POWER MACHINERY

UDC 681.51:621.452.3(045)
DOI:10.18372/1990-5548.72.16938

S. S. Tovkach

CONTROL LAWS OF THE AVIATION GAS TURBINE ENGINE

Automation & Power Management Department, National Aviation University, Kyiv, Ukraine
E-mail: ss.tovkach@gmail.com

Abstract—*The article is devoted to the solution of an important scientific and applied problem of improving the dynamic characteristics of an aviation engine and ensuring flight safety and the efficiency of aircraft operation, taking into account the properties of adaptive control of an aviation gas turbine engine: <structure><functioning><adaptation><development>. Based on the concept of creating perspective aviation engines with an increased level of control automation and with units operating at elevated temperatures and protected from high-energy electromagnetic radiation, the basic laws of controlling an aviation gas turbine engine in throttle modes, low-throttle mode, gas intake and discharge modes, and start-up mode are defined. To improve the working process of the engine, it is proposed to use the gas turbine engine control system as a mechatronic system based on the principle of adaptation. With the help of the Laplace transformation, the dynamic characteristics of the power plant were determined and the mathematical model of the power plant was investigated as a constructive aspect of the automatic control system. The gas turbine and the supersonic air manifold can to some extent be considered as independent control objects, replacing the connections between them with disturbing influences. For the control and limitation circuits, it is necessary to create control programs that calculate the values of the control parameters of the turbocharger rotor speed and gas temperature behind the turbine. Regulation of fuel consumption is carried out according to the derivative of the control parameters.*

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

I. INTRODUCTION

It is known from the theory of aviation engines [1], [4] that under constant external conditions, thrust and engine efficiency are determined by the values of pressure increase $\pi^*_{pincr} = p^*_{ec} / p^*_{in}$ and heating of the working body $\tau_0 = T^*_g / T^*_{in}$, which are characterized by two parameters: the degree of pressure increase in the compressor π^*_c and the gas temperature in front of the turbine T^*_g. For an engine with an afterburner, heating $\tau_f = T^*_f / T^*_{in}$ and gas temperature in the afterburner combustion chamber are added. These parameters make it possible to determine the level of mechanical and thermal loads acting on the engine structure. In practice, gas turbine regulation is carried out according to parameters that indirectly characterize π^*_c, T^*_g and T^*_f: rotor rotation frequency n_i, gas temperature behind the turbine T^*_t, sometimes the temperature of the turbine blades T_{bl} (instead of temperature T^*_g), a set of parameters G_t / p^*_c, $G_{t.f} / p^*_c$ etc.

Under constant external conditions (H, M, T_{en}), maintenance of set constant values of control parameters allows to ensure effective and stable operation of the engine.

The influence of external conditions is primarily related to the change in pressure p^*_{in} and temperature T^*_{in} of the air entering the engine. The change in pressure p^*_{in} ($T^*_{in} = \text{const}$) is determined by the proportional change in air flow and pressure in the engine path, but the given parameters $\left(n_{giv}, \pi^*_c, \pi^*_T\right)$, which determine the characteristics of the engine components and their modes of operation, do not change to a large extent during operation.

When the value changes T^*_{in}, the given parameters also change, as well as the position of the operating points and characteristics of the nodes, and accordingly, the conditions of similarity of the engine operating modes. Therefore, the effect of changing the flight mode can be taken into account for most modes by using temperature-dependent T^*_{in} control programs. In flight modes, for example, at high altitudes, it is necessary to take into account the change in pressure p^*_{in} and some other factors.

II. PROBLEM STATEMENT

The number of regulating factors of the gas turbine depends on its scheme and the degree of mechanization of the flow part and includes the fuel consumption in the main G_t and afterburner $G_{t.f}$ combustion chambers, the area of the critical cross-section of the jet nozzle F_{cr}, the setting angles of the guiding devices (GD) compressor blades, etc. A distinctive feature of the gas turbine as a control object is the excess of the number of regulated parameters over the number of regulatory factors, which determines the specifics of the construction of the automatic control system gas turbine engine.

The choice of a combination of adjustable parameters and regulating factors of the engine depends on the purpose of the engine, the requirements for its characteristics, the construction scheme, the number of adjustable elements, etc. These combinations are specified in the form of control programs, which represent the dependence of control parameters (or control factors) on external conditions (T_{in}^*), control factors, and sometimes other control parameters (Fig. 1).

