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WIRELESS-BASED INFORMATION MODEL OF THE COMMON OPERATION OF THE ELEMENTS OF THE AVIATION GAS TURBINE ENGINE

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Abstract. The paper is focused on ensuring an automatic reliable operation of aviation engine in a wide range of modes using wireless data transmission. This also helps to reduce the weight of it's control system, the mass and dimensions of the modular construction of the engine. It is possible only on the basis of complex study of the transition processes of the aviation engine with the mutual influence of the course, from the theoretical point of view. Firstly, it is necessary to define method for start up as the process of engine transition from a state of rest in ground conditions or autorotation mode in flight to minimum stable operation mode. Then, in process start up for the initial spin up of the engine rotor, fuel supply and ignition a special starting system based on the Wireless Distributed Automatic Control System must be used in the combustion chamber. In practical application, this study can be used to create the new generation of aviation gas turbine engines and their control systems for subsonic and supersonic aircraft, identification their models based on the diagnosing the state of the engine according to dynamic ones parameters.

Keywords: aviation engine, operating modes, transition processes, wireless elements, automatic, isothermal, data transmission.

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1. Introduction

The improvement of aviation gas turbine engines (GTE) and power plants based on them is on the way to further improvement specific indicators, while simultaneously tightening the requirements on reliability and resource. Distinctive features of perspective power plants are recognized: a variety of operating modes and conditions, proximity working modes to restrictions on strength (Karpenko et al., 2023), temperature, etc functional parameters, a large number of regulatory parameters.

The use of information technology, especially wireless data transmission, significantly determines success in creating new generations of aviation engines (Litricio et al., 2022; Novakovic, 2023). A complex technical system, such as an aviation engine, in its development inevitably reaches a stage when the effective organization of its life cycle (Gutakovskis & Gudakovskis, 2021; Yepifanov & Bondarenko, 2023) in general and, above all, at the development stage requires using a systematic approach, dynamic formation of a simulation models for structural and parametric optimization.

A modern gas turbine engine is a complex dynamic system with the interrelated influence of gas dynamic and thermo physical processes occurring in its wireless nodes (Mathiyalaan & Khot, 2023; Pinelliet et al., 2023). Operation engine occurs under the influence of internal and external disturbances, and for maneuverable aircraft with a predominance of transition modes. Development of a method for mathematical modeling of thermo gas dynamic GTE processes in transition modes and its implementation in a simulation modeling system are one of the general tasks problems of computer support and automation of design stages. Due to the constant increase in requirements for modern aircraft, to their take off and acceleration characteristics, as well as to agility, the development of methods and means of increasing the efficiency of transition processes in aviation GTE allows them to study the dynamics and influence of various factors (flight modes, data exchange in Automatic Control System (ACS), environment atmospheric disturbances, inertia of rotors, gas dynamic inertia, non stationary heat exchange of the working body with the structure of the environment, dynamics of heat supply processes from the energy source, study of currents in the elements of the gas turbine, calculation of fuel afterburning in the turbine (cycle with heat supply)) on transition engine operating conditions at the design stages and fine tuning.

Researches of eminent scientists in area of design the automatic control systems the aviation engine can be defined by J. Chen in the field of aero engine real time modeling method in control system design, integration and testing for model based engine intellectual controls and health management, W. Jiao (Choo, 2019) in the field of design of a multichannel 10–14 Bits event driven single slope ramp ADC for automatic control system, H. Wang investigates advanced microelectronics technology based on emerging semiconductor materials and devices for AI hardware, Ekram Hossain in the field of design, analysis, and optimization beyond 5G cellular wireless network for adaptive control systems, Viktors Gutakovskis in the field of CNC manufacturing, material technology manufacturing automation industry, robotics, Meguid S. A. in the field of analysis of geometry effects of an artificial bird striking an aeroengine fan blade, Giuliana Litricio investigates characteristics of surfaces properties of aluminum flat products related with different annealing temperature and cleaning properties for aeroengines, Neno Novakovic published hardware design and implementation of the Landing Gear Control Algorithm, Sergiy Yepifanov interests in deviation problem in gas turbine health monitoring, synthesis of turbine engine control and diagnosing system, fault classification for gas turbine diagnostics at steady-states and transients, Shreya Mane in the field of space technologies for aeroengines, by international companies Securaplane technologies, Boeing, Dryden Flight Research Center NASA, Honewell according to the standards of EUROCAE (Meguid, 2024; EUROCAE, 2024), Radio Technical Commission for Aeronautics, Eurocontrol, ICAO, EASA and many others.

