POWER MACHINERY

UDC 681.51:621.452.3(045)
DOI:10.18372/1990-5548.65.14984

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TRANSITION PROCESS REGULATOR OF SELF-ORGANIZING AVIATION ENGINE CONTROL SYSTEM

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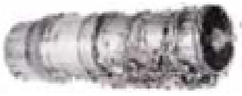
Abstract—*The article considers the trends in the development of aviation engine construction, which are determined by the use of the latest advances in science to ensure high requirements for operational reliability, cost-effectiveness, environmental and safety. Each new generation of aviation gas turbine engines is characterized by a set of technologies implemented in production and put into operation, a short list of which allows to form the definition of generations of aviation gas turbine engines based on the analysis of world practical training of aviation engines. The main features of the process of designing adaptive automatic control system gas turbine engines in order to integrate the control of the workflow in the engine and flight modes to reflect the methodological, mathematical, cybernetic and informational side of research have been defined. The main control laws and structural schemes of automatic control system can be defined in the form of control programs on the maximum mode of operation of the engine, throttle modes, the mode of small gas, reception and release of gas, on the forced and transition modes.The use with a variable structure of the regulator for the investigation of transition processes automatic control system is proposed and the practical implementation of transition processes is presented.*

Index Term—Automatic control system; aviation gas turbine engine; transition process; adaptive regulator; self-organizing.

I. INTRODUCTION

The aviation engine of modern aircraft has reached a very high degree of perfection. The history of its development is determined by a vivid illustration of the continuous work of designers in the direction of improving the efficiency of the aviation engine and ensuring flight safety [1]. Thus, during the development of aircraft, five generations of aircraft engines were created, each of which was determined by improved performance:

1)  2nd, 3rd generation (1960s and 1970s) is high thrust; $M_n = 2.5 \dots 3.0$;

2)  4th generation (1980s and 1990s) is reduction of specific fuel consumption by 20% at $M_n < 1$; fighting survivability, high maneuverability;

3)  5th generation (2000s and 2015s) is decrease in specific weight and increase in frontal traction by 20%; without afterburner cruising at $M_n > 1$; low visibility;

4)  6th generation (2020s and 2030s) is improvement of fuel efficiency by 35%; high ratio of thrust to engine weight; adaptive engine integrated with the aircraft;

and aviation has become a major factor in the development of the world transport system and defense capabilities [1] – [3].

Nowadays, development indicators have been formulated to reduce the specific fuel consumption in cruising mode [1] – [4]:

- increase of flight efficiency is engines "open rotor", but there is a decrease in specific thrust, the sizes increase, noise and vibrations increase;
- increase in cycle parameters, but limited opportunities to increase effective efficiency;
- distributed power plants, with the need for close integration with the glider.

High requirements for fuel efficiency and environmental performance are determined for 6th generation engines with the level of perfection of 2025s and 2030s. They must provide [1] – [3]:

- reduction of specific fuel consumption by 17–25% (compared to PD-14);

- provision of a stock at the level of NOx emission of 55-65% relative to the norms of SAE ICAO Section 6;
- reduction of noise level by 25-30 EPN relative to ICAO Section 4 standards;
- reduction of the cost of after-sales service and production by 30-40%.

It is believed [1], that all engines of the 6th generation should be "electric", i. e. with no air extraction from the path by electric actuators, starter-generator on the shaft of the high pressure cascade and generator on the shaft of the low pressure cascade, with intellectual automatic control system (ACS), combined with a diagnostic system, that provides control of the technical condition and accounting of residual resources.

For 6th generation engines, it is planned to introduce a variable workflow (VWF) to ensure optimal performance in different flight conditions. That’s why in this direction that research is being conducted [3] to create advanced technologies.

II. PROBLEM STATEMENT

The practical training of applying the automatic control system in industry shows that as our ideas about the control process grow, so do the control systems.

The requirements for the characteristics of the control process are such that the parameters of the control device must change depending on the operating conditions of the control object (carry another level of automatic adjustment of the control device parameters, and accordingly, the system acquires adaptive properties). In some management tasks there is a need to study the control process and use the learning outcomes to improve the characteristics of the control process.

In this case, ACS widely uses algorithms for learning and recognition, acquiring the properties of intellectual machines.