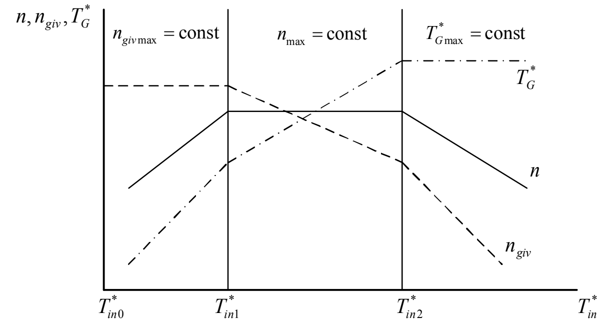

Fig. 1. Combined control program

As a result, the aim of the research is to develop the latest methods of control of aviation gas turbine engines that will optimize its operation in throttle modes, low-throttle mode, gas intake and discharge modes, and start-up mode based on principle of adaptation and wireless technologies.

III. ENGINE OPERATING MODES

A. Gas turbine engine regulation on throttle modes [1] – [3]

Throttle modes are set using the engine control regulator (RCE) and are carried out mainly when reducing fuel consumption. The main requirement for these modes is to obtain the greatest economy, primarily in cruise modes [1], [3], [7].

The best economy of the engine at cruising modes can be achieved if the reduction in thrust is accompanied by a significant decrease in gas temperature T_g^* with a minimal change in air flow G_{ch} and the degree of pressure increase π_c^*. On the characteristics of the compressor, the area of the location of the lines of throttle modes with different control programs can be highlighted. The limits of this area are the lines of the throttle modes, which correspond to the programs $n = n_{\max} = \text{const}$, $T_G^* = T_{G\max}^* = \text{const}$. Implementation of such programs requires control of the critical cross-sectional area of the nozzle F_{cr} [1], [3] – [5].

If there is a minimum on the curve $C_{spec}(n)$, it is advisable to use combined programs to optimize the engine in terms of economy, for example, those in which the initial state of throttling is carried out according to the program $n_{\max} = \text{const}$ until the mode suitable $C_{spec\min}$ for this program is reached, and then when reducing n. It should be borne in mind the need to obtain a sufficiently high rotation frequency in the low gas mode (LG), which allows to reduce the reception time. In an engine with an adjustable nozzle, its opening in this mode allows by reducing T_g^* to obtain the necessary thrust at increased values $n_{\lg}$ of frequency and specific consumption C_{spec}. Deterioration of economy in the GLG mode is not of great importance. At the same time, the reduction of the range of changes n in the interval $n_{\lg} \ldots n_{\max}$ and the possibility of a more significant increase T_g^* from $T_{g\lg}^*$ to $T_{g\max}^*$ in the process of engine reception leads to a decrease in reception time. The program for adjusting the fuel consumption with a decrease in the rotation frequency $n = f\left(T_{in}^*, \alpha_{rce}\right)$ was the most widespread for control in throttle modes. Such throttling occurs when reducing C_{spec} in cruising modes [6], [7].

A number of additional control programs are also used to improve economy in cruising modes, for example, a special damper control program that changes the flow of air taken from the compressor to cool the turbine of high-temperature engines.

Reducing the intake of air at the speed of rotation corresponding to the range of cruising modes contributes to the reduction C_{spec}.

B. Control programs in low gas mode

Peculiarities of gas turbine engine (GTE) regulation in the LG mode follow from the necessary requirements for this mode. The main one of them is the requirement to obtain the minimum thrust at engine operating mode parameters that provide the required time of intake and the necessary reserves of stability of the compressor and combustion chamber, when there is a limitation of the area of stable operation of the latter due to "poor" failure [6].

When choosing control programs in the LG mode, it is necessary to take into account the problems of engine and aircraft integration [3], [6], [7].

In the ground low gas (GLG) mode, it is advisable to maintain a constant thrust when external conditions change. The required thrust in flight low gas (FLG) modes is determined by the type and characteristics of the aircraft, as it depends on the allowable glide slope angle, the aerodynamic quality of the aircraft, and its take-off thrust armament. Thus, for a subsonic passenger aircraft, the thrust required for a safe descent is significantly greater than for a maneuverable supersonic aircraft, the descent trajectories of which are steeper. In some cases, for example, in the presence of long braking modes, the economy of the PMG mode is of some importance. When flying at high supersonic speeds, it is necessary to limit the throttle range of the engine due to the limitation of the movement of the software control bodies. In this case, an increase in flight speed should be accompanied by an increase in the rotation frequency n_{LG} in the FLG mode.

