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COMPUTER SIMULATION OF TRANSIENT PROCESSES IN A TURBOJET ENGINE, WITH SPECIAL ATTENTION TO AMPLITUDES OF THERMAL SHOCKS IN SOME SELECTED FAULT MODES OF OPERATIONS

Results of mathematical modelling and computer simulation of transient processes in the turbine jet engine SO-3 have been presented. The transient processes result from two different fault conditions. In the first case, the transient process has been induced with a rapid fuel shut-off. In the second case, the transient process follows some failure to the shaft that connects the turbine rotor to that of the compressor. The failure occurred in the area of the middle engine bearing support.

Nomenclature

A_d – conventional accumulation space of the convergent nozzle (simulation model's block),

A_{ks} – conventional accumulation space of the combustion chamber (simulation model's block),

Cp_{12} – average specific heat of the working medium in the compressor duct,

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

Cp_{34} – average specific heat of the working medium in the turbine duct,

Cp_{45} – average specific heat of the working medium in the convergent nozzle,

D – convergent nozzle,

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

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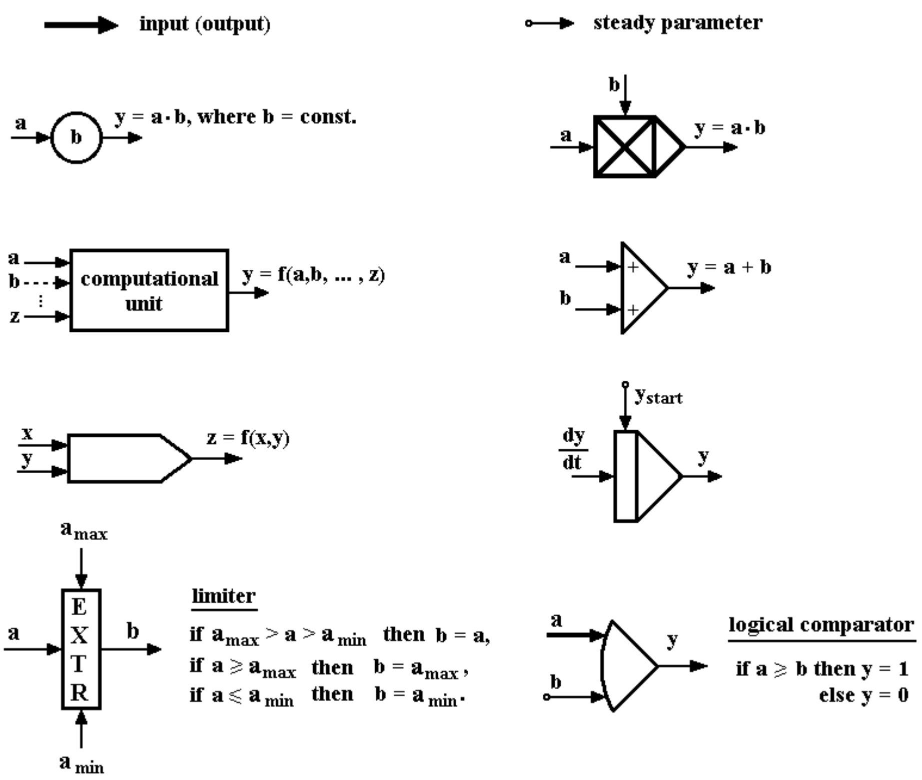
$G2_r$ – reduced mass flow of the working medium at the compressor outlet,
G3 – mass flow of the working medium at the combustion chamber outlet,
G3t – reduced mass flow of the working medium through the turbine,
Ga – mass flow of the working medium at the entry into the ‘V’ volume,
Gb – mass flow of the working medium at the exit out of the ‘V’ volume,
I – enthalpy of the working medium accumulated in the ‘V’ volume,
I_d – enthalpy of the working medium accumulated in the convergent nozzle,
I_{ks} – enthalpy of the working medium accumulated in the combustion chamber,
I_t – polar moment of inertia of the turbine rotor, including compressor-to-turbine connecting shaft,
I_s – polar moment of inertia of the compressor rotor,
I_{ts} – polar moment of inertia of the turbine-compressor assembly,
k – isentropic exponent of the working medium accumulated in the ‘V’ volume,
k_{23} – isentropic exponent of the working medium in the combustion chamber,
k_{34} – isentropic exponent of the working medium in the turbine duct,
k_{45} – isentropic exponent of the working medium in the convergent nozzle,
KS – combustion chamber,
LSU – steady-state line,
M – Mach number (here: air speed),
m – mass of the working medium accumulated in the ‘V’ volume,
m_d – mass of the working medium accumulated in the convergent nozzle,
m_{ks} – mass of the working medium accumulated in the combustion chamber,
n – rotational speed of the rotor of the turbine-compressor assembly,
n_{bj} – idle run of the engine,
n_{max} – maximum rotational speed,
n_s – rotational speed of the compressor rotor,
n_t – rotational speed of the turbine rotor, including compressor-to-turbine connecting shaft,
N_s – input power of the compressor,

n_{sr} – reduced rotational speed of the compressor,
nt_{start} – initial rotational speed of the turbine rotor,
ns_{start} – initial rotational speed of the compressor rotor,
n_{szr} – reduced rotational speed of the rotor,
n_{start} – initial rotational speed of the rotor of the turbine-compressor assembly,
N_t – turbine power,
n_{tr} – reduced rotational speed of the turbine,
P – average total pressure of the working medium accumulated in the ‘V’ volume,
P0 – total pressure of the working medium at the engine inlet,
P1 – total pressure of the working medium in front of the compressor,
P2 – total pressure of the working medium behind the compressor,
P4 – total pressure of the working medium in the convergent nozzle,
Pd_{start} – initial average total pressure of the working medium in the convergent nozzle,
PH – ambient pressure,
Pks_{start} – initial average total pressure of the working medium in the combustion chamber,
Q – rate of fuel flow,
Qg – upper limit of the fuel flow during acceleration,
R – engine thrust,
Rg – gas constant,
s1, s2, s3, s4 – logical control commands,
T – average temperature of the working medium accumulated in the ‘V’ volume,
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,
T4 – total temperature of the working medium behind the turbine,
T4t – temperature of the working medium measured with a set of thermocouples,
Ta – total temperature of the working medium at the entry into the ‘V’ volume,
Tb – total temperature of the working medium at the exit out of the ‘V’ volume,