Satisfaction of the above requirements for the controlled process and its ACS becomes possible with the development of methods of adaptive and integrated engine control, which will obtain engine characteristics for specific flight conditions: the best engine efficiency in cruising, high maneuverability of the fighter aircraft, the necessary reserves of gas-dynamic stability perturbations and when flying at high altitudes, etc.

The Central Institute of Aviation Engine Engineering (CIAM named after P. I. Baranov) formulated proposals for the structure and specific methods of software and algorithmic construction of an adaptive automatic control system, which, in addition to traditional, must perform the following control functions [1]:

- recognition of the state of the engine (deterioration of characteristic units, the occurrence of failures, work in steady or transition modes, etc.);
- formation of the control purpose according to results of recognition of a condition of the engine;
- the choice of engine control method that ensures the achievement of a given goal (selection of a set of control programs that are optimal for these engine operating conditions);
- formation and selection of parameters of control algorithms that allow to ensure a given quality of control, when using selected programs.

However, today, in conditions of fierce competition, significant lag behind the leading foreign producers and the disruption of established economic ties, the time factor has an increasing influence on the process of developing ACS. Unfortunately, not all of the above requirements can be met in a short time, especially in the presence of an acute shortage of experienced professionals. On the other hand, the task of fault detection, diagnostics of deterioration of individual components and units is aimed at using the model of the engine, sensors and actuators embedded in the unit of automatic control and monitoring. This model has the most stringent performance requirements, and its accuracy directly affects the quality of diagnostics and the probability of failure.

Development of new and adaptation of existing mathematical methods in the process of creating ACS gas turbine engines in the shortest possible time and with minimal costs of material and engineering resources is an actual task. It is complex and is reduced at different stages to solving various mathematical and engineering problems. Without the involvement of computers and thoughtful use of mathematical models to solve the problem is not possible.

There was a unique situation when a number of important factors influencing the development of ACS aviation engines coincided, namely:

- revolutionary development of electronic computing devices, that allow to solve the problems of control and diagnosis of gas turbine engines at a new level with the involvement of previously unavailable means;
- there is a need to modernize existing ACSs in order to reduce their cost and increase the reliability of work;

- delay in the widespread introduction of modern digital ACS, due to the crisis of recent years and in this regard, the gap between the results of theoretical research and the mathematical technique of the devices actually used.

Today, automatic control systems for power plants are characterized by the following main features [1] – [3]:

- Modern electronic ACS type FADEC are built on a centralized principle. In this case, all tasks of signal processing, formation of programs and algorithms of control, monitoring and diagnostics are carried out in the central computer of ACS gas turbine engine (GTE). The sensors and actuators of such systems have analog inputs and outputs and are connected to the computer via analog communication lines; to increase the reliability of the ACS, a two-channel construction of the system is used, in which a hydromechanical backup regulator can be used.
- Gas turbine engine fuel supply systems are built on the basis of unregulated performance from drives from the drive box of engine units.
- Algorithmic support of ACS GTE is formed in the form of programs and control algorithms, which are based on control parameters available for measurement.

It is necessary to expect improvement of ACS of engines in the following directions [1], [3]:

1) creation of perspective methods of GTE control, carrying out adaptation of control of power plant to operating conditions (change of thermal condition of the engine, wear of knots, etc.) integration of control of working process in the engine and modes (stages) of flight, compensation of failures in the engine and ACS (operational control, recognition) situations, system reconfiguration);

2) the implementation of these methods in intellectual ACS will allow to move to the construction of an intellectual gas turbine engine, which actively controls the combustion process in the combustion chamber, gaps in the blades, reserves of gas-dynamic stability of compressors, etc. Creating an intellectual gas turbine engine requires the development of new intellectual engine components, which allow depending on the engine mode to change the fuel distribution in the fuel combustion zones, change the flow profile of the engine in compressors and turbines, control the injection and extraction of air in blades, etc;

3) transition from the centralized to the distributed architecture of construction of ACS GTE will allow to reduce quantity of radial communication lines due to transition to multiplex channels of information exchange, to simplify troubleshooting, localization of failures and reorganization of structure, integration of aircraft and engine hardware, to reduce probability of destruction of all system and thus increase its survivability. The use of distributed ACS allows to reduce the cost of system upgrade, simplify the certification process and reduce the cost of the full life cycle of the system from design to operation. The basis for the creation of a distributed ACS should be intellectual sensors and actuators, high-temperature element base and high-speed information lines;

4) introduction of wireless technologies in control and monitoring systems of gas turbine engines will allow to create highly efficient systems of new generation with flexible, easily changeable structure, reduce weight and dimensions by reducing the number of connectors and cables, increase ACS reliability, reduce maintenance costs and increase fire safety.