The most complete requirements for the LG mode can be satisfied by the use of type regulation programs $n_{LG}=f\left(T_{in}^{*},p_{in}^{*}\right)$. But simpler programs are often used for hardware implementation $n_{LG}=f\left(T_{in}^{*}\right)$, $n_{LG\,giv}=\text{const}$, $G_{T\,LG}=\text{const}$, $G_{T\,LG_{giv}}=\text{const}$, $n_{LG}=\text{const}$, as well as their combinations. To protect against flame failure in the main combustion chamber, programs for limiting the minimum fuel consumption are used, for example, the program $G_{T\min}=\text{const}$.

IV. CONTROL CIRCUIT AND REGULATOR WITH ADAPTIVE STRUCTURE OF ACS GTE

Let's get the control program (control law) for the low gas mode in the form of ACS GTE by rotation frequency.

Automatic control system (ACS) is a closed circuit of the main feedback, which performs deviation control. In the circuit there is also a flexible local feedback, which is designed to stabilize the ACS, which helps to ensure that the ACS is quite stable. The presence of feedback loops in the ACS indicates that the system may be unstable, so the analysis of the ACS should include an estimation of its stability and, if necessary, the selection of measures and means for its stabilization.

Main transfer functions:

1) The transfer function of the *amplifier*:

$$W_y(s)=\frac{k_y}{sT_y+1}=\frac{34}{0.074s+1}.$$

2) The transfer function of the *thyristor converter*:

$$W_{thc}(s)=\frac{k_{thc}}{sT_{thc}+1}=\frac{43}{0.064s+1}.$$

3) Transfer function of the *generator*:

$$W_g(s)=\frac{k_g}{sT_g+1}=\frac{1.44}{0.22s+1}.$$

4) *Flexible voltage feedback* transfer function

$$W_{fvf}(s)=\frac{k_{fvf}sT_{fvf}}{sT_{fvf}+1}=\frac{0.29\cdot 0.19\cdot s}{0.19s+1}.$$

5) Transfer function of the *tachogenerator*:

$$W_{tg}(s)=k_{tg}=0.062.$$

6) Transfer function of the direct current (*DC) motor* through the control channel

$$W_{DCM}(s)=\frac{k_{DCM}}{T_aT_Ms^2+T_Ms+1}$$
$$=\frac{2.6}{0.1048\cdot 1.2s^2+1.2s+1}=\frac{2.6}{0.12576s^2+1.2s+1}.$$

7) Transfer function of the *DC motor* through the disturbance channel:

$$W_{DCM}(s)=\frac{-k_{DCM}(sT_a+1)}{T_aT_Ms^2+T_Ms+1}=\frac{-1.45(0.1048s+1)}{0.12576s^21.2s+1}.$$

8) 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:

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

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

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

10. The transfer function of the PID controller has the form:

$$W_r(z) = \frac{Ck_P(1-k_D) + CTz + Tk_I + CT\sin(\pi z/2)}{4(z^2 - z)}.$$

The set of transfer functions of the elements and the functional scheme allows to build a structural-algorithmic model of the ACS GTE, as well as an analytical model, which is a transfer function of the entire ACS. In this example, an analytical tool is used – the VisSim program, which eliminates the need for cumbersome explanations for obtaining an analytical model of the ACS (Fig. 2).

