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NONLINEAR OBSERVER IN CONTROL SYSTEM OF A TURBINE JET ENGINE

The time period of a jet engines full acceleration (from idle run rotating speed to full thrust) is a very important operational parameter. Minimization of this period is an important problem to be solved during the design of the fuel supply and control system. There are many methods of acceleration process control, especially in the case of engines with complicated design configurations. This work presents the problem of acceleration of a simple, single spool turbine jet engine with a so-called stable geometry, in which only one input (control) signal exists – fuel flow rate. Two methods of acceleration control consisting of limitation of the maximum allowable temperature of working medium in front of and behind the turbine in transient states were analyzed. In order to avoid difficulties associated with the direct measurement of actual temperatures, the so-called nonlinear engine observer was applied. With the use of the computer simulation method it was proven that the control algorithm with the limited maximum temperature in front of the turbine makes it possible the shortening of the acceleration time period significantly in comparison with a similar algorithm, that realizes the limitation of temperature behind the turbine.

NOMENCLATURE

Cp_{23} – average specific heat of the working medium in the combustion chamber,

D – convergent nozzle,

G2 – mass flow rate of the working medium at the compressor outlet,

$G2_r$ – reduced mass flow rate of the working medium at the compressor outlet,

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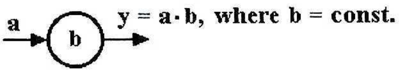
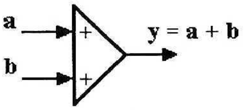
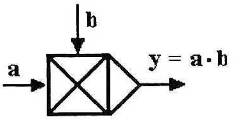
$G3$ – mass flow rate of the working medium at the combustion chamber outlet,
$G3_r$ – reduced mass flow rate of the working medium at the combustion chamber outlet,
H – flight altitude,
I_0 – polar moment of inertia of turbine-compressor assembly,
k_{34}, k_{45} – isentropic exponents,
KS – combustion chamber,
LSU – steady state curve,
M – Mach number,
n – rotational speed of the rotor,
n_{sr} – reduced rotational speed of the compressor,
n_{start} – initial rotational speed of the rotor,
n_{tr} – reduced rotational speed of the turbine,
$P1$ – total pressure of the working medium in front of the compressor,
$P2_{start}$ – initial total pressure of the working medium behind the compressor,
$P4$ – total pressure of the working medium in the convergent nozzle,
$P4_{start}$ – average initial total pressure of the working medium in the convergent nozzle,
PH – ambient pressure,
Q – fuel flow rate,
Q_1 – fuel flow rate during full acceleration with the limited $T3_{max}$,
Q_2 – fuel flow rate during full acceleration with the limited $T4_{max}$,
Rg – gas constant,
$T0$ – total temperature of the working medium at the engine inlet,
$T1$ – total temperature of the working medium in front of the compressor,
$T2$ – total temperature of the working medium behind the compressor,
$T3$ – total temperature of the working medium in front of the turbine,
$T3_{max}$ – maximum allowable total temperature of the working medium at the combustion chamber outlet,
$T3_{start}$ – initial value of total temperature of the working medium in front of the turbine,
$T4$ – total temperature of the working medium behind the turbine,
$T4_{max}$ – maximum allowable total temperature of the working medium behind the turbine,

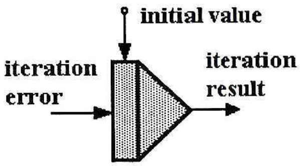
$T4_{start}$ – initial value of total temperature of the working medium behind the turbine,
T4t – temperature of the working medium measured with the use of the thermocouple set,
u_1, u_2, u_3 – iteration error,
V – flight speed,
w_1, w_2, w_3 – amplification factors of iterative loops,
Wo – fuel heat value,
Wu – compressor bleed coefficient,
ΔP – fuel pressure drop through the injectors,
$\Delta T12$ – increase of temperature of the working medium flowing through the compressor,
Π – compressor pressure ratio,
ε_{start} – initial value of decompression pressure ratio of the flow through the turbine,
ε – decompression pressure ratio of the flow through the turbine,
ϕ – convergent jet nozzle flow ratio,
η_{ks} – efficiency of heat emission in the combustion chamber,
η_t – isentropic efficiency of the turbine,
σ_{23} – coefficient of total pressure retention in the flow through the combustion chamber,
τ – time constant of the thermocouple set.

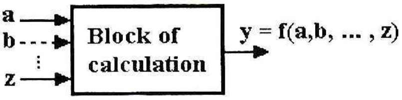
GRAPHIC SYMBOLS

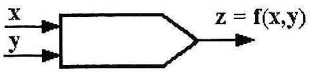


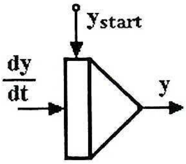












1. Introduction

Jet engine transient processes are accompanied by thermal choking of the working medium. It is manifested with the phenomenon that all transient processes observed on phase trajectories ran far away from the steady state curve. During acceleration these processes run above the steady state curve and during the deceleration – below it. One of the significant kinds of transient states is the so-called full acceleration. It is the engine acceleration from the idle run to full thrust rotational speed realized by the rapid full displacement of a control lever. For justifiable reasons the time of the process realization should be as short as possible. For simple single spool jet engines, for instance SO-3 or K-15 the acceptable time of full acceleration in on-ground conditions cannot exceed 10 seconds.