As a result, the task of developing the latest methods of control of aviation gas turbine engines and methods of building control systems that will optimize the work of gas turbine engines in terms of changing its mathematical model during operation, taking into account the new capabilities of digital electronic systems is actual. At the same time, it became possible to refine a number of successfully used algorithms to improve the quality and reliability of their work.

III. FEATURES OF ADAPTIVE CONTROL OF AVIATION GAS TURBINE ENGINES

The characteristics of the engine in operation can deviate significantly from the optimal under the influence of various external and internal factors: changes in pressure and temperature of air (gas) in flight; deterioration of the characteristics of the engine components during wear or when changing the thermal state of the structure in transition modes of operation; changes in the power taken from the engine shaft and the amount of air from the tract; uneven flow at the inlet; the appearance of damage and failures in the engine and its systems, etc. At the same time it is necessary to provide an opportunity to receive in the set conditions characteristics, to keep (GDS), to prevent destruction of the engine, to provide stability and quality of control processes, that is to adapt to operating conditions. This possibility is largely determined by the ACS, which must be built as adaptive to solve problems.

Elements of adaptation are found in the first ACS GTE. Modern digital electronic ACS, which process a large amount of information and implement complex control algorithms, allow for a deeper adaptation of engine characteristics by methods and means of control.

Automatic control system is performed at two levels [1]. At the upper level the control purpose is formed and the correction of control programs is carried out, at the lower level adaptive control algorithms are formed, which allow to implement the control programs formed at the upper level for all conditions of engine operation.

Recognition of the state of the engine is a basic task and necessary for the formation of the purpose of control and selection of the appropriate set of programs and algorithms. Here you can select:

1) Recognition of deterioration of node characteristics [5], [6]: at steady-state operating modes of reduction of engine thrust under the action of factors of different physical nature, which leads to deterioration of gas generator node characteristics (wear, unheated structural elements, etc.) can be identified by analysis of change dependence $\pi_p^*(T_{T.g}^*)$, where π_p^* is the degree of pressure increase in the engine; $T_{T.g}$ is the temperature of the gas behind the turbine. The reduction of thrust by the same amount corresponds to the same offset of this dependence. To recognize the condition in the ACS can be introduced dependence $\pi_p^*(T_{T.g}^*)_n$ which corresponds to the engine with rated characteristics. The difference between the nominal and actual value of the parameter π_p^* can be used as a measure of the deterioration of the characteristics of the engine and the control signal in the system.

2) Recognition of steady-state and transition modes of operation of the engine [1], [5], [6] is necessary for the introduction of adaptive programs and control algorithms that allow to determine the steady-state operation of the engine, in which the modulus of deviations of adjustable engine parameters from setpoints and absolute values of their derivatives do not exceed setpoints. Inertial calculation of derivatives for the purpose of noise filtering is allowed.

3) Recognition of the defective control channel [5] by the mechanization of the flow part in the gas turbine engine with adjustable compressors and adjustable nozzle can be performed using the dependence $S = f(\pi_T^*)$, where S is the sliding of the rotors; π_T^* is the total degree of expansion of the gas on the turbine.

The movement of the operating point in the plane of the coordinates S, π_T^* [5], [7] when reducing the thrust of the engine in case of failure of one of the control channels of these regulators and during normal throttling occurs in significantly different directions, regardless of the flight mode. If when the thrust decreases, as the parameter decreases π_p^*, the value π_T^* increases with a small change in slip S, then the failure occurred in the nozzle control channel [7]. If the value S decreases sharply, and the value π_T^* changes slightly, the failure occurred in the control circuit of the fan [1], [2], [5], [7]. And, if the increase S is accompanied by a slight change π_T^*, the failure occurred in the control circuit of the compressor [1], [2], [5], [7].

Based on the results of the identification in the ACS, a control reconfiguration can be performed to minimize the impact of the failure on the engine characteristics.

