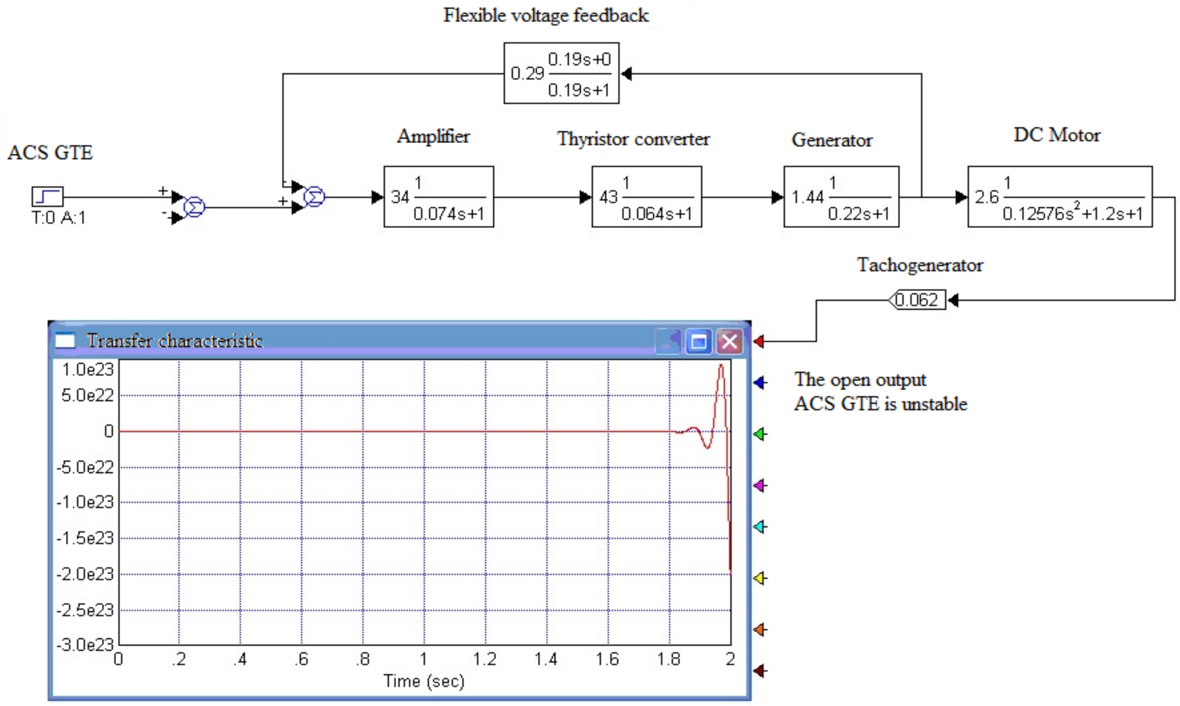


Fig. 2. Checking the stability of the open circuit of the ACS GTE. The graph of the transition function shows that the open loop is unstable because its output signal is an oscillation with a rapidly increasing amplitude