Theoretically, the shortest possible time of full acceleration may be reached at maximum thermal choking in transient states. The top limit of the thermal choking range (for a single spool jet engine) is defined by maximum allowable temperature at the combustion chamber outlet (T3) and the limit of the compressor steady operation ($\Pi_{max} = f(n_{sr})$). In the majority of jet engines the process of acceleration control is realized significantly below the mentioned limits. This results from the difficulties with direct measurement of real temperature at the combustion chamber outlet in transient states [1], [10], [17] and accurate detection of the compressor steady operation limit [3], [4], [6], [7], [8], [11], [20]. There are many practically verified methods of solving this problem. They consist in avoiding the direct measurement of temperature and the compressor steady operation limit, assuming the substitutive top limit of thermal choking, which is easier for direct measurement. For instance it may be expressed by a $\Pi_{max} = f(n_{sr})$ programmed function for the whole range of the engine reduced rotating speed.

In recent years, thanks to widespread microprocessor technology, another possibility of acceleration control system design appeared. The system is based on the usage of the indirect (T3) temperature measurement signal at the combustion chamber outlet or behind the turbine (T4). Direct measurement of average actual value of (T4) temperature in the nozzle with the use of a thermocouple set is burdened with a significant and difficult to determine measurement error resulting from high thermal inertia of measuring junctions. Direct measurement of average actual value of (T3) temperature at the combustion chamber outlet is practically impossible, because of low durability of commonly used thermoelements in this range of temperatures, which are much higher than temperature behind the turbine (Fig. 4 and 5). It results from the above mentioned fact that, in transient states, the actual values of temperature at the combustion chamber outlet and behind the turbine belong to a category of the so-called non-measurable parameters.

In order to measure actual values of temperatures, one can apply the well-known technique of the so-called observers. This name describes analytical algorithms used for calculating the actual values of non-measurable parameters of any dynamic object (in this case a jet engine) on the basis of easily measurable values of its other parameters.

2. Examples of turbine jet engine observers

The proposed observer of the SO-3 engine has a form of nonlinear algebraic equations, which describe flow parameters of the working medium in all necessary analytical cross-sections of the engine duct. The major data for the system of equations are static characteristics of the compressor and the turbine, determined on the basis of numerical analyses, and the measurements performed on special test stands for each type of engine. The assumption of the observer in a form of system of algebraic equations is equivalent to the assumption that a turbine jet engine considered an object of control is a first order dynamic object. It means that dynamics of the working medium enthalpy and mass accumulation in different elements of the engine duct volume may be neglected. In the case of engines equipped with long exhaust nozzles and afterburners the correctness of such a simplification has to be verified. For the SO-3 and K-15 engines the assumed simplification is correct [15].

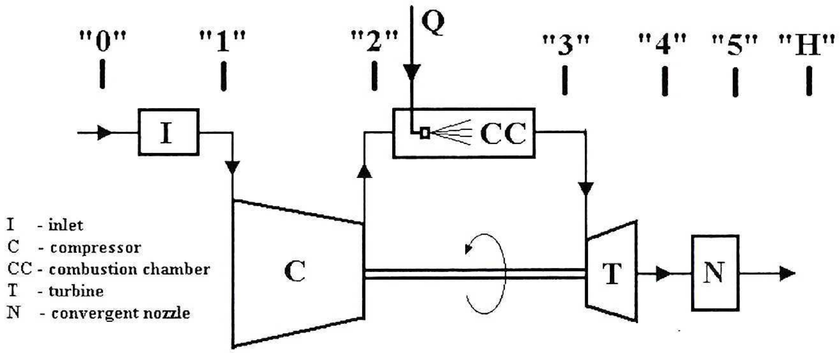


Fig. 1. Analytical scheme of the SO-3 engine

It has to be emphasized that the present work is focused on presentation of the analytical block schemes of the observers, giving up the presentation of all necessary equations, what for the subject of the work herein is not necessary.

Reader may find them in numerous handbooks on theory of turbine engines and mechanics of fluids.

Analog diagrams of two different observers (observer No. 1 and observer No. 2) of the same single spool turbojet engine intended a power unit for TS-11 ISKRA airplane are presented in the figures No. 2 and 3. The engine has a convergent nozzle of the critical section uniform area and an axial-flow compressor without any guide vane adjusting mechanism and without an anti-pumping system of bleed valves.