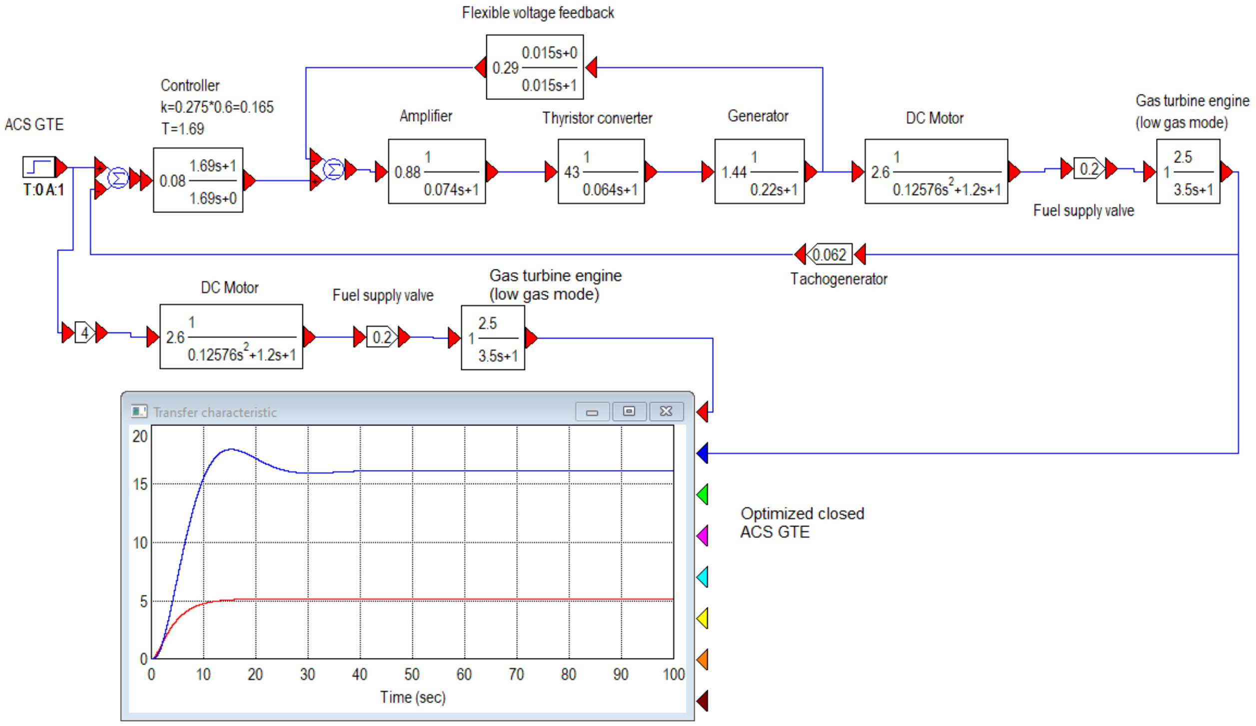

Fig. 2. Engine operation at low throttle

V. CONCLUSIONS

An important factor in modeling the adaptive control of the GTE is the emergence of adaptation properties to specific flight conditions and their impact on the engine's work process.

Formulated requirements for the selection of programs and control algorithms of the ACS GTE, which affects the construction of strength and thermodynamic characteristics, ensuring the stability of work processes, in turn, economy, flight safety and maneuverability.

A combination of adjustable parameters and engine control factors is established in the form of control programs, combined control programs. Formulated control programs for regulating GTE in throttle modes; low gas mode; gas intake and discharge modes, start-up mode.

With regard to the control circuits, the algorithms for the operation of the Onboard digital machine (OnBDM) ACS of the gas turbine according to the channel for regulating the temperature of the gases behind the turbine and the frequency of rotation of the gas turbine have been formulated. Dependences of parameters for construction of control laws of ACS of GTE, time diagram of BCM operation, characteristic equations of the system were obtained, and quality and accuracy of ACS were investigated.

Most often, digital laws are used in control circuits of control systems (P-, PI-, PD-, PID-regulators). In addition, due to the significant logical and computational capabilities of the BCOM, nonlinear control, changing the coefficients of the regulators according to the operating modes of the engine and aircraft are added to the laws in order to obtain adaptive properties of the system and optimize characteristics.

To create an adaptive ACS, it is suggested to use soft computing: fuzzy logic and artificial neural networks. The main methods of setting the PID controller can be: "classic", fuzzy and neuron-fuzzy.

The obtained ACS GTE regulator is built on the basis of the Liebman averaging process.

REFERENCES

[1] Yu. M. Tereshchenko, L. G. Volanska, M. S. Kylik, and V. V. Panin, *Theory of aviation gas turbine engines*, Manual, 2005, 500 p. (in Ukrainian).

[2] EUROCAE – standarts for future aviation. Access mode: http://www.eurocae.net/

[3] Yu. M. Tereshchenko, V. A. Boguslaev, E. V. Doroshenko, I. F. Kravchenko, I. A. Lastivka, M. M. Mitrakhovich, and Yu. Yu. Tereshchenko, "Aerodynamics of compressors of gas turbine engines with gas dynamic flow control," *Monograph*, 2019, 408 p. (in Russian).

[4] Laine Campbell, *Database Reliability Engineering: Designing and Operating Resilient Database Systems*, *O'Reilly Media*, 2017, 294 p.

[5] Biwen Lia, Jingjing Huang, Donglung Wang, "Robustness Analysis of Control Laws in Complex Dynamical Networks Evoked by Deviating Argument," *Discrete Dynamics in Nature and Society*, 2022, pp. 1–14. https://doi.org/10.1155/2022/2033708.

[6] V. P. Zakharchenko, S. V. Yenchev, S. S. Tovkach, S. S. Ilienko, "System efficiency of programmed operations of avionics," *Monograph*, 2018, 192 p. (in Ukrainian).