Td_{start}	–	initial average total temperature of the working medium in the convergent nozzle,
TauASS	–	time constant of the fuel supply system,
TH	–	ambient temperature,
Tks_{start}	–	initial average total temperature of the working medium in the combustion chamber,
t	–	time,
t_{prog1}	–	time instance when blow-out occurs in the combustion chamber,
t_{prog2}	–	time instance when the shaft (connecting compressor rotor to that of a turbine) fails,
t_{prog3}	–	time instance when the fuel shutting off is initiated,
V	–	volume of the selected part of the engine-duct space,
V_d	–	volume of the duct of convergent nozzle,
V_{ks}	–	volume of the combustion-chamber duct,
Wo	–	fuel calorific value,
WS	–	fuel shut-off controlling signal,
Wu	–	air bleed coefficient,
t	–	time interval when the fuel is getting shut off,
T12/T2	–	relative increment of temperature of the working medium due to compression,
Π	–	pressure ratio (of the compressor),
ε	–	pressure ratio of decompression of the working medium while flowing through the turbine,
ϕ	–	rate-of-flow coefficient of a convergent nozzle,
η_{ks}	–	efficiency of heat emission in the combustion chamber,
η_{ms}	–	coefficient of mechanical efficiency of compressor,
η_{mt}	–	coefficient of mechanical efficiency of the turbine,
η_t	–	isentropic efficiency of the turbine,
ρ	–	average specific density of the working medium accumulated in the 'V' volume,
σ_{12}	–	the total-pressure-retention coefficient for the compressor flow,
σ_{23}	–	the total-pressure-retention coefficient for the combustion-chamber flow.

Graphic symbols



1. Introduction

In the light of the Author's experience, the correct analysis of transient states of a turbojet engine treated as a controllable source of thrust t impart propulsion to an aircraft should be conducted on the basis of a suitable simulation model. There are both economical and substantial points that are for this suggestion.

Experimental work on a real jet engine is very expensive because of the cost of an engine itself and its hourly installation life, of fuel, and special measuring/recording systems. Furthermore, what appears while investigating transient processes that take place in real engines are problems with taking measurements of actual values of hard-to-measure parameters. These comprise thrust and temperatures of gas in some selected sections of the engine duct, i.e. behind the compressor, at the combustion-chamber outlet, behind the turbine [6], [7], [8], [10], [11].

Therefore, making use of an adequate simulation model while studying transient processes of jet engines proves of potentially great significance. This is the right way to reduce costs of research and testing work, first and foremost, by means of limiting time and scope thereof. It is also possible to increase cognitive value of the work – because of the capability to observe how the above-mentioned hard-to-measure parameters keep changing.

Hence, some hybrid approach, promoted also by the Author, seems very promising. It consists in matching the directly taken measurements of easy-to-measure parameters with computations made for hard-to-measure and non-measurable ones by means of a special mathematical model of the engine under examination. The point is how to make practical use of some special variation of the mathematical model of an engine, i.e. the so-called non-linear observer [6], [7], [8], [10], [11].

Of particular cognitive value are experiments with a computer simulation based model, ones conducted to recognise transient processes of the engine under some faulty modes of operation, since in such a case any experimental work on real objects remains practically out of question. In Poland, the studying of transient processes due to various kinds of failures to real engines has been possible until now only by means of analysing records from flight recorders, including FDRs – flight data recorders colloquially also called crash recorders or 'black boxes'. However, difficulties may occur also in such a case, most often due to both a very limited number of simultaneously recorded parameters of engine and aircraft operation, and too low sampling frequency (in the case of digital recording).

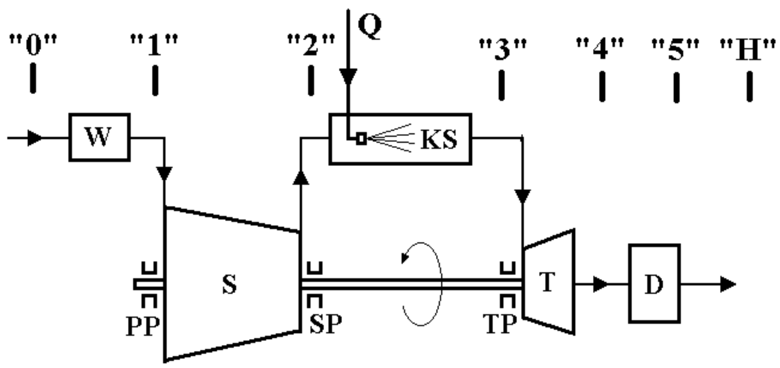


Fig. 1. A block diagram of the SO-3 engine (W – inlet, S – compressor, KS – combustion chamber, T – turbine, D – convergent nozzle, PP, SP, TP – engine bearing supports: forward, mid and rear ones, respectively)

The paper has been intended to present results of simulation of two exemplary transient processes of turbojet engines S)-3, produced by faulty modes of operation under normal ambient conditions at ground level (PH = 760 mm Hg, TH = 288.2 K, M = 0). In the first case, parameters of engine running were observed while the engine was severely decelerated (due to a rapid fuel shut-off at full thrust). In the second case, observed were transient states produced by disintegration of the shaft that connects the turbine rotor with the compressor rotor. The failure occurred while the engine was running at some steady rotational speed. The reported work was undertaken to check whether the methodology of the modelling of turbojet engines, developed by the Author to meet needs of designing engine fuel supply systems and automatic controls [5], [9] could be adapted to analyse operation/ performance of such engines while in faulty modes of operation.

The simulation-model's code has been written using the Borland Turbo-Pascal. Simulations were generated using a PC microcomputer with the Pentium processor (R), CPU clock of 3.0 GHz, and random access memory (RAM) of 1.0 GB.

2. Adaptation of a model of an engine to simulate some selected faulty modes of operation

It has been recognised that any simulation of faulty modes of operation produced by some rapid fuel shut-off or disintegration of the shaft that connects the turbine and compressor rotor requires some special version of the model of an engine. Apart from the kinetic energy accumulation in the rotor, this version should also take account of the accumulation of both the enthalpy and the mass of the working medium in some selected sections of the engine duct [1], [2], [3], [4], [9], [12]. This results from the supposition that transient processes of the engine while in one of the above-described faulty modes should be observed within a frequency band higher than that of transient processes resulting from the normal run/operation of the engine controlled by the fuel supply and control system.