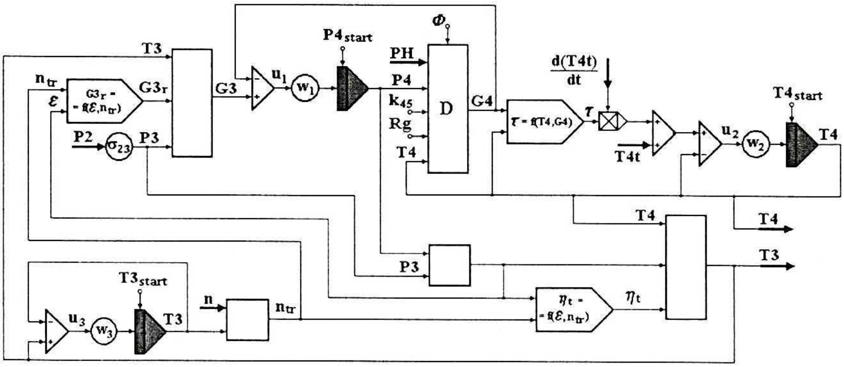


Fig. 2. Block scheme of observer No. 1

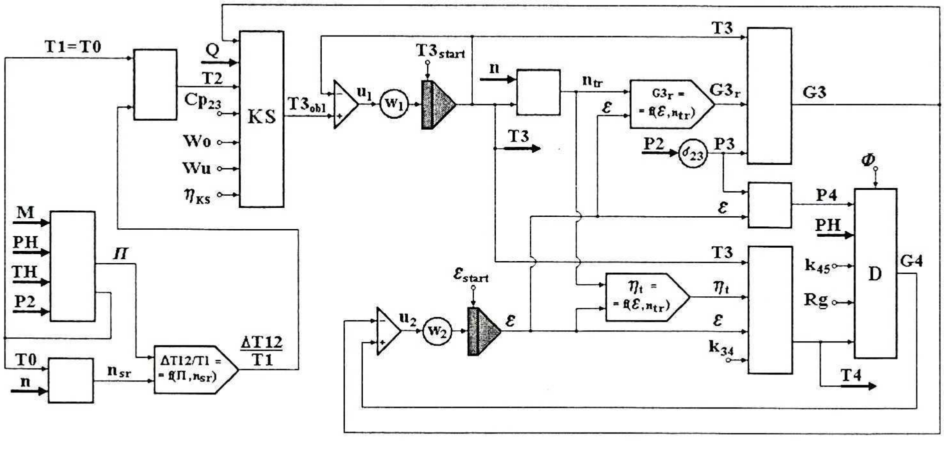


Fig. 3. Block scheme observer No. 2

The block scheme of the engine is presented in the Fig. 1. A characteristic feature of each observer is a set of engine operating parameters measured directly. The parameters are depicted in the diagrams as input signals.

In observer No. 1, an average actual value of (T4t) temperature measured with the set of thermocouples in the nozzle and its first derivative (d(T4t)/dt) were used for this purpose. For calculation of a real actual value of temperature in the nozzle, it was necessary to implement the thermal inertia compensating system into the structure of observer No.1. Setting a correct compensation system requires a good knowledge about the mathematical model of a thermocouple. A model in the form of the following first order differential equation has been assumed:

$$\frac{d(T4t)}{dt} = \frac{1}{\tau} \cdot (T4 - T4t); \tag{1}$$

$$\text{where: } \tau = f(T4, G4); \tag{2}$$

The (2) nonlinear function of two variables is the so-called characteristic describing dependence of (τ) time constant of the thermocouple set on (T4) real temperature of working medium in the nozzle and on its (G4) mass flow rate.

In the conception of No. 2 observer, direct measurement with the use of thermocouples was neglected. Calculation of the determined temperature values was performed on the basis of the mathematical model of the combustion chamber (the KS block in the Fig. 3) and the reduced static characteristics of the compressor, given in the form of the following function of two variables:

$$\frac{\Delta T12}{T1} = f(\pi, n_{sr}); \tag{3}$$

The analytical algorithms of both observers include iterative loops necessary for solving the sets of nonlinear algebraic equations. Observer No. 1 includes three iterative loops and observer No. 2 only two. Convergence of the algorithms was obtained by a proper selection of ($T3_{start}$, $P4_{start}$, $T4_{start}$, ε_{start}) initial values of the iterated variables and the values of amplification coefficients of the iterative loops.

Both observers were applied for processing the data from K-15 engines operation on the I-22 IRYDA plane. The K-15 engine has a very similar design structure to the SO-3 engine. It differs in the compressor equipped with a bleed valves anti-pumping system. Therefore, the algorithm of observer No. 2 presented in Fig. 3 was provided with two separate generators of the (3) function for the case of the compressor operation with opened and shut anti-pumping valves. The generators were switched on the basis of indications of a special system indicating their operating regime. Figs. 4 and 5 show the exemplary results of application of observer No. 2 for processing records of K-15 engine operating parameters recorded during the approximately 90 minute long airplane flight. The phase diagram of this flight (H) altitude and speed (V) profiles is shown in Fig. 6.