The transition operating mode of a gas turbine engine make the influence for mathematical model of the gas turbine engine and must include self description with the elements of wireless modular construction (Mane, 2023; Patwardhan et al., 2021). The goal of these research is to define method for providing stability and optimality of operating processes with the elements of wireless data transmission in the modes of aviation engine.

2. The method of the common operation of the elements of the aviation gas turbine engine

The stable modes of operation of the GTE are modes, in which the engine rotor speed and other parameters characterizing its operation do not change over time during data transmission with influence to pressure value of the compressor. Practically, it is possible to assign conditions in the form $\frac{\partial\delta\chi}{dt} \le \varepsilon$, where $\delta x = \frac{\Delta\delta\chi}{\chi_B}$, χ_B is the basic value of the parameter, and ε is the accuracy of fulfilling the stationary conditions. If this condition is defined for the main mode parameters of the gas turbine, its mode can be considered as quasi stationary. The values of χ_B and ε are chosen taking into account the modeled engine, the process, and the design reference or operational problem to be solved.

When the compressor and turbine work together in the system of a single shaft turbojet engine in equilibrium modes, the conditions for the balance of air consumption (taking into account the fuel that is injected, sampled and passed for cooling and into the air unloading system) and the balance of the effective work of the compressor and the turbine must be fulfilled at the same time (Tovkach, 2021; Schuchard et al., 2023). In the most simplified form, they look like as follows (with operating process parameters of the aviation engine, A is air flow bandwidth, B is moisture content):

The condition of equality of air flow rates is expressed by the equation (Mane, 2023; Patel & Wu, 2022).

$$\pi_k^* = G_{us}\sqrt{\frac{T_G^*}{T_O^*}}A,\ \text{where}\ A = \frac{mF_1}{m_G F_{1NA} q_{NA}\sigma_{Cch}\sigma_{NA}} = const. \quad (1)$$

The condition for the balance of effective work is expressed by the equation:

$$\frac{T_G^*}{T_O^*} = B\frac{\pi_k^{*\frac{k-1}{k}} - 1}{\eta_k^*},\ \text{where}$$

$$B = \frac{\frac{k}{k-1}R}{\frac{k_G}{k_G-1}R_G\left(1 - \frac{1}{(\pi_T^*)^{\frac{k_G-1}{k_G}}}\right)\eta_T^*\eta_{MECH}}. \quad (2)$$

In this case, the equation of the line of common operating modes of the compressor and turbine for $F_{cCW} = const$ their joint solution is described as follows:

$$\frac{G_{US}^2}{\eta_k^*}\frac{\pi_k^{*\frac{k-1}{k}} - 1}{(\pi_k^*)^2} = \frac{1}{A^2B} = const. \quad (3)$$

A line that satisfies this equation and passes through the calculation point is called a working line or a working characteristic (the abbreviation LWM is more often used is the line of working modes (Patwardhan et al., 2021; Eriksen Hammer et al., 2023)). The Equations (1), (2), (3) are obtained taking into account a number of assumptions: only for the supercritical pressure drop at the nozzle outlet, changes in the turbine characteristics ($\eta_T^* = \text{const}$), the possibility of changing air selection in the path and leakage, the area of the critical cross section of the nozzle $F_{NCR} = const$ and the flow coefficient $\mu_n = \text{const}$ were not taken into account.