The block diagram of the suggested simulation model has been composed of two parts. The first one, shown in Fig. 2, refers to a system of non-linear differential equations that describe the flow of the working medium through the engine duct. The second one, shown in Fig. 5, refers to a differential equation of motion of the rotor of the turbine-compressor assembly. There are two blocks in the structure of the first part, i.e. the 'Aks' and the 'Ad' ones. Both include differential equations that describe accumulation of mass and enthalpy of the working medium in the combustion chamber (Aks) and the convergent-nozzle (Ad) volumes. Both the blocks show identical structure presented in detail in Fig. 3. They have been constructed using the system of equations (1–6):

$$Tb = 2 \cdot T - Ta; \tag{1}$$

$$\rho = \frac{P}{Rg \cdot T}; \tag{2}$$

$$m = V \cdot \rho; \tag{3}$$

$$I = Cp \cdot T \cdot m; \tag{4}$$

$$\frac{dT}{dt} = \frac{1}{m}[Ga \cdot (k \cdot Ta - T) + Gb \cdot (T - k \cdot Tb)]; \tag{5}$$

$$\frac{dP}{dt} = (Ga - Gb) \cdot \frac{Rg \cdot T}{V} + \frac{P}{T} \cdot \frac{dT}{dt}. \tag{6}$$

An additional figure, Fig. 4, shows the ordering of inputs and outputs, and of steady parameters of the Aks and Ad blocks; symbols shown are those used in the system of equations (1–6).

In the literature, one can find an alternative solution for the structure of the Aks block [1], [4], [12]. It consists in joining equations (1–6) with the equation of heat balance of the combustion chamber. In the model's structure presented in Fig. 2, this equation is to be found in a separate block KS. Both the modelling techniques have been verified, both give exactly the same results.

It has been assumed that there are only two spaces where processes of accumulating the enthalpy and the mass of the working medium take place. These are the combustion chamber (Aks) and the nozzle (Ad). Similar processes in the inlet duct, the compressor and the turbine have been neglected. Disregard of the inlet duct's volume has been justified by the fact that the planned simulation-based experiments are limited to those of running engines with short air intakes only. Disregard of the turbine duct's volume has resulted from the fact that it is a single-stage turbine. The compressor duct's volume has not been treated separately, since it has been assumed to consider it together with the combustion chamber's volume.

Characteristic of the model is that in each subsequent step of integration, on the grounds of known initial values of all integrating elements (n_{start}, Tks_{start}, Pks_{start}, Td_{start}, Pd_{start}) one can directly, without resorting to iteration, calculate values of all derivatives that occur in the differential equations (dn/dt, dTks/dt, dPks/dt, dTd/dt, dPd/dt).

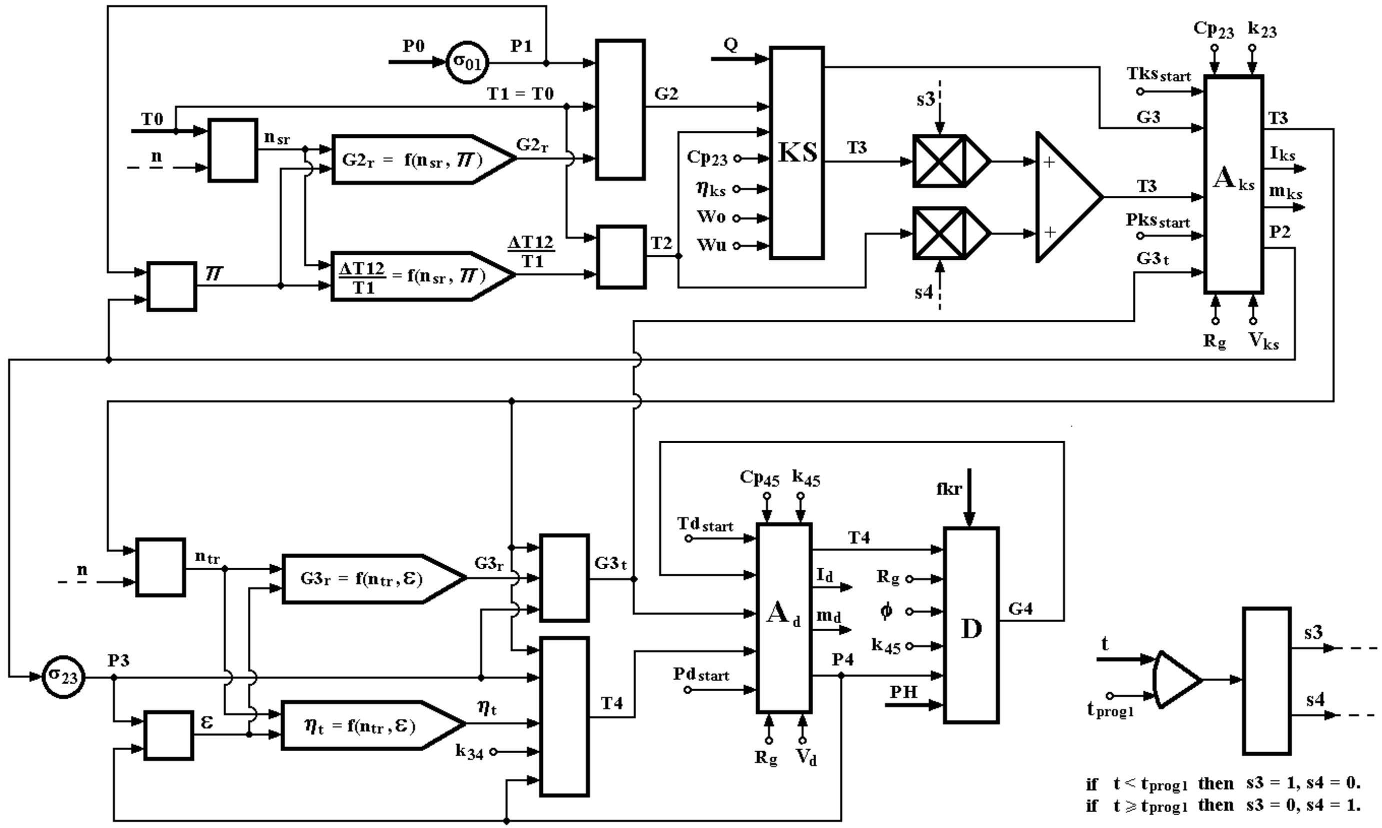


Fig. 2. A block diagram of a circuit for integrating differential equations that describe actual values of parameters of the working medium. Evident is a logical system to simulate the blow-out in the combustion chamber