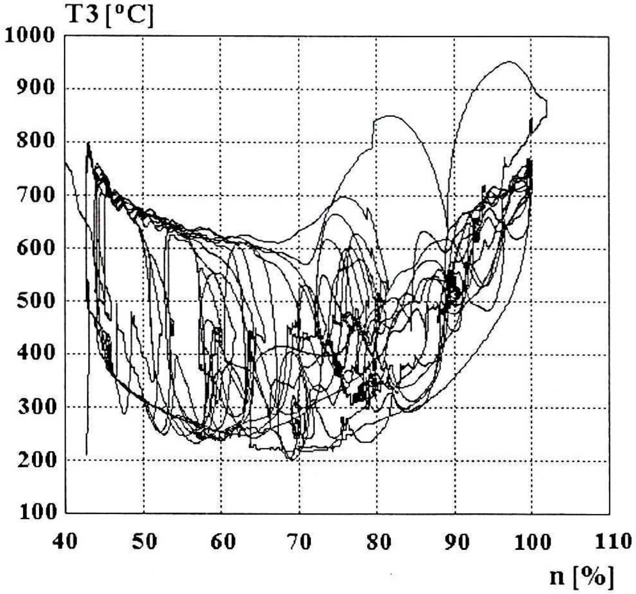


Fig. 4. Curve of average value of the working medium temperature at the combustion chamber outlet versus rotor speed

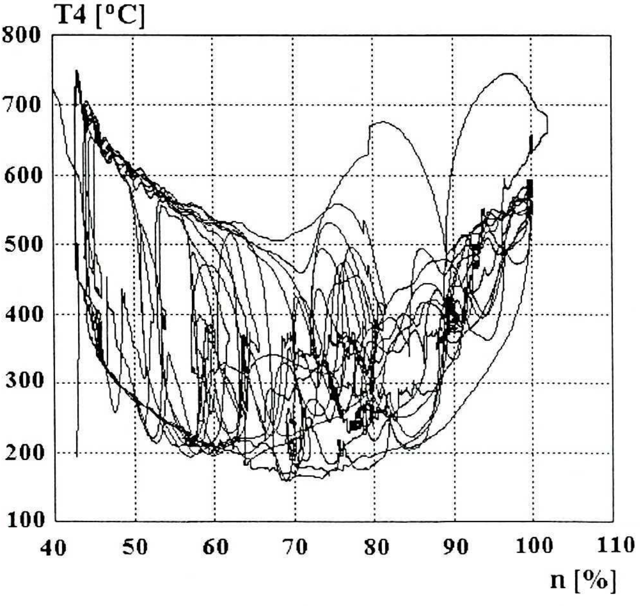


Fig. 5. Curve of average value of the working medium temperature behind the turbine versus rotor speed

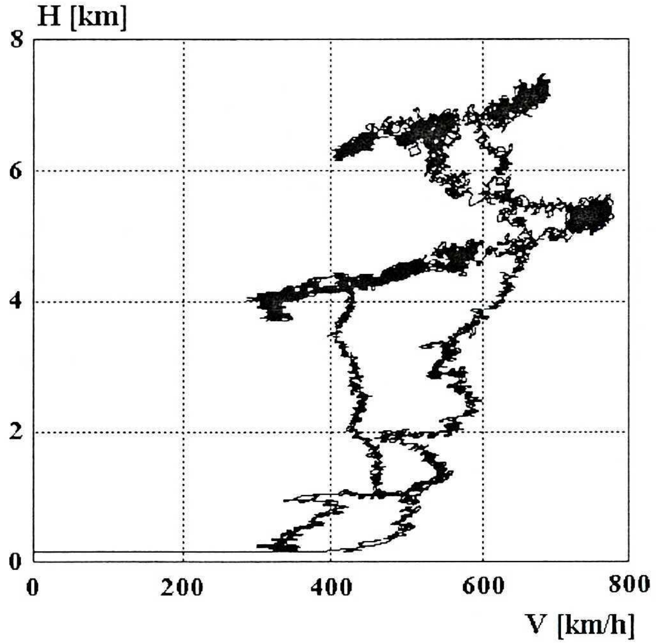


Fig. 6. Range of flight altitude and speed, for which the results presented in Fig. 4 and 5 have been obtained

The presented results prove the effectiveness of observer No. 2. They have been obtained by computer processing of the measurement data file sampled with a frequency of 64 samples/s. The time of processing on the microcomputer (with the Pentium II – 400MHz processor) was approximately 20 minutes. It has to be noticed that after optimization of the source program code aimed at increasing its operating speed, this time can be many times shorter. Therefore, we can draw the conclusion that the algorithm of the proposed observer may easily be realized in the real time scale in the hypothetical microprocessor engine control system (Full Authority Digital Electronic Control – FADEC).

Because of limited size of the present article, the results of processing of the same measurement data with the use of observer No. 1 are not presented. The curves of T3 and T4 temperatures obtained in this case are similar to the previous one in the range of positive and small negative engine accelerations. Relatively low accuracy of the applied mathematical model of the thermocouple set (1, 2) is the reason for discrepancy. To the best of the author's knowledge, a correct and satisfactorily accurate methodology of mathematical modeling of thermocouples for measurement of jet engine exhaust gas temperatures in transient states is a problem still awaiting a solution. Therefore, the conclusion is that, in the turbojet engine automatic control systems, the usefulness of the measured signal obtained directly from the thermocouples is poor. It is very probable that temporarily the best method of solving this problem is the application of the observers, which use other easily measurable engine operating parameters as for instance the ones assumed for the conception of observer No. 2.

It is evident that the accuracy of results of calculations performed with the use of an observer depends both on accuracy of measurement of the parameters measured directly and on the accuracy of all the data used for its design. This comment was formulated considering as the most important factor, the static characteristics of a compressor and a turbine especially. Allegorically saying, an observer is a sort of a virtual sensor. Therefore, its practical usage requires as careful calibration as in the case of commonly used measuring sensors.