The similar considerations were carried out to obtain the equation of the operating line of unstable modes (phase trajectory of the transient process), in which the engine rotor speed and other parameters characterizing its operation change over time.

Operating line (phase trajectory) on the characteristic of the compressor

$$F(\pi_k^*, n, t) = 0 \quad (4)$$

proceeds from the following premises:

1) equality of gas flow through characteristic cross sections

$$G_G = G_k + G_F - \Delta G_{sel}, \quad (5)$$

where $G_G = q(\lambda_{NA})\frac{p_G^*}{\sqrt{T_G^*}}F_{NA}m_G\sigma_{NA}$, (6)

$$G_k = f(G_k, T_G^*, T_k^*), \quad (7)$$

where $$T_k^* = T_O^* \cdot \left(1 + \frac{\pi_k^{*\frac{k-1}{k}} - 1}{\eta_k^*}\right). \quad (8)$$

For the sake of simplicity H_u and η_G, the constants are assumed at this stage.

2) equality of rotation frequencies of compressor and turbine rotors ($n_K = n_T$);

3) power balance on the turbojet engine shaft:

$$N_T - N_k - N_{agr} = \left(\frac{\pi}{30}\right)^2 Jn\frac{dn}{dt}, \quad (9)$$

$$N_T = G_G \frac{K_G}{K_G - 1} R_G T_G^* \left(1 - \frac{1}{(\pi_T^*)^{\frac{k_U - 1}{k_U}}}\right)\eta_T^*, \quad (10)$$

$$N_C = G_C \frac{K}{K-1} R T_O^* \left(\pi_C^{*\frac{k-1}{k}} - 1\right)\frac{1}{\eta_k^*}. \quad (11)$$

From Equation (5) by means of transformations under the condition that $\Delta G_{sel} = 0$ and G_F is small compared to G_G, it is obtained

$$\pi_k^* = \frac{mF_1}{m_G F_{NA} q(\lambda_{NA})\sigma_{Cch}\sigma_{NA}}\sqrt{\frac{T_G^*}{T_O^*}}q(\lambda_C). \quad (12)$$

From Equation (9) we get:

$$T_G^* = \frac{\frac{k}{k-1} R T_O^* (\pi_k^{*\frac{k-1}{k}} - 1)\frac{1}{\eta_k^*} + \left(\frac{\pi}{30}\right)^2 Jn\frac{dn}{dt}}{\frac{k_G}{k_G - 1} R_{\dot{G}} (1_{mech} - \frac{1}{\pi_T^{*\frac{k_{\bar{A}}-1}{k_{\bar{A}}}}})\eta^* \eta}. \quad (13)$$

Joint solution (Equation (13)) and (Equation (12)):

$$\frac{\pi_k^*}{q(\lambda_k)} = \frac{mF_1\sqrt{\frac{k}{k-1} R T_O^* (\pi_k^{*\frac{k-1}{k}} - 1)\frac{1}{\eta_k^*} + \left(\frac{\pi}{30}\right)^2 Jn\frac{dn}{dt}}}{m_G F_{NA} q(\lambda_{NA})\sigma_{Cch}\sigma_{NA}\sqrt{T_O^*}\sqrt{\frac{k_G}{k_G - 1} R_G (1 - \frac{1}{\pi_T^{*\frac{k_G-1}{k_G}}})\eta_T^*\eta_{mech}}}. \quad (14)$$

From the continuity equation for the section in the nozzle diaphragm and the jet nozzle (Sun et al., 2021; Choo, 2019, performing similar transformations, it is obtained:

$$\pi_T^* = \frac{q(\lambda_{RN})}{q(\lambda_{NA})}\frac{F_{RN}}{F_{NA}}\frac{\sigma_{RN}}{\sigma_{NA}}\frac{1}{\sqrt{1 - (1 - \frac{1}{\pi_T^{*\frac{k_G-1}{k_G}}})\eta_T^*}}. \quad (15)$$

The system of Equations (14) and (15) is a working line (phase trajectory) on the characteristic of the compressor of a single shaft gas turbine engine in a wide range of changes at the critical and before the critical end in the jet nozzle, taking into account a number of assumptions: the absence of heat exchange, without taking into account the compressibility of air and volume filling and others.