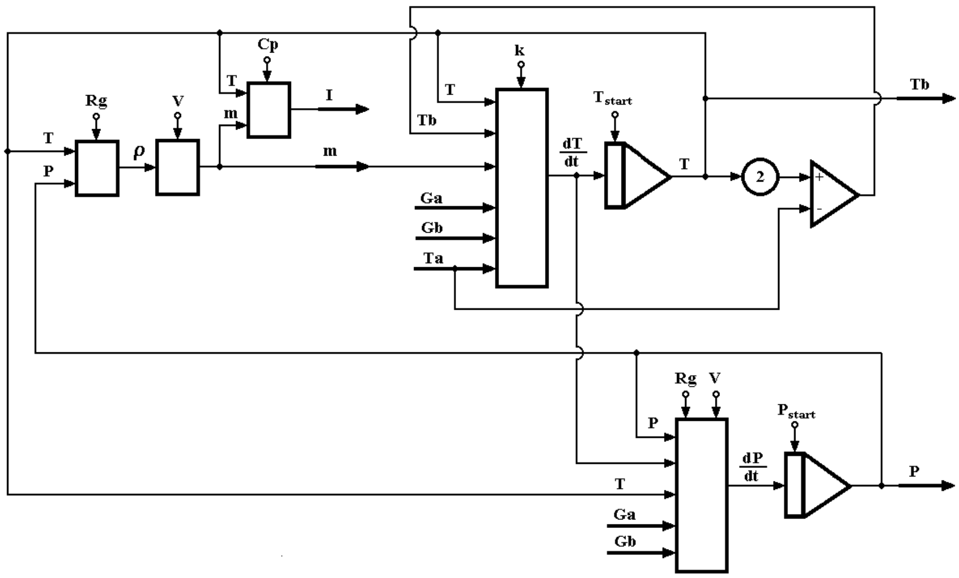


Fig. 3. A block diagram of a circuit of integrating equations that describe accumulation of the mass and the enthalpy of the working medium in the combustion-chamber's volume (V_{ks}) or that of the nozzle (V_d)

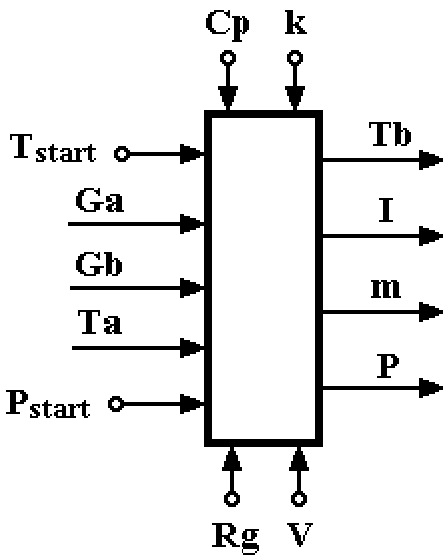


Fig. 4. The ordering of the variable inputs/outputs and steady parameters included in the diagram shown in Fig. 3

The above-described model has been adapted to simulate some selected faulty modes of operation. Therefore, a special logical circuit has been built in the part of the model shown in Fig. 2, designed for the calculating of average actual values of parameters of the working medium. In time instance $t \geq t_{prog1}$, it makes an actual temperature of the working medium at the combustion-chamber outlet (T3) equal the actual temperature of air behind the compressor (T2). This is the way to simulate a rapid blow-out in he combustion chamber (hence, a simplified assumption has been made that the blow-out in the combustion chamber at time instance $t \geq t_{prog1}$ is rapid and complete).

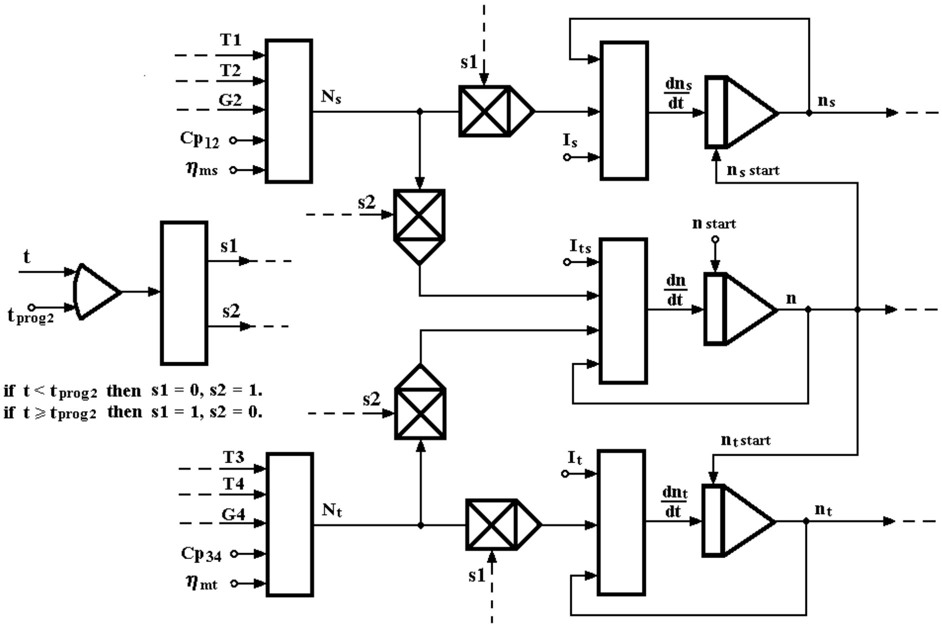


Fig. 5. The integrating circuit for the equation of motion of the entire rotor, and for separate equations of motion of the compressor and turbine rotors after the shaft that connects both the rotors has failed

The part of the model presented in Fig. 5 has been designed in particular for integrating equations of motion of the entire rotor, and two parts thereof after the shaft that connects the turbine and the compressor has failed. That is why the logical circuit shown in Fig. 5 has been built in. This circuit makes that at time instance $t \geq t_{prog2}$ the integrating circuit designed to calculate an actual value of rotational speed of the entire rotor (n) stops working. Then, activated are two separate integrating circuits to calculate actual values of rotational speed of the compressor itself (ns) and that of turbine rotor with a fragment of the failed shaft (nt). Corresponding values of polar moments of inertia I_{ts}, I_s, I_t have, therefore, been assumed, according to the following relationship: $I_{ts} = I_s + I_t$.

3. Simulation of the engine's fuel-supply and control system

Experiments on simulation models of an engine should be similar to those that hypothetically are feasible using a real engine. Hence, the idea emerges to combine a simulation model of an engine with one of the fuel-supply and control system. A real fuel-supply and control system of the SO-3 engine is a complicated set of hydraulic-and-mechanical and pneumatic-and-mechanical units; the principle of operation of this set can be described with a block diagram shown in Fig. 6. This description is simplified, however, sufficient to conduct and understand experiments presented further on.