3. Top limit of engine thermal choking

The results of No. 2 observer operation prove that it may be applied in the engine automatic control system in the assembly of maximum temperature limiter. Therefore, it is worth noticing that limiting the (T4) temperature behind the turbine applied on some engines (for example on the K-15) is not an optimal solution. A better solution allowing for advantageous shortening of the engine full acceleration time is a limitation of the (T3) temperature at the combustion chamber outlet. This is easy to conclude analyzing the location of the top limit of engine thermal choking for both cases. For this purpose we have used presented below results of experiments performed on the simulation model of the SO-3 engine [13], [14], [15], [16].

Fig. 7 and 8 present results of thermal choking of an engine operating in the on-ground test stand in normal ambient conditions. The experiments were conducted for various assumed constant values of engine rotating speed in the range between idle run and full thrust. In the case presented in Fig. 7, the top thermal choking limit observed in the T3 = f(n) coordinate system, marked with the (□) point symbols, results from the assumption of maximum allowable temperature of the working medium behind the turbine ($T3_{max}$ = 900K). In the case presented in Fig. 8, the top limit of thermal choking observed in the T4 = f(n) coordinate system results from assumption of such a maximum allowable temperature in front of the turbine that the (T4) temperature behind the turbine across the whole range of rotating speed can't be higher than 900K. Additionally in both figures with the use of special point symbols the (■) line of the engine steady states and the (×) line of compressor steady operating limit have been shown. Fig. 9 and 10 illustrate similar limits of thermal choking in the coordinate system Q = f(n).

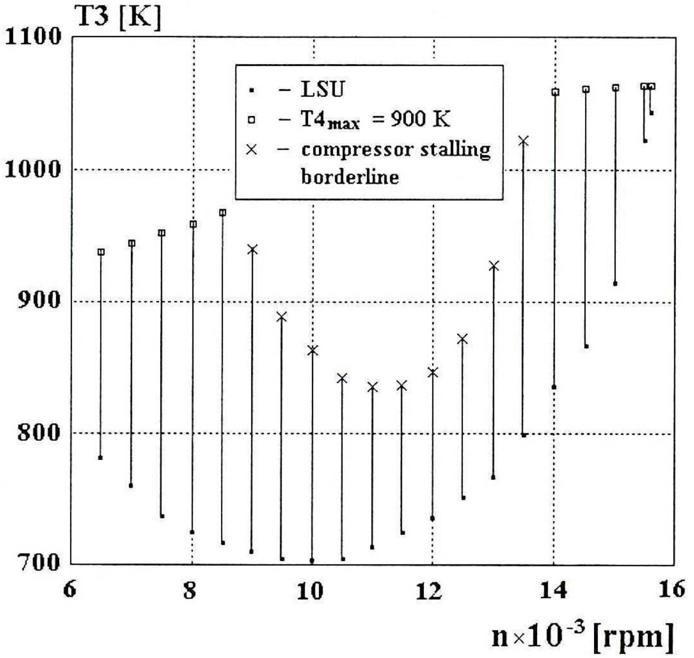


Fig. 7. The range of engine thermal choking for positive values of rotor speed accelerations

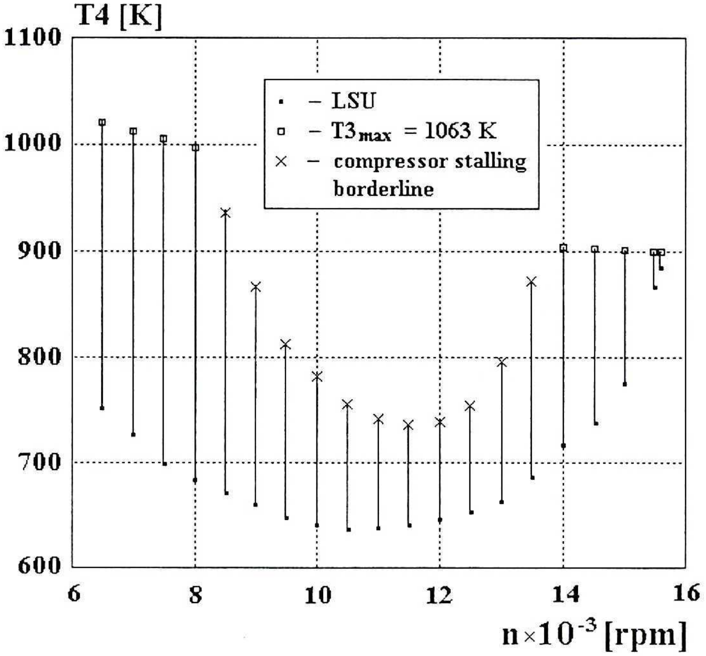


Fig. 8. The range of engine thermal choking for positive values of rotor speed accelerations