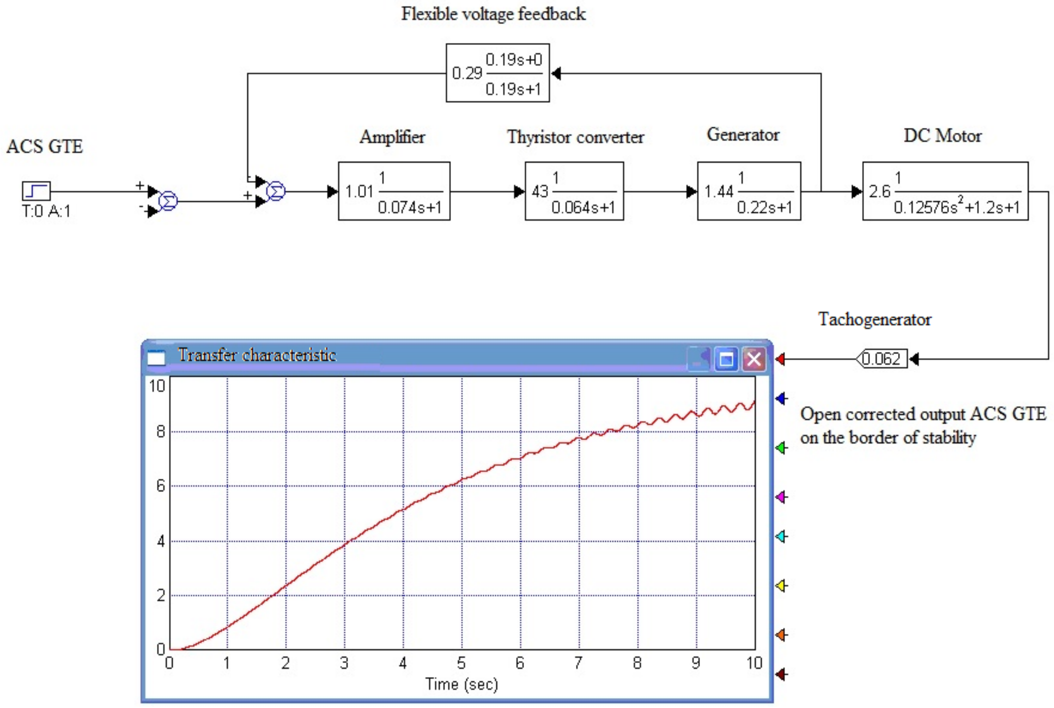


Fig. 3. Gain reduced from 34 to 1.01. The transient characteristic has an oscillatory component, the amplitude of which decreases relatively slowly over time. The open circuit is not yet stable, but close to the critical, limiting mode

VI. STABILIZATION BY CHANGING THE PARAMETERS OF THE AMPLIFIER AND THE FVF LINK

In principle, it is now possible to proceed to the correction of the closed ACS, since formally the stability of the open circuit is provided with a margin of 6 dB.

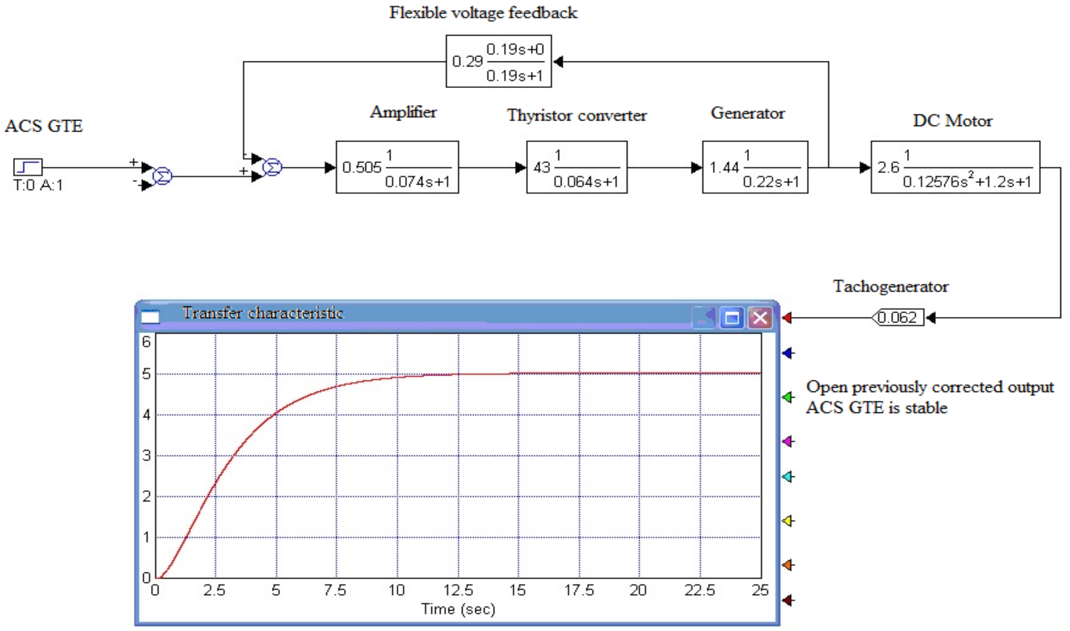
However, this margin is quite small, as is the small gain of the entire open loop, equal to 5.03, as can be seen from the set value of the transient function of the loop. Therefore, in order to prevent possible difficulties that may arise during the final correction of the ACS, we will change the parameters of the FVF link. By the method of trial and error, we will change the time constant of the inertial-differentiating link of the FVF and the gain of the amplifier.

The goal is to bring the open circuit to the limit of stability at a significantly greater than 1.01, the value of the gain of the amplifier, achieved in the circuit of Fig. 3.

As a result of the selection of parameters, let's stop at the circuit diagram of Fig. 5.