The equation of the working line of the unsteady mode turns into the equation of the working line of the steady mode of operation (Equation (3)) at $\frac{dn}{dt} = 0$. With a supercritical pressure drop in the jet nozzle, it can be considered simplified $q(\lambda_{RN}) = 1$, $q(\lambda_{NA}) = 1$ and $\pi_T^* = const$.

Equations (14) and (15) of the operating line at unstable modes for engines of more complex schemes (two shaft, two circuit, etc.) become even more complicated. Creating a universal calculation algorithm for arbitrary GTE schemes with the explicit inclusion of control and control elements in the model using these equations is a very difficult task.

So, for example, in Rozman et al. (2023), Lee et al. (2015), the behavior of the control system during acceleration of a single shaft turbojet engine, when a retarder is used in the acceleration system, is considered.

The Equation of motion of the engine rotor is written in the usual form, that is

$$2\pi J\frac{dn}{dt} = M_T - M_K. \quad (16)$$

Let's assume that the excessive torque of the turbojet engine is a function of two variables is speed and fuel consumption

$$\frac{dn}{dt} = \frac{f(n, G_F)}{2\pi J}. \quad (17)$$

The expression for $\Delta M = f(n, G_F)$ can be found from the Equations (with data transmission channel):

$$\left.\begin{aligned} &2\pi J\frac{dn}{dt} = M_T - M_K - M_{agr};\\ &\frac{T_K^*}{T_1^*} = 1 + \left(\pi_K^{*\frac{k-1}{k}} - 1\right)\cdot\left(\frac{1}{\eta_K}\right);\\ &1 - \left(1 - \pi_T^{*\frac{k_G-1}{k_G}}\right)\eta_T = \frac{T_T^*}{T_G^*};\\ &G_F H_u \eta_{c.ch.} = G_G\left(c_p^G T_G^* - c_p T_K^*\right). \end{aligned}\right\}; \quad (18)$$

$$\left.\begin{aligned} &M_T = f\left(T_G^*, G_G, n, \pi_T^*\right);\\ &M_K = f\left(G_G, n, \pi_K^*, p_1^*; T_1^*\right);\\ &G_K = f\left(\pi_K^*, n, p_1^*, T_1^*\right);\\ &G_G = f\left(p_G^*, T_G^*\right);\\ &G_N = f\left(p_T^*, T_T^*, F_N\right); \end{aligned}\right\} \quad (19)$$

and from the known characteristics of the compressor, turbine and combustion chamber.

The rate of change of fuel consumption is constant, i.e.

$$\frac{dG_F}{dn} = \frac{2\pi Jm}{f(n, G_F)}. \quad (20)$$

Given a constant value of the fuel derivative, it is possible to determine in the same coordinates a line