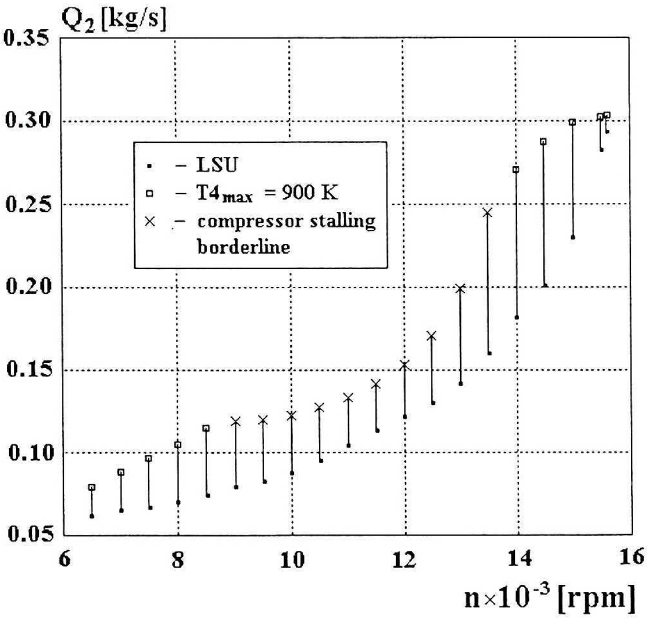


Fig. 9. The range of engine thermal choking for positive values of rotor speed accelerations

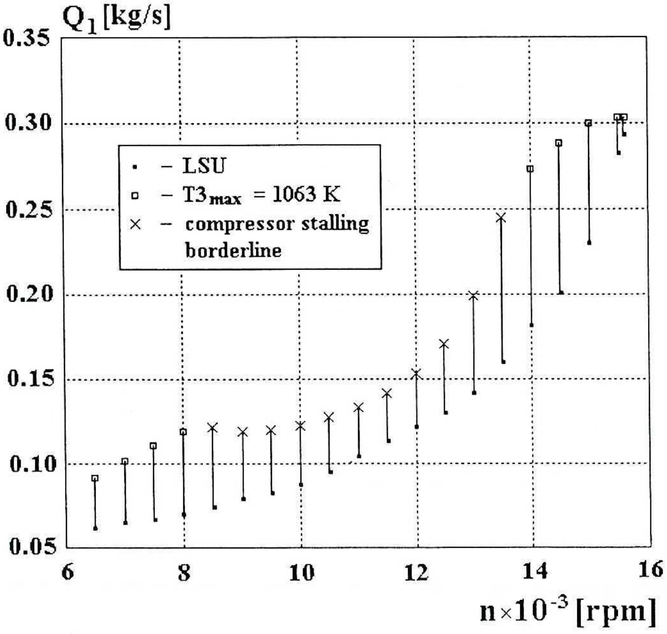


Fig. 10. The range of engine thermal choking for positive values of rotor speed accelerations

The allowable engine steady state thermal choking area for (dn/dt > 0) positive values of rotating speed acceleration is located between the steady state curve and the top limit of the engine thermal choking. The full engine acceleration time is shortest, when its trajectory runs as closely as possible to the top limit of thermal choking. However, the larger the area between the steady state curve and the top limit of choking, the shorter the absolute time of acceleration. In the analyzed case this area becomes larger when limitation of the T3max temperature is applied, what can be clearly seen when we compare the diagrams in the Fig. 9 and 10.

4. Measurements of full acceleration time

Measurements of full acceleration time for both cases of maximum allowable temperature of the working medium limitations were done by the experimental method on the simulative model of the SO-3 engine. The method of the experiment is shown in Fig. 11. A specific feature of the SO-3 single spool engine was used for this purpose. The engine considered as an object of automatic control may be described by a first order nonlinear equation, which provided a good approximation [13], [15]. This way the goal of the experiment was achieved and the connection of the engine model with an adequate model of an automatic control system equipped with T3max or T4max temperature limiter was not necessary. The connection between the engine model and function generators realizing both cases of thermal choking described in subsection 3 (Fig. 9 and 10) was sufficient.

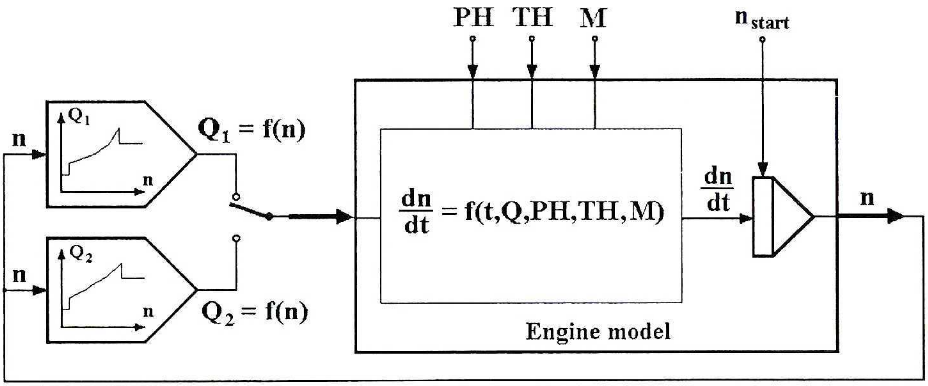


Fig.11. System of full acceleration excitation on the simulative model of the SO-3 engine

Full acceleration was realized on the model by excitation with an input signal given as a functional dependence of fuel flow rate on rotor speed ($Q = f(n)$). The variant of the acceleration was selected with the use of the key shown in Fig. 11. The (n_{start}) rotor speed initial value was set slightly higher than the initial value of the idle run speed set in the generator of the function realizing the Q = f(n) excitation. This resulted in an acceleration startup witch run along a selected top limit thermal choking curve until the final steady state was reached with a maximum rotating speed.