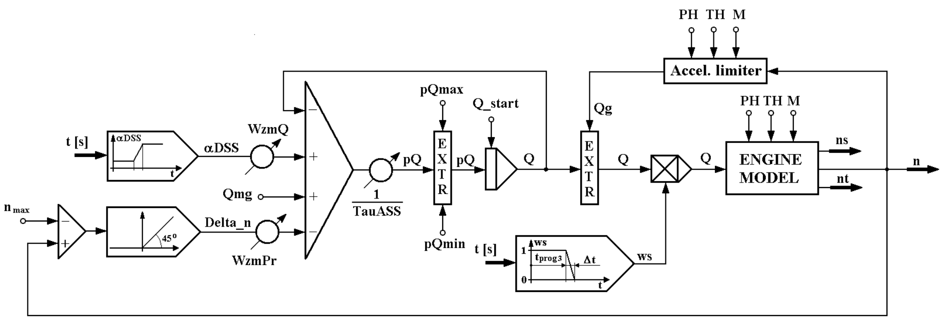


Fig. 6. A block diagram of the engine fuel-supply and control system

It comes out that for the range of rotational speed from the idle run up to n Ł nmax the open-loop control is practised; value of the rate of the fuel flow (Q) in steady states is a function of the angle of the engine-control-lever positioning (αDSS). In transient states, e.g. in the course of full-range acceleration, an actual value of the rate of fuel flow is limited from above by means of the in the diagram shown limiter of the Q_{max} value. A proportional controller – limiter of the maximum rotational speed – n_{max} – has also been shown in the diagram. Since simulation-based studies have been limited to the case of engine running under normal weather conditions (PH = 760 mm Hg, TH = 288.2 K, M = 0), Fig. 6 does not show any barometric-pressure-induced correction of fuel flow that occurs in reality and is necessary in case aircraft flight altitude and speed change. For the sake of simplification, it has been assumed that operation of the limiter of actual values of the rate of fuel flow in the course of acceleration shows the quasi-static nature. Alike an actual control system, it has been assumed that any change in the rate of fuel flow (Q), resulting from the switch of the engine control lever (αDSS) and probable actuation of the limiter of the maximum rotational speed is delayed due to the value of time constant of the engine control unit (TauASS) shown in the diagram. Another system to initiate the time-programmable process of the fuel shut-off has also been shown in the diagram. The shutting-off process starts at $t = t_{prog3}$ and terminates at $t = t_{prog3} + \Delta t$. Linear nature of the process of modifying fuel supply has been assumed. The length of time interval Δt is optional, which enables simulation of the rate (speed) of moving the lever of the cut-off valve in a real engine's fuel-supply and control system.

Simulation of the fuel-supply and control system while failed due to disintegration of the shaft that connects rotors of the turbine and the compressor has been reduced to the maintaining of some pre-set rate of fuel flow (Q) effected with some specific position of the engine control lever (αDSS). The admissibility of such simplification results from the principle of operation of a real fuel-supply and control system of the SO-3 engine. It has been found[1] that some rapid decrease in rotational speed of the fuel pump (mechanically connected with the compressor rotor) effected with the reduction of rotational speed of the compressor rotor after disintegration of the shaft that connects it to the turbine rotor (down to the value $ns = n_{bj}$) results in only slight, of approximately 1%, decrease in the rate of fuel flow.

4. Effects of simulating transient processes of the engine due to the fuel shut-off

Simulation-effected findings presented in this chapter have been gained for two different rates of fuel shutting off. These rates are defined with Δt parameter. They were $\Delta t = 0.2$ s and $\Delta t = 0.5$ s. The first check of whether the model is correct consists in comparing the simulated changes – with time – in rotational speed of the rotor (n), effected with the fuel shut-off (Q), to those gained in the course of the test running of a real SO-3 engine. Unfortunately, the rate of moving the engine control lever by the operator has not been recorded. Comparison of results shown in Fig. 7 with those in Fig. 8 allows us to agree that the simulation model of the SO-3 engine is correct.

The exemplary simulated changes – with time – of some other selected parameters of the engine are shown in Figs 9 and 10. These include, respectively: the average total temperature of gas at the combustion-chamber outlet (T3), and mass flow thereof (G3) due to the fuel shut-off. Of particular interest are two changes of temperature (T3) with time, presented in Fig. 9.

[1] The finding of the Author's studies on a simulation model of the fuel-flow rate control system of the SO-3 engine

What follows from the figure is that the rate of the fuel shutting off directly affects the gradient of the engine's getting cooled. The higher thermal gradient, the greater destructive effect on structural members of the so-called hot section of the engine duct, i.e. the combustion chamber, the turbine, the nozzle.

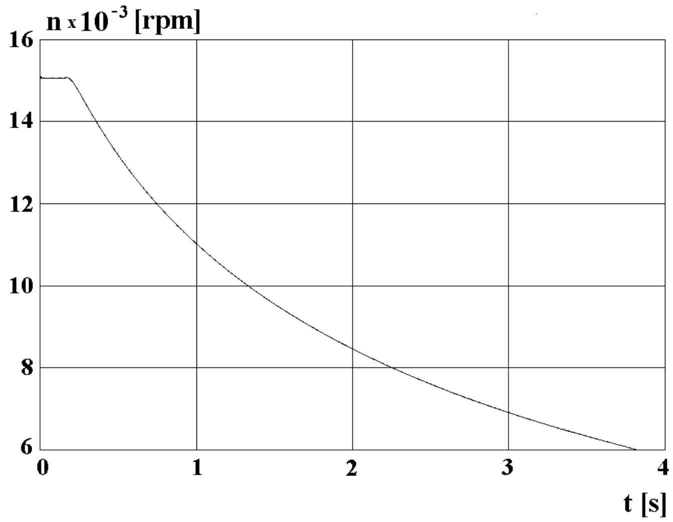


Fig. 7. Rotational speed of the rotor of a real SO-3 engine after fuel shut-off under steady-state conditions at rotational speed n = 15000 rpm (ground testing)

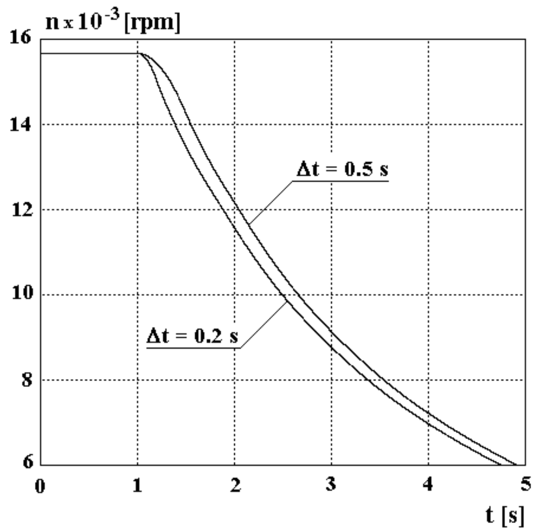


Fig. 8. Simulated two instances of the rotor's rotational speed changing after fuel shut-off under steady-state conditions, at full-thrust range