Expanding the possibilities of engine adaptation is associated with the use of control methods adapted for these purposes.

As one of such methods can be used an alternative method of throttling the gas turbine engine with a small change in the speed of the rotors, developed by O.S. Gurevich and F.D. Holberg [2], [3]. It can be used on a motor that has a wide range adjustable compressor and nozzle. To implement it, the control program for setting the angles of the compressor φ_{cA} and the critical cross-sectional area of the nozzle F_{cr} is adjusted according to the position of the CRE, and fuel consumption in the combustion chamber is determined by providing a small change in compressor speed during throttling [2], [5]:

$$n_{C\min} = 0.9 \ldots 0.95 \cdot n_{rma},$$

where $n_{C\min}$ the speed at minimum thrust.

With traditional methods of controlling the throttle of the engine by thrust from its maximum value $P = P_{\max}$ to the value $P = P_{SG}$ corresponding to the small gas (SG) mode, is carried out by significantly reducing the speed of the rotors [1], [2], [5], [7].

For obtaining the maximum range of thrust change during throttling by the alternative method when approaching the mode $P = P_{\min}$, the nozzle is fully opened and covered by the compressor. It is possible to form control programs in such a way as to obtain and maintain the efficiency of the engine in cruising modes as in conventional control [1], [2], [5], [7].

The use of this method of throttling can be used to adapt engine characteristics to operating modes by reducing the duration of the processes of intake and discharge, increase the GDS of the compressor in these modes, to reduce thermocyclic damage to the turbine blades and increase engine life of multi-mode aircraft.

If the purpose of control is to increase the service life of a multi-mode aircraft engine, where the resource is significantly affected by low-cycle fatigue, the fuel metering program at the intake is selected from the condition of maintaining the intake time as in normal control. But in this case, the maximum rate of change of the blade temperature in the transient mode is reduced by more than 2 times compared to the same process under normal control, significantly reduces the extent of deformation in the cycle of pick-up in the range of SG-MAX. The cyclic durability of TFE blades at critical points of the blade increases by 1.5–2 times [1], [2], [5], [7]. At the same time all other requirements to characteristics of the engine on transition operating modes are carried out.

Another possibility for adaptation in transition modes of operation of the gas turbine engine is provided by the use of air bypass at the CHP with interconnected control of its size and fuel consumption in the combustion chamber. In this case, adaptive management of the stocks of gas-dynamic stability of the CHP can be carried out.

If the purpose of control at a particular stage of the flight is to reduce the intake time of the engine (for example, to perform a maneuver), then increasing the intake of air at the intake and increase, thus increasing its GDS reserves, you can increase excess fuel entering the combustion chamber. The process will proceed with increased acceleration of the rotors and, as a consequence, the intake time will decrease. Restrictions in this case will be permissible gas temperature.

If it is necessary to increase the stocks of GDS CHP in the process of engine intake, the increase in air intake may not be accompanied by an increase in fuel consumption. The ability to reduce GDS stocks consumed in transient modes also allows you to improve engine performance and steady-state modes by using part of the stocks that are reserved for transition modes.

Since the control programs under consideration in this method of control are different for transient and steady-state modes of operation of the engine, the system must provide for the recognition of the operating mode.

In recent decades, the most studied class of adaptive control systems are searchless and search adaptive systems, that provide the required quality of control in the circuits of automatic stabilization and tracking, when changing the characteristics of the environment and the object [2], [3].

In search systems, some quality indicator is characterized by some unstable dependence on some input variables. The task of the system is to maintain this indicator, which is equal to the extreme value, by changing the input values of the system. The reasons that require adjustment are changes in the effects on the system and the deviation of the parameters of objects from their optimal values. Deviations can be detected by the organization of test movements of the system with the subsequent analysis of input and output information or by analyzing the operating signals. The first method is implemented through the use of special search motions (test signals), the second is on the basis of analytical calculations performed by a computing device.

More effective are searchless methods, that are characterized by high speed and accuracy. These methods are based on schemes of direct or indirect adaptive control [5], [7].

In the case of direct adaptive control during the operation of the system, some characteristics of the system model are measured, which are then used to correct the adjusting parameters of the controller in order to further reduce them to zero or a small allowable value.

In the case of indirect (identification) adaptive control, the object is pre-identified, after which the controller settings are calculated according to the evaluation parameters.