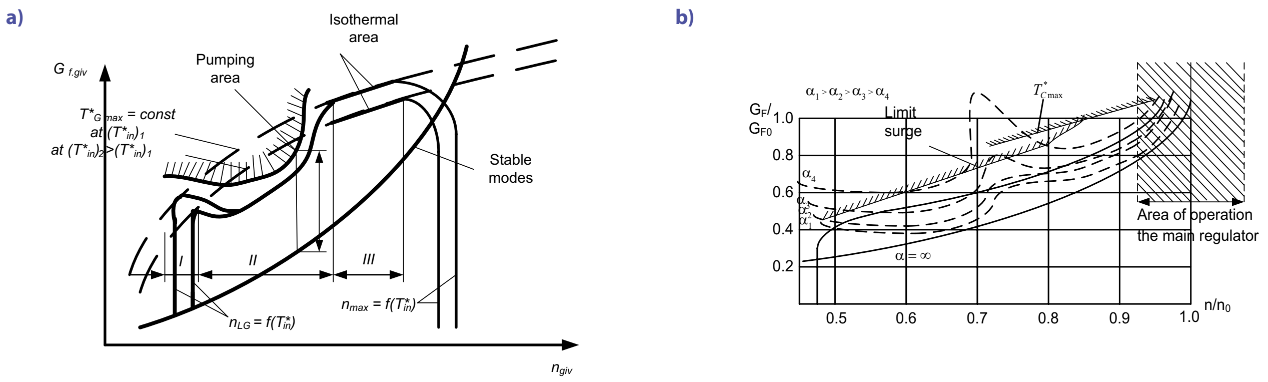

Figure 1. Diagrams for: (a) – lines of operating modes of the turbine and compressor corresponding to transition modes during data transmission with influence to pressure value, (b) – isoclines for turbojet engine with automatic acceleration

corresponding to a constant slope of the desired line, that is, an isocline, in the form

$$G_F = \frac{2\pi Jm}{a} f(n). \tag{21}$$

The perfection of the acceleration system is determined by how close the dependence $G_F = f(n)$ is to the limit lines of the maximum gas temperature and stable operation of the compressor (Figure 1a), and axial compressor with the help of an automatic acceleration (AA) on wireless pressure value (Figure 1b).

3. Wireless technical implementation of the aviation engine operating modes

Let's consider the characteristic of the engine with automatic acceleration (AA) during wireless data transmission with influence to pressure value.

The equation of forces acting on the valve and fuel consumption (Garcia-Oliver et al., 2023; Markowski et al., 2017):

$$\left.\begin{array}{l} F_m p_m + C_{spr} l_{valve} = F_{valve} p_T \\ G_P = G_F \end{array}\right\}, \tag{22}$$

where F_M, F_{valve} are the effective areas of the membrane and valve, respectively; p_T, p_M are respectively, fuel pressure behind the pump and in the cavity above the membrane; l_{valve} is the coordinate that determines the position of the valve; C_{spr} is stiffness coefficient of the membrane spring; G_p, G_F is respectively, fuel consumption through the pump and through the injectors.

For each value p_H, the pressure in the supra membrane cavity depends only on the value of the pressure behind the compressor p_2^*, i.e. $p_i = f(p_2^*)$. The fuel consumption through the pump and nozzles can be expressed in the form $G_P = m_1 \cdot n \cdot l$ and $G_F = m_2\sqrt{p_T}$, where l is the coordinate of the servomotor (swash plate).

Then the equation can be rewritten:

$$F_M f(p_2^*) + C_{spr} l_{valve} = F_{valve} \frac{G_F^2}{m_2^2}; \tag{23}$$

$$m_1 n l = G_F. \tag{24}$$

Therefore, the initial system of equations are as follows:

$$\frac{dn}{dt} = \frac{f(n, G_F)}{2\pi J}; \tag{25}$$

$$\frac{dG_F}{dt} = f_1(n, G_F, p_2^*);\ p_2^* = f_2(n, G_F). \tag{26}$$

The engine acceleration system includes both devices in question, i.e. and retarder, and AA (Alomar & Elmenshawy, 2022; Guo et al., 2022). The practical application of the description is associated with rather cumbersome calculations, and for changes in the engine scheme, fuel control system, the writing of the systems of equations are repeated anew.

In contrast to a described universal approach is proposed that allows simulation of transition modes of operation of gas turbines of various schemes together with fuel regulating equipment, other control and monitoring elements (Szczepankowski et al., 2017; Ghojel, 2020).