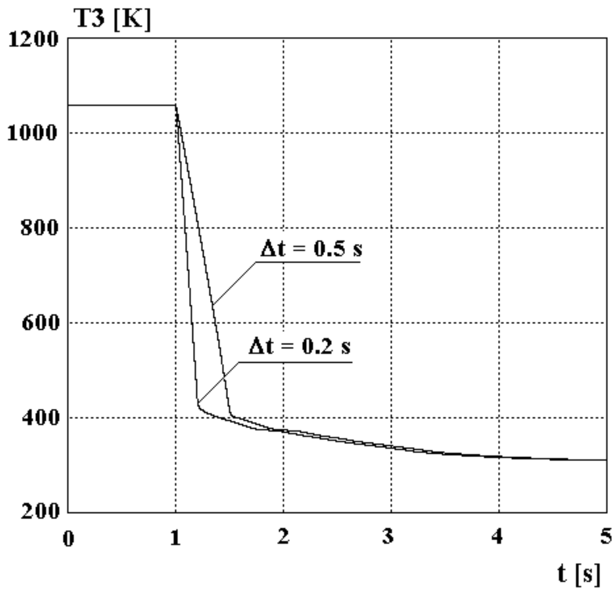


Fig. 9. Simulated two instances of average total temperature at the combustion-chamber outlet, changing after fuel shut-off under steady-state conditions, at full-thrust range

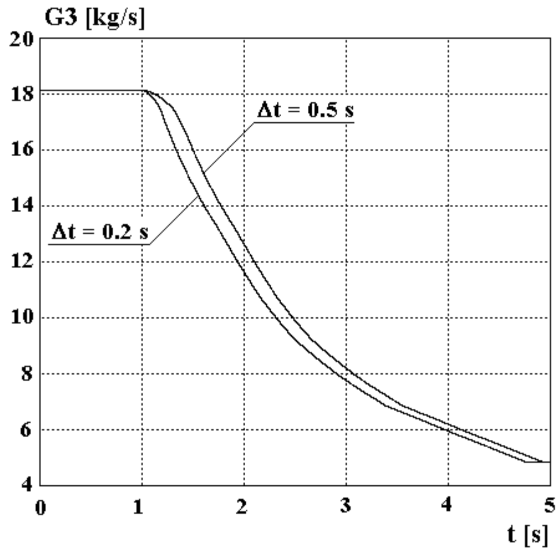


Fig. 10. Simulated two instances of mass flow of the working medium at the combustion-chamber outlet, changing after fuel shut-off under steady-state conditions, at full-thrust range

Phase diagrams shown in Figs 11 and 11 a, illustrate amplitudes of the engine's rapidly getting cooled. They refer to three characteristic instances discussed below.

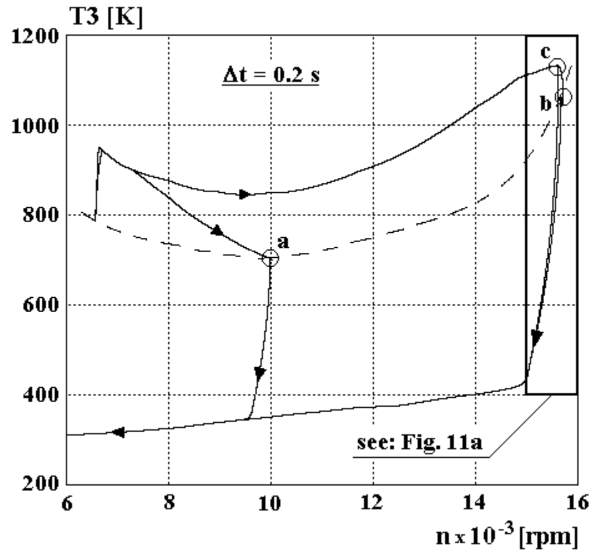


Fig. 11. Phase diagrams of simulated different instances of how the average total temperature of the working medium at the combustion-chamber outlet changes after fuel shut-off: in two different steady states (points 'a' and 'b'), and at final stage of full acceleration (point 'c')

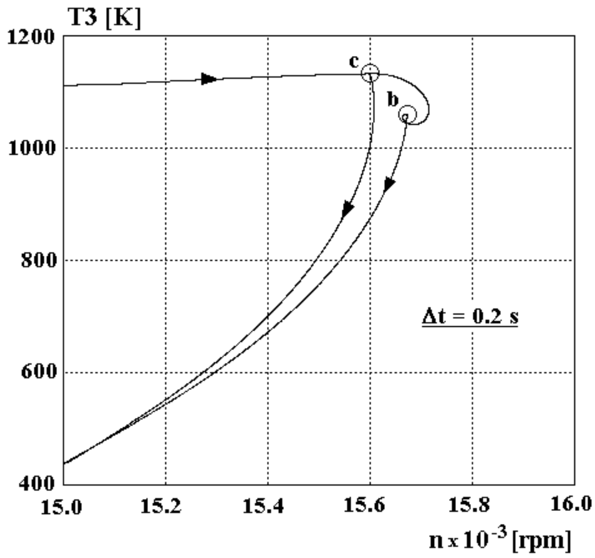


Fig. 11a. A scaled-up section of phase diagrams plotted in Fig. 11

The fuel shut-off can put an engine into thermal shock, if gas temperature before the turbine (T3) is highest possible under given ambient conditions. The maximum steady temperature occurs while the engine is run at the full-thrust range (Fig. 11, point 'b'). The maximum actual value of the temperature before the turbine occurs, however, in a transient state, at final stage of full acceleration of the engine (Fig. 11, point 'c'). It may prove much higher than the maximum steady-state temperature, due to the overrun of rotational speed of the rotor beyond the permissible maximum. The overrun results from the dynamics of the limiter of the maximum rotational speed included in the engine-automatic-control system (Fig. 6). The fuel shut-off results in the rapid cooling of the working medium in the hot section of the engine duct. The amplitude of cooling reaches several hundred Kelvin degrees K; therefore, it can be labelled 'thermal shock'. Too frequent thermal shocks of high amplitudes result in deformations and disintegration of key structural components of the engine and lead to premature wear-and-tear. In the utmost, they may result in the engine damage. To minimise the damaging effect of the phenomenon, the engine is shut down (in the course of normal operation/running) after it has been maintained in a steady state (to get cooled) at some rotational speed, which corresponds with the minimum steady-state temperature (Fig. 11a, point 'a').