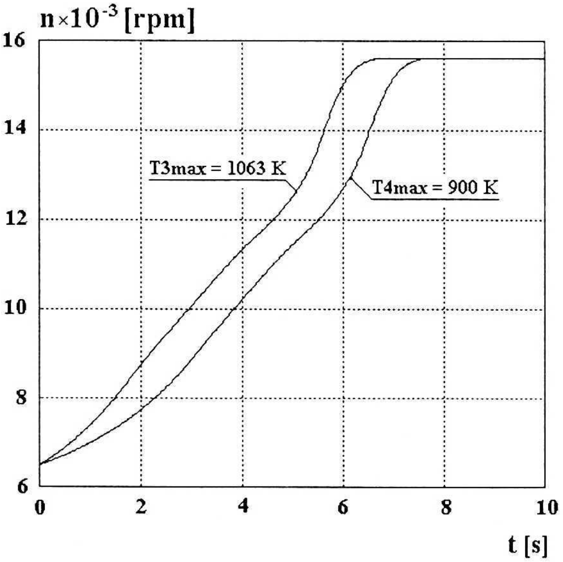


Fig. 12. Comparison of the engine full acceleration times for both limits of thermal choking

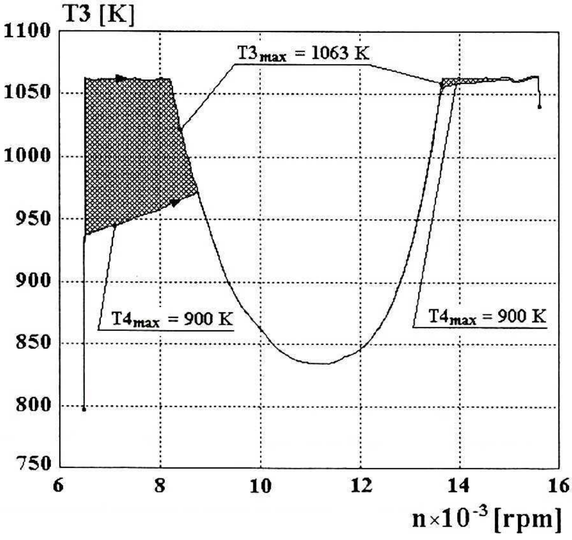


Fig. 13. Comparison of the temperature curves in front of the turbine during engine full accelerations for both limits of thermal choking

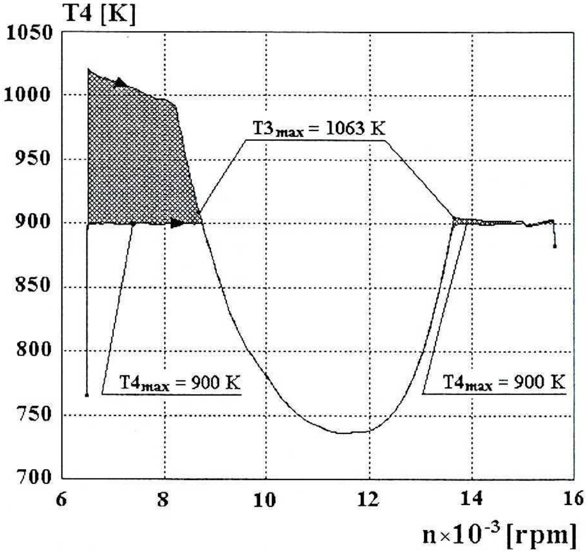


Fig. 14. Comparison of the temperature curves behind the turbine during engine full accelerations for both limits of thermal choking

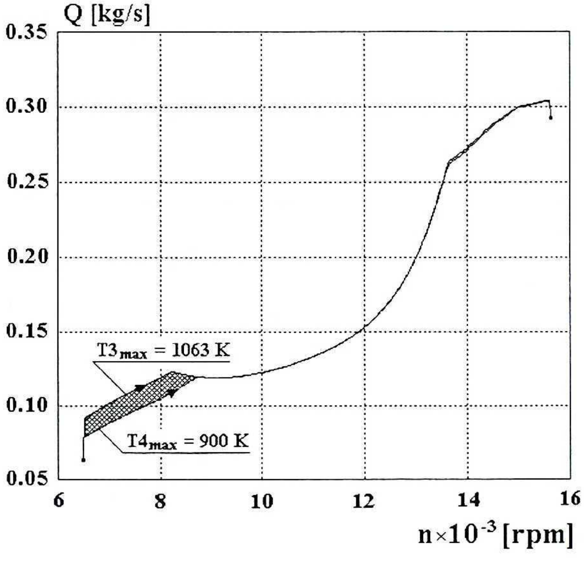


Fig. 15. Comparison of the fuel flow rate curves during engine full accelerations for both limits of thermal choking

Fig. 12 shows the time diagrams of full accelerations for both cases of temperature limitation. It is clear that the application of a temperature limitation at the combustion chamber outlet resulted in a shorter full acceleration time. Figs. 13 and 14 presents curves of temperatures in front of the turbine and behind it versus rotating speed for both cases of acceleration. Based on these graphs, one can conclude that the limitation of the temperature in front of the turbine enables the use of a significant margin of thermal choking, which appears in the range of low rotating speeds, which is depicted in Fig. 13 and 14 by the shaded areas.