[7] S. S. Tovkach, "Control Circuits and Limitations for the Construction of an Automatic Control Systems for an Aviation Gas Turbine Engine," *Aerospace Technic and Technology,* 4(182), pp. 68–72, 2022. https://doi.org/10.32620/aktt.2022.4sup2.10.

Received March 20, 2022

Tovkach Serhii. Candidate of Science (Engineering). Associate Professor.
Automation & Power Management Department, National Aviation University, Kyiv, Ukraine.
Education: Bohdan Khmelnytsky National University of Cherkasy, Cherkasy, Ukraine, (2011).
Research area: methods of building of control systems and diagnosing of aircraft systems.
Publications: 114.
E-mail: ss.tovkach@gmail.com

С. С. Товкач. Закони керування авіаційним газотурбінним двигуном

Статтю присвячено вирішенню важливої науково-прикладної проблеми удосконалення динамічних характеристик авіаційного двигуна та забезпечення безпеки польотів і ефективності експлуатації повітряних суден із врахуванням властивостей адаптивного керування авіаційного газотурбінного двигуна: <будова><функціонування><адаптація><розвиток>. Ґрунтуючись на концепції створення перспективних авіаційних двигунів із підвищеним рівнем автоматизації керування та з агрегатами, працюючих при підвищених температурах і захищених від електромагнітних випромінювань високої енергії визначено основні закони керування авіаційним газотурбінним двигуном на дросельних режимах, режимі малого газу, режимах прийомистості і скидання газу, режимі запуску. Для вдосконалення робочого процесу двигуна запропоновано використання системи керування газотурбінним двигуном, як мехатронної системи за принципом адаптації. За допомогою перетворення Лапласа визначено динамічні характеристики силової установки та досліджено математичну модель силової установки в якості конструктивного аспекту системи автоматичного керування. Газотурбінний двигун і надзвуковий повітрозбірник до деякої ступені можна розглядати як самостійні об’єкти керування, замінюючи зв’язки між ними збурюючими впливами. Для контурів керування і обмеження необхідним є формування програм керування, де обчислюються значення керуючих параметрів частоти обертання ротора турбокомпресора, температури газів за турбіною. Регулювання витрат палива здійснюється за похідною керуючих параметрів.

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

Товкач Сергій Сергійович. Кандидат технічних наук. Доцент.
Кафедра автоматизації та енергоменеджменту, Національний авіаційний університет, Київ, Україна.
Освіта: Черкаський національний університет імені Б. Хмельницького, Черкаси, Україна, (2011).
Напрям наукової діяльності: методи побудови систем керування та діагностування систем повітряного судна.
Кількість публікацій: 114.
E-mail: ss.tovkach@gmail.com

С. С. Товкач. Законы управления авиационным газотурбинным двигателем

Статья посвящена решению важной научно-прикладной проблемы усовершенствования динамических характеристик авиационного двигателя и обеспечения безопасности полетов и эффективности эксплуатации воздушных судов с учетом свойств адаптивного управления авиационного газотурбинного двигателя: <строение><функционирование><адаптация><развитие>. Основываясь на концепции создания перспективных авиационных двигателей с повышенным уровнем автоматизации управления и с агрегатами, работающих при повышенных температурах и защищенных от электромагнитных излучений высокой энергии, определены основные законы управления авиационным газотурбинным двигателем на дроссельных режимах, режиме малого газа, режимах приемистости и сбросе газа, режиме. Для усовершенствования рабочего процесса двигателя предложено использование системы управления газотурбинным двигателем в качестве мехатронной системы по принципу адаптации. С помощью преобразования Лапласа определены динамические характеристики силовой установки и исследована математическая модель силовой установки в качестве конструктивного аспекта системы автоматического управления. Газотурбинный двигатель и сверхзвуковой воздухосборник в некоторой степени можно рассматривать как самостоятельные объекты управления, заменяя связи между ними возбуждающими воздействиями. Для контуров управления и ограничения необходимо формирование программ управления, где вычисляются значения управляющих параметров частоты вращения ротора турбокомпрессора, температуры газов за турбиной. Регулирование расхода топлива осуществляется по производной управляющих параметров.

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

Товкач Сергей Сергеевич. Кандидат технических наук. Доцент

Кафедра автоматизации и энергоменеджмента, Национальный авиационный университет, Киев, Украина.

Образование: Черкасский национальный университет имени Б. Хмельницкого, Черкассы, Украина, (2011).

Направление научной деятельности: методы построения систем управления и диагностики систем воздушного судна.

Количество публикаций: 114.

E-mail: ss.tovkach@gmail.com