The structure of the adaptive system in the conditions of immeasurable perturbations with parallel operation of adaptation methods is shown in Fig. 1.

The task of synthesis of an adaptive engine control system includes [7]:

1) Selection of structure and configurable parameters of the controller: unknown parameters of the object are replaced by the corresponding configurable parameters using identification algorithms.

2) Synthesis of the adaptation algorithm and substantiation of the efficiency of the adaptive controller.

Improvement of ACS PP engines will allow to create methods of control of GTE which carry out adaptation of control of PP to operating conditions, integration of control of working process in the engine and flight modes, compensation of failures in the engine and ACS.

IV. SELF-ORGANIZING TRANSITION PROCESSES OF ACS GTE

Consider the block diagram of the ACS GTE, in which the two channels have a zone of joint work (Fig. 2).

Nonlinear elements NE$_1$ and NE$_2$ exclude the joint operation of the channels $|\Delta X_1|$ and $|\Delta X_2|$ more than the linearity of the regulators. If the actuator is an astatic link, then each autonomously operating channel is astatic. However, in the zone of linearity when working together, each channel becomes static and a static error appears. Indeed, for the control channel X_1, the astatic servomotor is covered by feedback containing $W_{E_2}(s)$ and $R_2(s)$. The transfer function of the open parameter control system will take the form [1]

$$W_{\text{o.s}}(s)=\frac{R_1(s)W_E(\text{s})k_{\text{i.M}}}{s+k_{\text{i.M}}W_{E_2}(\text{s})R_2(s)}. \qquad (1)$$

Since neither $W_{E_2}(s)$ is, nor $R_2(s)$ is it a differentiating link, it is a transfer function of a static system. Similar results are obtained when consideration of the parameter control channel X_2. The value of the static error may be unacceptably large.

As can be seen, from expression (1), the structure of the open system of each channel changes, which, in the general case, can lead to a decrease in the areas of stability of the system in the area of joint work.

The most expedient integration of control loops of several parameters with one regulating influence by means of the selector. The ideal selector eliminates the area of joint work. Such selectors include electronic and digital. Hydraulic selectors allow joint work in a fairly narrow area. In integrated ACS GTE built on the basis of electronic devices, the channels are combined using a selector.

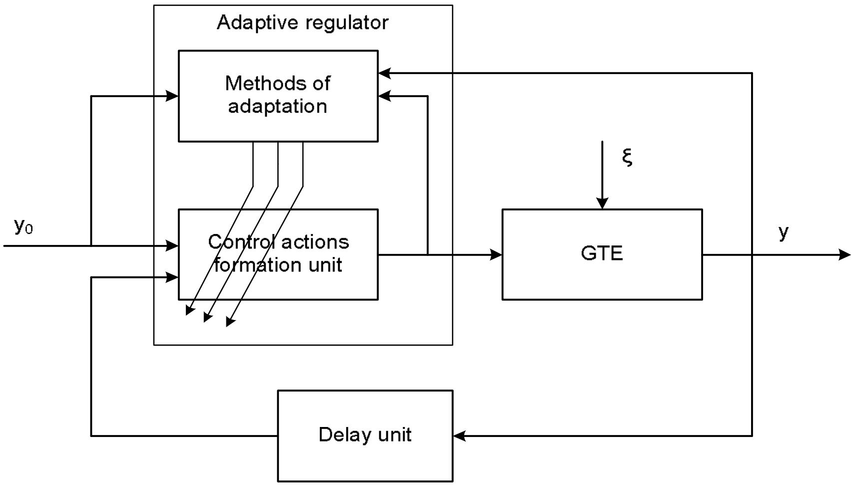


Fig. 1. Structural diagram of the adaptive ACS GTE [2]