In Fig. 15, the trajectories of both cases of acceleration are presented in the Q = f(n) coordinate system. It shows clear that the increase in the rate of acceleration is the result of much higher actual values of fuel flow rate in the range of low rotating speeds.

5. Conclusions

- The value and the possibilities of application of observers' technology in control systems of turbine jet engines results from accessibility of modern digital microelectronic systems, especially microprocessors.
- All the problems presented herein concern the case of the engine operation on an on-ground test stand in normal ambient conditions. Discussion on additional, difficult problems of turbine jet engine acceleration control in the full range of an airplane flight altitude and speed is beyond the scope of the present work. However, these problems may be solved with the use of application of the observers' technology presented herein. This was proven by the results of operation of observer No. 2 presented in subsection 2 in Fig. 2.
- The full acceleration curves presented in subsection 4 pertain to the case of the acceleration trajectory staying almost accurately in line with the assumed top limits of thermal choking. In the case of a real control system operating on the basis of observer No. 2 described in p. 2, the acceleration trajectory will be slightly different than the assumed one, because of the dynamics of fuel supply.
- The described problems are exclusively related to the subject of limitation of the working medium temperature during engine acceleration, whereas a large portion of the acceleration trajectory results from the limit of a compressor steady operation. The method of fast acceleration control proposed in the present work may be also applied to this portion of the trajectory. Therefore, in the proposed limiter system, the compressor steady operation limit has to be defined in the $T3_{\max} = f(n)$ coordinate system.
- Realization of the described method of acceleration control requires the application of an inertialess method of measurement of actual temperature values of the working medium in front of the turbine. In practice it can be done by application of such an observer variant, in which the temperature value

measured directly not exist (for instance observer No. 2 or a similar one). A program realizing the observers' algorithm may be installed in the memory of the engine microprocessor control system and operate in the real time mode.

- A temperature signal obtained directly from the thermocouple set installed in the exhaust nozzle has a poor usability for the jet engine supply and control system. The major reason is high thermal inertia of measuring junctions of thermocouples, which are difficult for accurate compensation. The result of inertia is a significant and difficult to evaluate error of gas temperature measurement during transient states of a jet engine. Compensation of this error requires an adequate mathematical model of the thermocouples assumed for the measurement of variable gas temperature in the flow with high (subsonic) velocities. This problem is still awaiting solution.
- Acceleration time of the engine equipped with the system of the ($T3_{max}$) combustion chamber outlet temperature limiting is shorter than that in the case of limiting the ($T4_{max}$) temperature in the nozzle. Therefore, in systems of temperature limiters operating on the basis of the signal of temperature measured directly in the nozzle, the ($T4_{max}$) raised temperature value may be applied in the lower range of rotor speed (Fig. 14). Consequently, a visible shortening of the full acceleration time may be expected without any concerns about the engine overheating.
- The engine observers may find other applications [15], [16], for instance for measurement of actual thrust values during aircraft flight, for specific fuel consumption monitoring, engine performance degradation monitoring, etc.

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Nieliniowy obserwator w układzie sterowania turbinowego silnika odrzutowego

Streszczenie

Czas pełnej akceleracji silnika odrzutowego (od prędkości obrotowej biegu jałowego do pełnego ciągu), jest ważnym parametrem eksploatacyjnym. Minimalizacja tego czasu jest jednym z ważnych problemów do rozwiązania podczas projektowania układu zasilania i sterowania silnika. Istnieje wiele sposobów sterowania procesem akceleracji, szczególnie w przypadkach silników o złożonych konfiguracjach konstrukcyjnych. Tu przedstawiono zagadnienie akceleracji prostego, jednowirnikowego turbinowego silnika odrzutowego o tzw. stałej geometrii, w którym występuje tylko jeden sygnał wejściowy (sterujący) – wydatek paliwa. Przeanalizowano 2 sposoby sterowania akceleracją, polegające na ograniczaniu w stanach nieustalonych dopuszczalnej maksymalnej wartości temperatury czynnika roboczego przed lub za turbiną. W celu uniknięcia występujących przy tym trudności, związanych z bezpośrednim pomiarem chwilowych wartości temperatury, zastosowano tzw. nieliniowy obserwator silnika. Przy użyciu metody komputerowej symulacji wykazano, że algorytm sterowania z ograniczeniem maksymalnej wartości temperatury przed turbiną pozwala na znaczące skrócenie czasu pełnej akceleracji – w porównaniu z analogicznym algorytmem realizującym ograniczenie temperatury za turbiną.