5. Results of simulating transient processes of an engine due to the disintegration of the compressor-to-turbine connecting shaft

An extremely rare in aeronautics event, i.e. a failure to (the cracking of) the shaft that connects the turbine rotor to that of the compressor results in an engine damage and may contribute to/cause a fatal air accident. It may prove extremely hazardous to a single-engine aircraft. The studying of processes that take place in the engine due to such an event needs access to aircraft/engine parameters recorded by flight data recorders, colloquially called crash recorders or 'black boxes'. However, even in such a case recorded is rotational speed of the entire rotor (n), and not of separate components thereof, i.e. of the compressor rotor (ns) or the turbine rotor (nt). Furthermore, transient processes that could be observed in the course of such a fault condition, usually take place at so high rates (the below presented results of simulation deliberately prove it) that taking digital records with crash recorders usually requires much higher sampling frequency than that found in practice. To sum up, the analysing of the engine failure, given consideration in this paper, by means of a simulation-model-based experiment proves very reasonable.

Results of the simulation are gained on the assumption that after failure to the shaft both parts of the rotor rotate unimpeded. However, in the case of a real failure, axial forces cause that the turbine rotor is quickly dislocated and stopped due to its rubbing against parts of the engine structure behind the turbine.

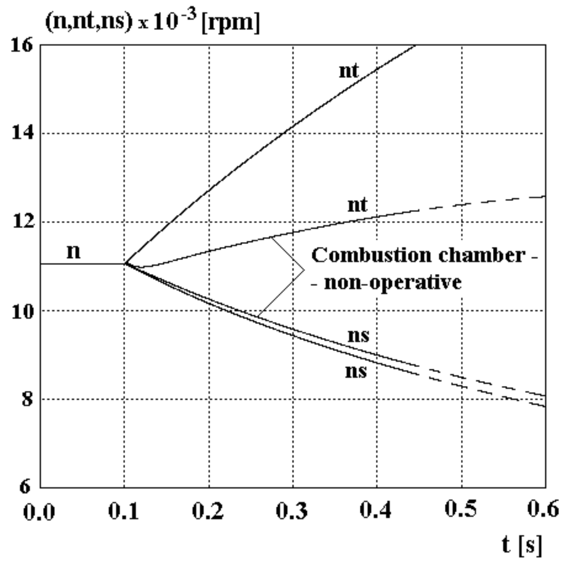


Fig. 12. Two instances of simulated changes with time in rotational speed of the compressor rotor (ns) and the turbine rotor (nt) after failure to the shaft

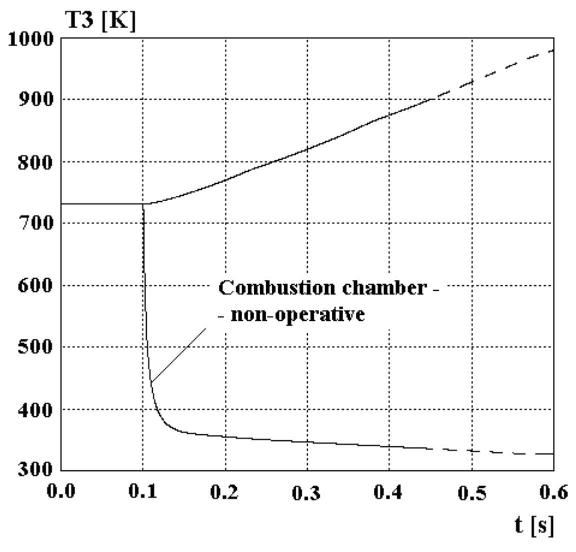


Fig. 13. Two instances of simulated changes with time in the average total temperature of the working medium at the combustion-chamber outlet, after failure to the shaft that connects the turbine rotor to that of the compressor

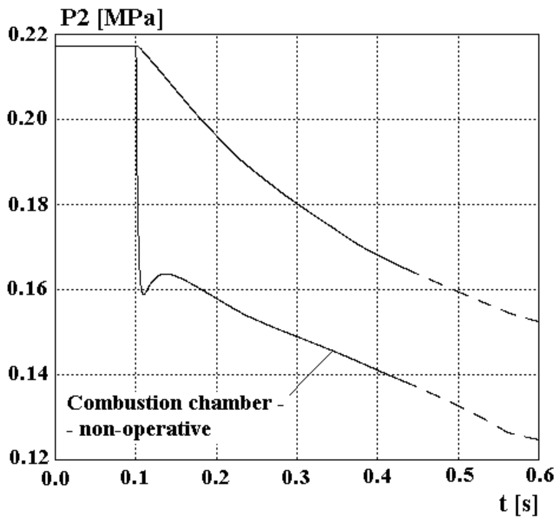


Fig. 14. Two instances of simulated changes with time in the total pressure of air behind the compressor (P2), after failure to the shaft that connects the turbine rotor to that of the compressor

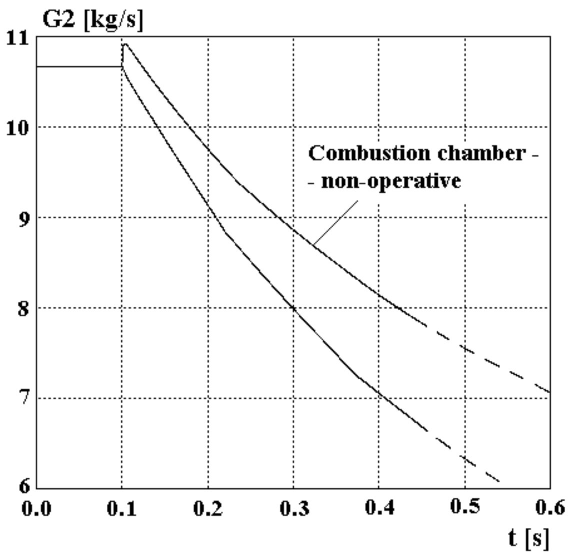


Fig. 15. Two instances of simulated changes with time in the mass flow of the working medium at the compressor outlet (G2), after failure to the shaft that connects the turbine rotor to that of the compressor