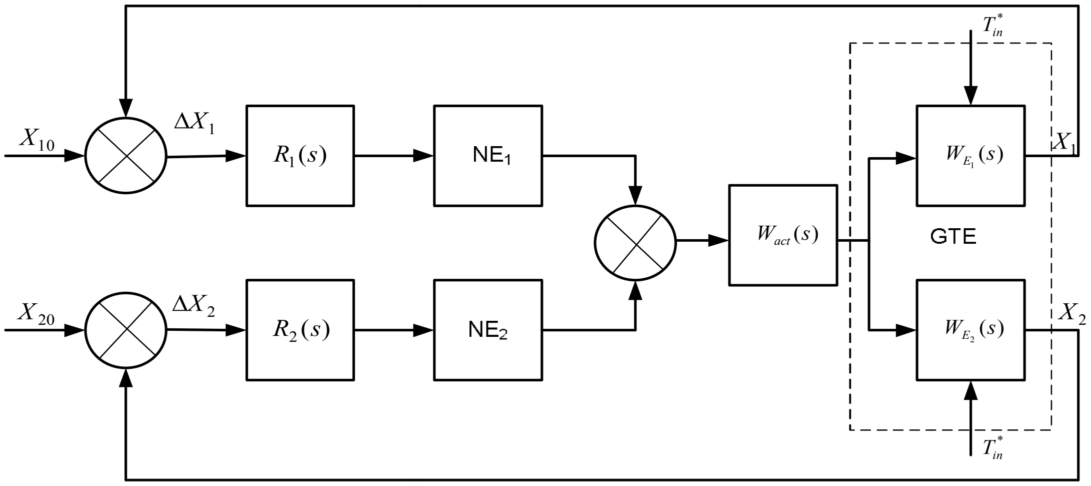


Fig. 2. Block diagram of ACS with two adjustable parameters and one regulating influence [1], [7]

In Figure 3 shows the transitions with accurate compensation of the inertia of the thermocouple (*a*), undercompensation (*b*) and overcompensation (*c*). It is seen, that in case of undercompensation, there are accusations of parameters due to the late entry of the limiter into operation, but the thrust increases faster; at overcompensation the temperature regulator comes to work earlier, than the put moment therefore processes on all parameters are tightened.

In order to ensure the required quality of channel interaction in multidimensional multiconnected ACS, it is necessary to formulate these requirements at the stage of synthesis. Although this can be done most often in a linear approximation, issues such as autonomous control, invariant control [1] – [8], etc., can be solved at this stage.

The block diagram of a separate channel of the ACS GTE has the form of Fig. 4. Transfer function for GTE can be obtained from [1] – [3].

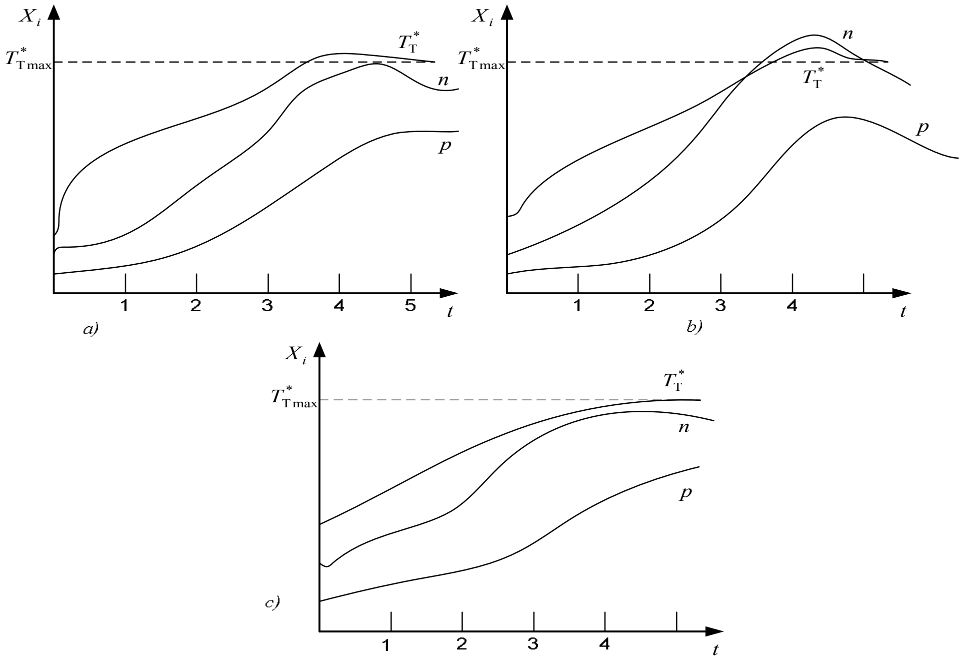


Fig. 3. Dependence of transitions in the integrated ACS of the gas turbine engine on the parameters of the gas temperature regulator [1], [7]: (a) compensation of the inertia of the thermocouple; (b) undercompensation; (c) overcompensation