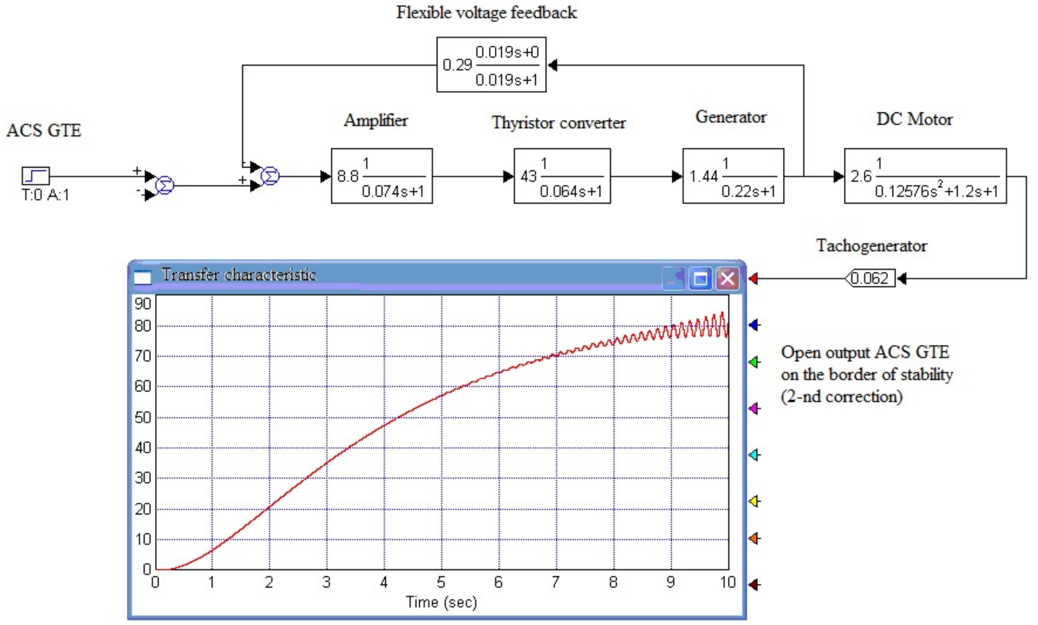
As can be seen in Fig. 5, after the second correction, which consisted in reducing by 10 times the time constant of the FVF link, the value of the amplifier gain coefficient, in which the open circuit is close to the stability limit, increased from 1.01 to 8.8.

It remains to ensure a margin of stability in terms of the amplitude of the local feedback loop by reducing the gain of the amplifier (Fig. 6).



Open previously corrected output ACS GTE is stable

Fig. 4. Stabilized open ACS. The transition function is set at the level of 5.03, which indicates the stability of the open ACS, but the value of its contour at 5.03 (14.03 dB) is relatively small. It is desirable to have an open circuit gain of 20-40 dB, and a border of stability in terms of amplitude of 6-20 dB



Open output ACS GTE on the border of stability (2-nd correction)

Fig. 5. A slow increase in the range of oscillations of the transition function indicates that the open circuit is on the limit of stability. The reduction of the time constant of the FVF to 0.019 s made it possible to bring the value of the amplification factor to the critical value, the limiting mode of the ACS to the value of 8.8