The process of modeling various transition modes of gas turbine operation in the simulation modeling system is carried out in several stages:

1) in the operating window, a topological diagram of the simulated engine is formed from structural elements (SE) are "wireless modules" (input device, compressor, combustion chamber, turbine, jet nozzle, air intake, power consumer, etc., as well as system elements regulation various regulators, sensors). The reserved ports in SE models allow you to specify ("trace") the connections between them according to the formed diagram of the engine, its automatic control system (ACS). At the same time, the wireless modular principle and the object approach are implemented;

2) a preliminary calculation ("binding") is carried out in order to determine the basic values of the operational and design properties (geometrical, thermo gas dynamic, etc.) of the engine and its ACS;

3) depending on the simulated modes of operation of the gas turbine engine and the tasks to be solved (identification, VSC, DRX, transient processes, etc.), appropriate simulation conditions (engine regulation programs) are formed, which are implemented using the built in

processor ("solver"), which solves each of the equations recorded in the calculation conditions, maintaining the values of the specified constants (regulated parameters) or their changes (in accordance with the specified) depending on other parameters) due to the variation of the parameters (regulating or controlling influences).

The technology of developing modeling systems by introducing new factors into them is proposed. So, for example, to ensure the possibility of modeling transient processes, describing the external environment, a new parameter is time τ was introduced, thanks to which the model begins to exist not only in the space of design and mode parameters, but also in time. However, from the point of view of the simulation modeling technology used in this work, the parameter τ is an external factor, such as the previously introduced parameters *H* (flight height), *M* (flight speed), etc. During modeling, the model is adjusted (by the solver, taking into account the given modeling conditions) at the moment (subspace of time) $\tau_1 = 0$, then the transition into the subspace $\tau_2 = \tau_1 + \Delta\tau$, etc. d. (Figure 2).

The connection between the "time subspaces" is carried out through integrated parameters (wireless), which are the phase coordinates of the processes of accumulation (expenditure) in the elements of the gas turbine, its ACS and LCD of energy, matter, amount of motion, physical and chemical processes of combustion, phase transitions (derivatives of pressure, temperature, consumption, etc.):

$$\left(\frac{dp}{d\tau}\right)_i = \frac{p_i - p_{i-1}}{\tau_i - \tau_{i-1}}. \quad (27)$$

$$\left(\frac{dT}{d\tau}\right)_i = \frac{T_i - T_{i-1}}{\tau_i - \tau_{i-1}}. \quad (28)$$

$$\left(\frac{dG_T}{d\tau}\right)_i = \frac{G_{Ti} - G_{Ti-1}}{\tau_i - \tau_{i-1}}. \quad (29)$$

For example, for a compressor, the rotation frequency at each moment of time is determined by:

$$n_i = \left(\frac{dn}{d\tau}\right)_i (\tau_i - \tau_{i-1}) + n_{i-1}, \quad (30)$$

which corresponds to integration by the Euler method (the proposed modeling technology allows the use of other methods). In this case, a feature is used, the solver, when processing a network (graph) simulation model, uses the SE "General data of the engine" as the final vertex. This is what allows you to place the integration operators in this SE, while you have to describe all the integrated parameters as global and use these cells as buffers for integration in each series of iterations (at a certain step, for example, in time).

The integrated parameters take part in the corresponding operators of the algorithms of specific SE as dynamic additives and take into account the mass accumulation, the inertia of the mechanical and thermal state. For this, recurrent expressions are added to the algorithms of the