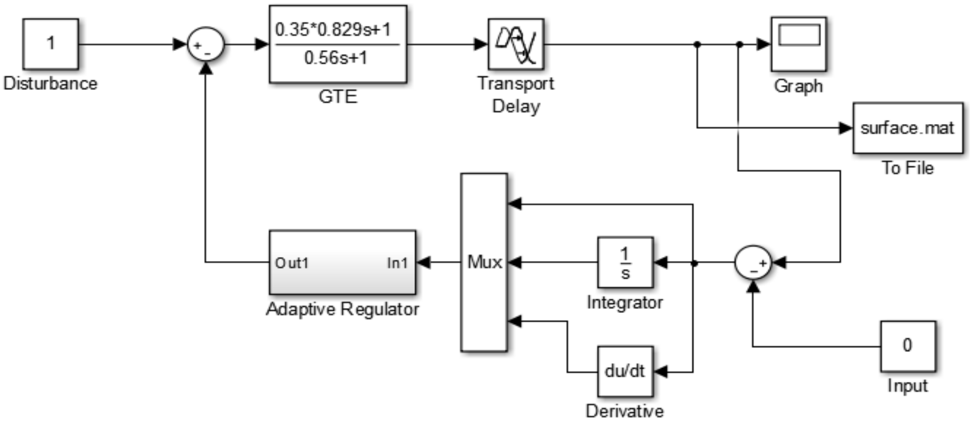


Fig. 4. Block diagram of a separate channel ACS GTE

For the implementation of PID a similar regulator, it is necessary in the structural diagram of the model to add a differential warehouse signal of failure, and a block of differentiation Derivative.

The file law.reg (surface.mat) can be used as a basis for the file that implements the PID-law of regulation.

For the design and investigation of the transition process of ACS GTE the graph solution "Surfer" have been presented (Fig. 5).

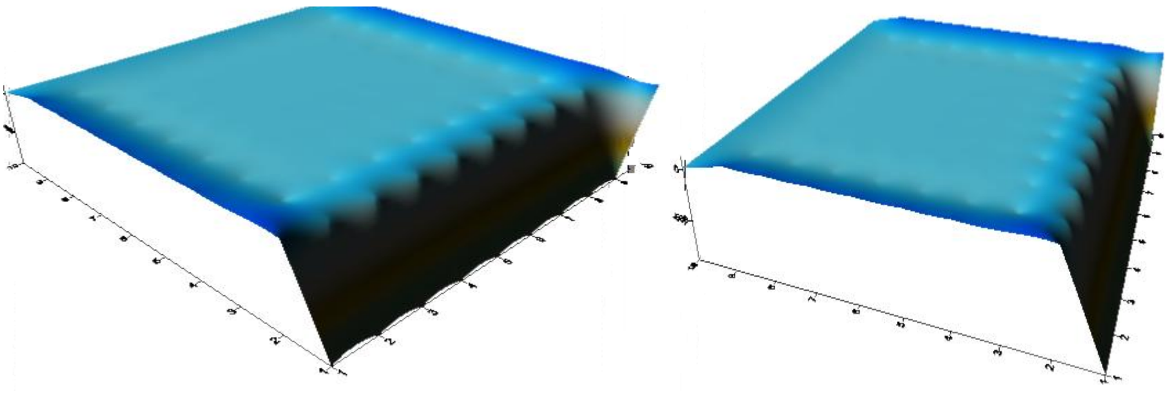


Fig. 5. Transient process graphs of ACS GTE

V. CONCLUSIONS

Analyzing the current state of development of gas turbine engine control systems, development prospects and their construction features, there is a need to develop adaptive control systems that are closely related to the development of electronic technologies for information exchange. This combination will allow automatic control to obtain engine characteristics for specific flight conditions, in particular, the efficiency of the engine on cruising flight, high maneuverability of the fighter aircraft, the necessary reserves of gas-dynamic stability under strong disturbances (external and internal) and at high altitudes.

Since the early 2000s, the United States has been actively working to create a scientific and technical development (STD) for 6th generation engines and their control systems (VAATE, AETD, INVENT, etc.), whose budget funding through the United States in recent years is 400...450 million dollars [1].