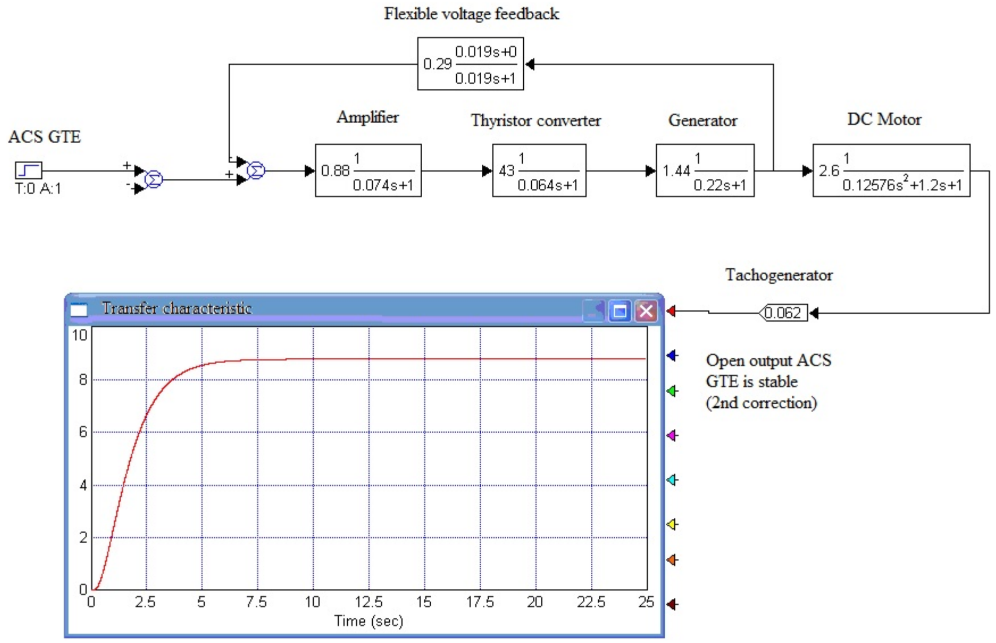


Fig. 6. The gain of the amplifier is reduced in comparison with its value in the critical state by 10 times, from 8.8 to 0.88, i.e. by 6dB – this is the margin of stability in terms of the amplitude of the loop of this feedback. The resulting gain is approximately 8.78 units (18.86 dB)

Therefore, the opened ACS GTE is stabilized. Therefore, the stability of closed ACS can be analyzed using the Nyquist test.

Let's ask whether the open circuit of which the closed circuit that has just been stabilized will turn out to be stable. To do this, let's close the feedback loop and check how the transient characteristic of the ACS will behave.

As can be seen from Fig. 7, the constant value of the transient function is approximately 14.5 rev/s, which is 11.6% less than the exact value equal to $1/W_{tg}(s)_{s=0} = 1/0.062 = 16.1\ \text{rev/s}$. That is, the accuracy of the obtained system is unsatisfactory even in the stable mode.

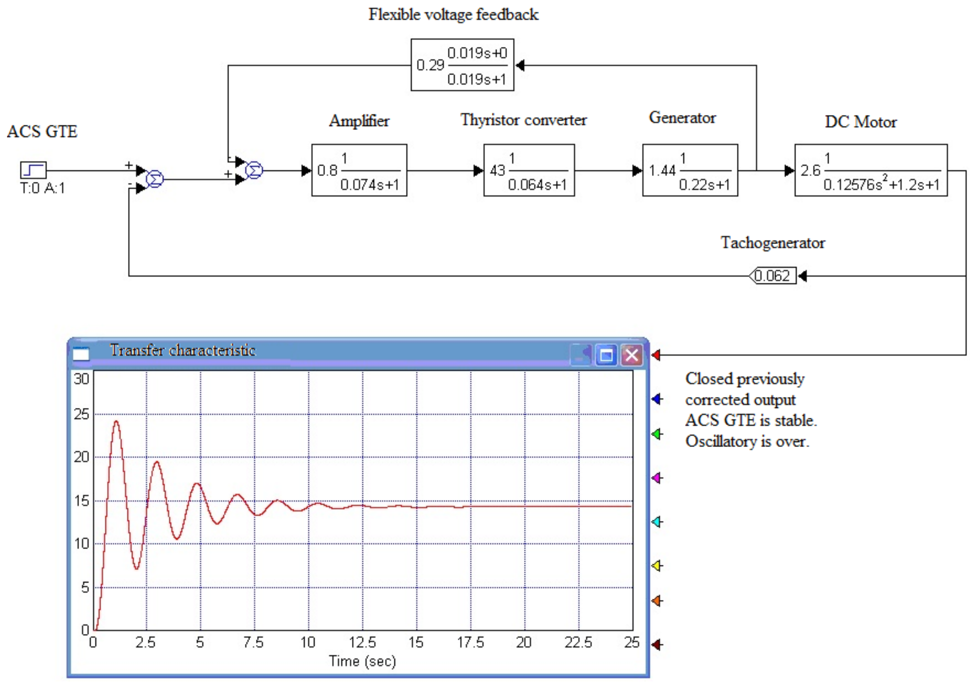


Fig. 7. ACS after stabilization of the open circuit. The system is stable, but such that the fluctuation of the transient characteristic is excessive (over)

VII. RESULTS

Construction of the ACS GTE model in the VisSim system modeling software package was completed, measures were taken to stabilize the system: reduction of the amplifier gain coefficient; changing the parameters of the amplifier and the FVF link.

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 $n_c \leq n_{c1}$ 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 $n_{tf} / p^*_{in} = f\left(n_c, T^*_{in}\right)$ using the first program to protect against gas dynamic stability (GDS) violation.