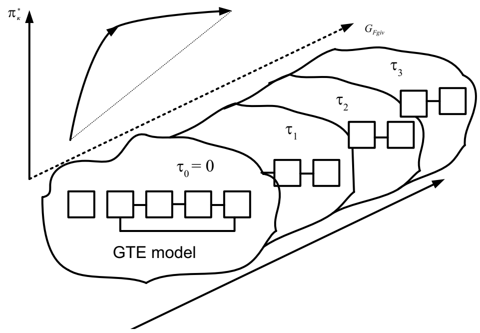

Figure 2. Alignment of the model in time space

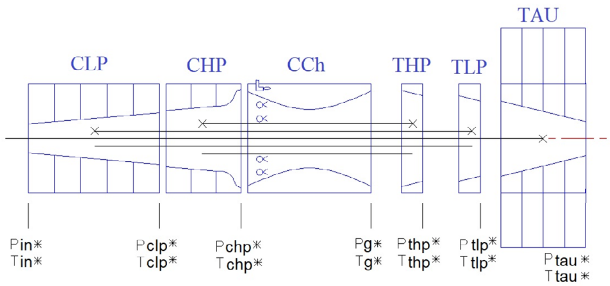

Figure 3. The information modeling system of the gas turbine engine

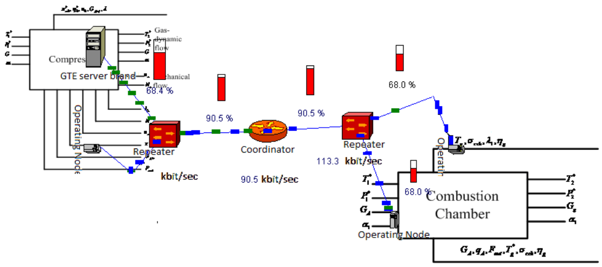

Figure 4. Information model of the compressor and combustion chamber in the simulation system

corresponding modules, taking into account the influence of various factors.

Motion through the subspace τ_i (time steps) can be performed by tabulating the time value in the calculation conditions, or by setting a phase trajectory of the type: $\frac{dP_i}{d\tau} = f(P_i)$ (for example, compressors is $\frac{dn}{d\tau} = f(n)$ or, more conveniently, setting the working line of the view $\pi_\kappa^* = f(G_{Fgiv})$ on the characteristic of the compressor, i.e. air flow variation, rotation frequency, acceleration, etc.

The main elements of the modeling system can be performed on (Figure 3):

The compressor is designed to organize the process of compression of the working body. The wireless information model of the compressor, combustion chamber in the simulation system is presented in Figure 4. Input parameters: $\pi_{k0}^*, \eta_{k0}^*, n_{giv0}, G_{giv0}, \pi_k^*, n_k, n_{k\,unstabl}$, where $n_{k\,unstable}$ is the rotation frequency of the compressor rotor at the initial time during simulation.