A conceptual study of the engine by Boeing, General Electric, Lockheed Martin, Nortrop Grumman, Pratt & Whitney and Rolls Royce has shown that the creation of an adaptive three-circuit engine [1], [3] will significantly improve fuel efficiency compared to the transition from turbojet engine to turbojet two-circuit engine.

Due to the wide adjustment of the nodes and the presence of an independently adjustable third circuit, the adaptive engine allows for low specific fuel consumption during long cruising flight at subsonic speed and barrage, inherent in engines with a high degree of double-loop, and high specific thrust in various modes, including short takeoff supersonic flight, maneuvering, interception, etc., inherent in engines of low degree of double-loop.

The main characteristics of electronic ACS, its connection with Onboard Electronic Computing Machine (OECM) are revealed and on the basis of the principle of adaptation according to the parameter of gas temperature behind the turbine gas turbine in the intake mode the use of a regulator with variable structure is proposed. At rather big stocks of stability, and also its distinctive feature is that in a control circuit definition of not value of temperature, and a signal from an exit of a thermocouple is carried out

Implemented programs of the described regulators in OECM are executed in time $(1.1...1.8)\cdot 10^{-3}$ s.

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Received September 17, 2020

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С. С. Товкач. Регулятор перехідного процесу самоорганізованої системи керування авіаційним двигуном

В статті розглянуто тенденції розвитку авіаційного двигунобудування, які визначаються на використанні новітніх досягнень науки для забезпечення високих вимог за експлуатаційною надійністю, економічною ефективністю, екологічністю і безпекою. Кожне нове покоління авіаційних газотурбінних двигунів характеризується комплексом реалізованих на виробництві і впроваджених в експлуатацію технологій, короткий перелік яких дозволяє сформувати визначення поколінь авіаційних газотурбінних двигунів на основі аналізу світової практики авіаційних двигунів. Виявлено основні особливості процесу проектування адаптивних систем автоматичного керування газотурбінними двигунами з метою інтеграції керування робочим процесом в двигуні і режимів польоту для відображення методологічної, математичної, кібернетичної і інформаційної сторони досліджень. Основні закони керування та структурні схеми системи автоматичного керування можуть визначатися у вигляді програм керування на максимальному режимі роботи двигуна, дросельних режимах, режимі малого газу, прийомистості і скидання газу, на форсованих і перехідних режимах. Запропоновано використання зі змінною структурою регулятора для дослідження перехідних процесів систем автоматичного керування та представлена практична реалізація перехідних процесів.

Ключові слова: автоматична система керування; авіаційний газотурбінний двигун; перехідний процес; адаптивний регулятор; самоорганізація.

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Освіта: Черкаський національний університет імені Б. Хмельницького, Черкаси, Україна, (2011).
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С. С. Товкач. Регулятор переходного процесса самоорганизующейся системы управления авиационным двигателем

В статье рассмотрены тенденции развития авиационного двигателестроения, которые определяются на использовании новейших достижений науки для обеспечения высоких требований по эксплуатационной надежности, экономической эффективности, экологичности и безопасности. Каждое новое поколение авиационных газотурбинных двигателей характеризуется комплексом реализованных на производстве и внедренных в эксплуатацию технологий, краткий перечень которых позволяет сформировать определение поколений авиационных газотурбинных двигателей на основе анализа мировой практики авиационных двигателей. Выявлены основные особенности процесса проектирования адаптивных систем автоматического управления газотурбинными двигателями с целью интеграции управления рабочим процессом в двигателе и режимов полета для отображения методологической, математической, кибернетической и информационной стороны исследований. Основные законы управления и структурные схемы систем автоматического управления могут определяться в виде программ управления на максимальном режиме работы двигателя, дроссельных режимах, режиме малого газа, приемистости и сброса газа, на форсированных и переходных режимах. Предложено использование регулятора с переменной структурой для исследования переходных процессов систем автоматического управления и представлена практическая реализация переходных процессов.

Ключевые слова: система автоматического управления; авиационный газотурбинный двигатель; переходной процесс; адаптивный регулятор; самоорганизация.

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Образование: Черкасский национальный университет имени Б. Хмельницкого, Черкассы, Украина, (2011).
Направление научной деятельности: методы построения систем управления и диагностики систем воздушного судна.
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