One of the possible combinations of turbojet bypass engine (TRBE)-type engine control programs that provide control in stable and transient modes of operation in any operating conditions shows in Fig. 8.

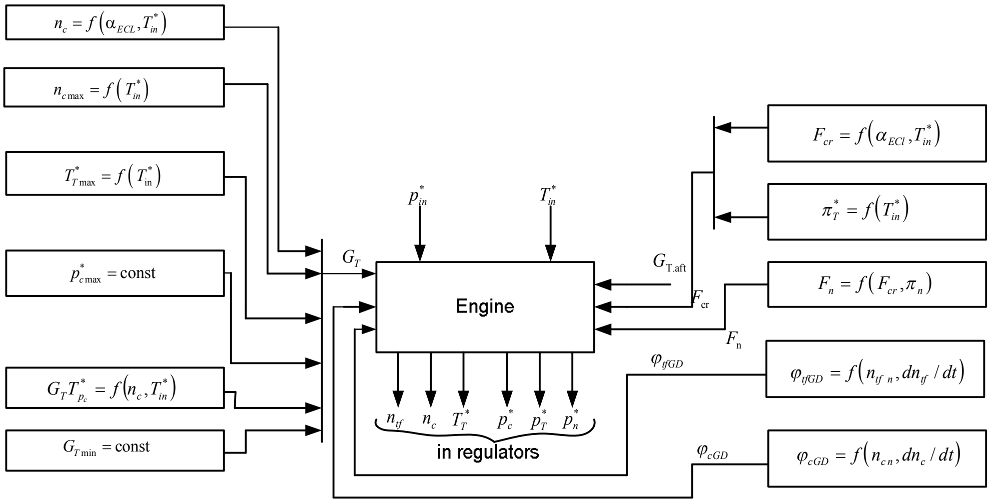


Fig. 8. (TRBE)-type engine regulation program

VIII. CONCLUSIONS

Important for ensuring the necessary characteristics of control processes in the main and afterburner circuits in forced modes is the issue of coordination of the regulators that determine the fuel consumption in the afterburner chamber and the area of the critical section of the jet nozzle. Such coordination is achieved by the appropriate selection of regulatory programs and the construction of regulators that implement these programs.

With the aim of improving the efficiency of the functioning of the ACS GTE it is necessary to implement the control (law) programs by software and hardware integration of the set of elements the aviation gas turbine engine.

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С. С. Товкач. Процес самоналаштування законів керування авіаційним газотурбінним двигуном

Статтю присвячено вибору параметрів та оцінці ефективності авіаційного двигуна на основі системного підходу, коли двигун і силова установка розглядається як підсистеми комплексу більш високого рівня ЛА. Для вирішення задач багатопараметричної оптимізації розробляються складні математичні моделі всієї системи, що складається з літака та систем керування, з урахуванням властивостей використовуваних палив. Інтеграція авіаційного двигуна і літального апарату здійснюється на основі умов забезпечення балансу мас, об'ємної компоновки стартового тяго-масового відношення. У комбінованих силових установках можна розглядати двигуни різних типів, наприклад, ТВД з паралельним або послідовним (тандемним) розташуванням контурів, ТРДДФ і ПВРД і пароводневі ракетно-турбінні двигуни кількох типів, параметри робочого процесу якого оптимізовані на основі умов типової програми польоту. Рішення задачі адаптації може здійснюватись за рахунок зміни, як програм керування, так і параметрів інтелектуальних регуляторів відокремлених підсистем, а також структури окремих підсистем і зв'язків між ними. Вищий рівень визначає, яку стратегію і який алгоритм адаптації в даній ситуації вибрати. Тут же визначається і оптимальна модель поведінки системи в ситуації, що склалася. На наступному рівні (рівні технологічного комплексу) формується стратегія інтеграції систем керування та планування ГТД, технологічного обладнання та інформаційної системи в залежності від режимів роботи ГТД і виконання поставлених перед ним задач. Виконана побудова моделі САК ГТД у програмному пакеті моделювання VisSim, проведені заходи зі стабілізації системи. Отримано передавальні функції основних елементів електронних САК ГТД: датчик частоти обертання, термопара, датчик тиску. датчик кутового положення, виконавчий механізм сопло-заслінка, рух літального апарата за кутом тангажу.

Ключові слова: закони керування; авіаційний газотурбінний двигун; самоналаштування; перехідний процес; адаптивний регулятор; режими польоту; програма польоту.

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