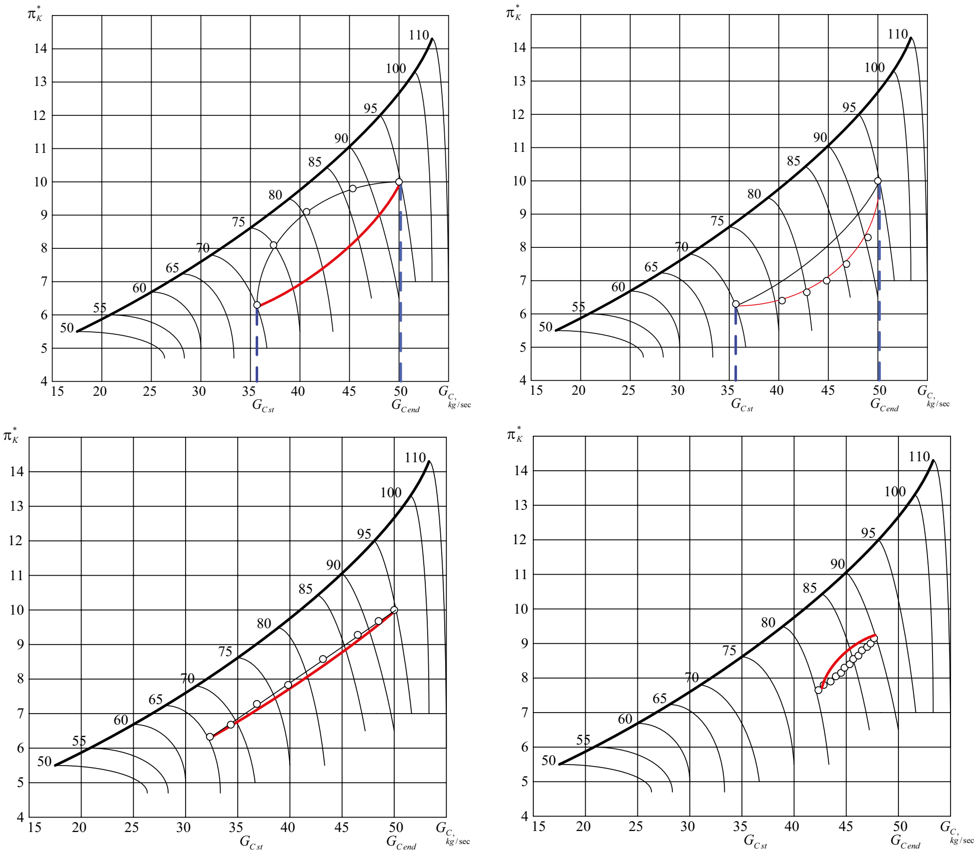

Figure 5. Operating lines on the characteristic of the compressor

The input data includes the possibility of selecting compressor indicators from the data bank (a large database of engine compressor parameters has been created), and even the possibility of creating one's own characteristics (Figure 5).

The implementation of information models of the compressor, combustion chamber, turbine and turbofan additional unit (TAU) can be obtained in the LabVIEW software environment.

4. Conclusions

A description of the modes of operation of the aviation gas turbine engine helps to operate the joint operation of the compressor and the turbine. Also, it keeps the conditions for the balance of air distribution between the circuits. It allows to estimate effectively the dynamic characteristics of the aviation gas turbine engines at the stages of design and proofing.

The influence of the transition operating mode of a gas turbine engine mathematical model with the elements of wireless modular construction is considered in the field of connections between engine elements, laws of change in fuel supply. Outcomes is the use a system of equations to form a line of operating modes based on the characteristics of the compressor, compressor and turbine. Also, can be defined the better operating process parameters of the aviation engine, air flow wireless bandwidth, moisture content.

During the "wireless" influence on the pressure value, the value of the pressure above the membrane cavity is determined more accurate (from 88% to 95%), that is, the effective use the fuel flow through the pump and nozzles, taking into account the coordinates of the servomotor (swash plate).

The main stages of modeling the operating modes of an aviation engine are defined, that allow to implement a suitable for practical application of the universal methodology and system of simulation:

- the topological diagram of the simulated engine is formed from structural elements are "wireless modules";
- preliminary calculation ("binding") in order to determine the main operational values and design properties (geometrical, thermogasdynamic);
- maintaining the values of given constants (regulated parameters) due to changing parameters (regulatory or controlling influences). Communication between "time subspaces" is carried out through integral pressure parameters (wireless), which are phase coordinates of accumulation processes (costs) in gas turbine elements. Integral parameters function as dynamic additives and take into account mass accumulation, inertia of the mechanical and thermal state.

The load of the wireless connection in information model of the compressor and combustion chamber in the simulation system reaches 88% in terms of pressure. It helps to determine the operating lines of the compressor, that depending on the degree of pressure compression and specific fuel consumption. It is received the point motion range is from 36 kg/s to 51 kg/s; from 51 kg/s to 37 kg/s (reverse); 34 kg/s to 50 kg/s; 48 kg/s to 43 kg/s; the degree of pressure compression is 6–10 units.

It is shown that the set of proposed principles allows model, explore and predict various unknowns modes of operation of gas turbines of arbitrary schemes together with elements of their control and with the possibility of accounting for the most significant ones factors, solve any project reference tasks.

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