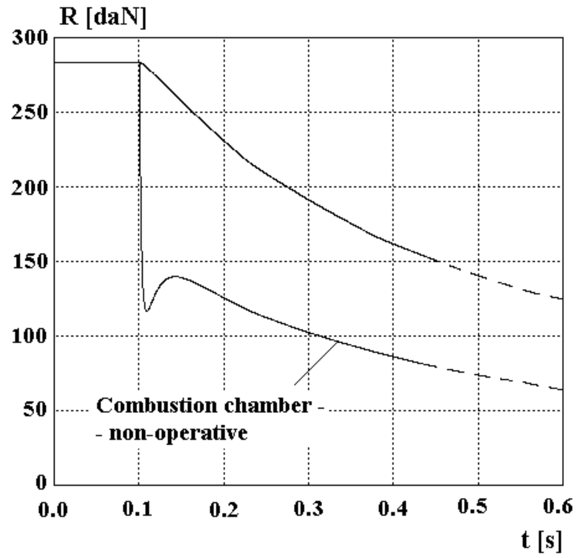


Fig. 16. Two instances of simulated changes with time in engine thrust, after failure to the shaft that connects the turbine rotor to that of the compressor

Simulation-based experiments have been performed for two instances. The first one has been based on the assumption that the rapid decrease in air pressure behind the compressor (P2) and mass flow of air (G2) after the shaft failure does not result in the combustion chamber blow-out. The second one has been based on the assumption that at the moment of the shaft failure, a rapid blow-out occurs in the combustion chamber. All the plots in Figs 12÷16 prove that both cases defined above significantly differ.

The simulation model of the SO-3 engine performs correctly only when rotational speeds of the compressor rotor (ns) and the turbine rotor (nt) remain within the range 6 ... 16000 rpm. If any of the above-mentioned rotational speeds (ns or nt) exceeds these limits, results of the simulation become inaccurate – see broken lines in Figs 12÷16. Hence, it is important to pre-set some steady rotational speed of the rotor (n), at which the shaft gets failed (Fig. 12).

6. Conclusions

The model of the SO-3 engine, formulated to meet the needs of the design and studying of the fuel-supply and control system of this engine [9] can also be used to simulate the above-described fault conditions. It is of particular importance to the capability of observing fat changes in temperature of the working medium that accompany either fuel shut-off or disintegration of the shaft that connects the turbine and the compressor.

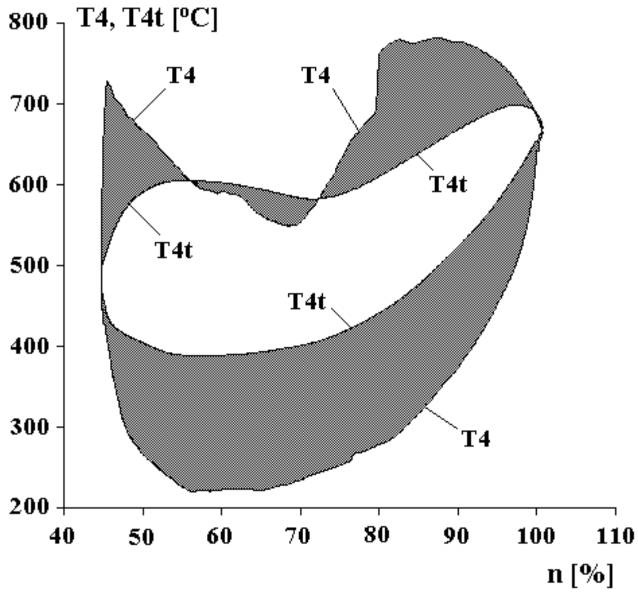


Fig. 17. The dynamic error of measuring the average total temperature of the working medium behind the turbine of the K-15 engine. (T4t – measurements taken directly with a set of thermocouples, T4 – indirect measurement [8] taken with the non-linear observer of the K-15 engine)

The capability to directly observe thermal shocks that occur on a real engine is very limited due to the lack of excellence of the measuring equipment in use hitherto to measure fast-changing temperature of the working medium. While carrying out the K-15 project to provide propulsion for the I-22 IRYDA it has been found that too great and poorly defined inertia of taking measurements of temperature of the working medium with thermocouples [8] is the main reason for these difficulties. In particular, it has been found that the dynamic error of measuring actual average total temperature of exhaust gas in the K-15's nozzle in the course of full acceleration and deceleration is approximately 200 K (Fig. 17). Also for this reason, findings of simulation-based experiments presented in this paper show considerable cognitive value.

In the course of engine failure due to the failure to disintegration of the shaft that connects the turbine and the compressor, one cannot exclude an instance of uninterrupted operation of the combustion chamber. It may happen because of rapid increase in temperature of the working medium at the combustion-chamber outlet (Fig. 13), which proves another fire hazard to both the engine and the airframe.

The with the shaft failure disturbed process of simultaneous deceleration of the compressor rotor and acceleration of the turbine rotor takes less than 1 s (Fig. 12). At the same time, some rapid loss of thrust takes place (Fig. 16). That is why correct identification of the fault condition by the pilot, who only gets indications of instruments in the cockpit and some acoustic cues, is hardly probable. It seems, therefore, that the engine automatic-control system should be designed in such a way that in the case the discussed fault condition occurs, the system initiates quick fuel shut-off and at the same time sends an explicit warning to the aircrew. In particular, it refers to a low-flying aircraft.

Suitability of the in the paper presented model of an engine is, however, limited. The reason is that permissible rotational speeds of the compressor and the turbine cover the range from the idle up to full thrust. It is exceptionally burdensome while modelling transient processes resulting from a failure to (cracking of) the shaft that connect the compressor rotor to that of the turbine (Fig. 12). Unfortunately, the extension of the range of modelling the above-mentioned rotational speeds requires access to static characteristics of the compressor and the turbine. These characteristics are expected to cover much wider range of parameters of operation of these engine members, since they are basic components of the simulation model of the engine (Fig. 2). In case of the compressor, this range should cover rotational speeds much lower than the engine's idle run (n_{bj} = 6500 rpm). In case of the turbine, the range should be extended beyond the full-thrust range (n_{max} = 15600 rpm) until the turbine disc experiences failure. The stipulated extension of range of the above-mentioned static characteristics could be done by means of computations and laboratory experiments. Unfortunately, more extensive discussion of the issue exceeds the limits of this paper.

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Komputerowa symulacja procesów przejściowych turbinowego silnika odrzutowego – ze szczególnym zwróceniem uwagi na amplitudy szoków termicznych w wybranych stanach awaryjnych

S t r e s z c z e n i e

Przedstawiono wyniki matematycznego modelowania i komputerowej symulacji procesów przejściowych turbinowego silnika odrzutowego SO-3, będących następstwem dwóch różnych stanów awaryjnych. W pierwszym z nich proces przejściowy jest wywołany nagłym odcięciem dopływu paliwa. W drugim przypadku, proces przejściowy jest spowodowany pęknięciem wału łączącego wirnik turbiny z wirnikiem sprężarki, w rejonie środkowej podpory łożyskowej.