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IMPACT OF RAPID THERMAL FLUCTUATIONS OF THE AIR FLOW INTO ENGINE INLET TO THE GAS-DYNAMICS STABILITY OF THE TURBOJET ENGINE

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The article deals with impact of rapid thermal fluctuations of the air flow into engine inlet to the gas-dynamics stability of the turbojet engine. Theoretical background of these processes, which causes many accidents in aviation, could be applied on operation stability of turbojet engines which are used as energetic units, cogeneration units or power units in many others transport vehicles.

Keywords: compressor stall, turbojet engine, non-stationary thermal field, unstable thermal field

1. Introduction

Thermal fluctuations of the air flow into the turbojet engine inlet in case of combat conditions could be caused intake of hot combustion products from rocket engines (air-air missiles, air-ground missiles), hot gasses which are released when the onboard cannon is running or intake of hot gasses from the another aircraft exhaust system in case of formation flight.

The phenomena of thermal fluctuation could be observed in case of turbojet engines which are used as energetic units, cogeneration units, power units transport vehicles (special cars, trains, ships etc.), gas pipeline, petroleum pipelines and many others. Causes of these thermal fluctuations could be for example fire, intake of own exhaust gasses and many others. [1]

According to negative impact of these rapid thermal fluctuations to turbojet engines is necessary to know a theoretical and physical background of this phenomenon and make measures to avoid these negative effects.

2. Impact of thermal fluctuations into the turbojet engine intake to the engine operation stability

Thermal fluctuation into the turbojet engine intake are characterized by intensity, time gradient their increase, and spatial inequality and duration of exposure. According to their character are known two basic groups:

- Thermal non-uniformity
- Thermal non-stationarity

Thermal non-uniformity of air flow before the turbojet engine is characterized by the cant mean temperature $T_{0t,ner.}$ in consideration of the turbojet engine intake area and in consideration to temperature of non-affected air flow T_{0t}. Similar to the case of flow non-uniformity the intake area is divided to sectors and the average temperature value is determined $T_{1t,r}$, in every sector, i.e. the temperature is determined for every radius. There is also an another dependence, the function of temperature $T_{1c,r}$“ on polar angle φ. By integration of this function is obtained averaged temperatures through entire surface at engine inlet for “hot” and “cold” zone as well ($T_{1t,hot.}$

a $T_{1t,cold}$). After that, is determined the hot zone angle range $\varphi_{hot} = \varphi_2 - \varphi_1$ (Fig. 1) or its proportional value $\overline{\varphi} = \varphi_{hor.}/2.\pi$. Based on received data is determined averaged air heat in entire area of intake $\Delta T_{1c} = T_{1c,str.} - T_{0c}$ and averaged proportional heat $\delta T_{1t} = \Delta T_{1t}/T_{0t}$.

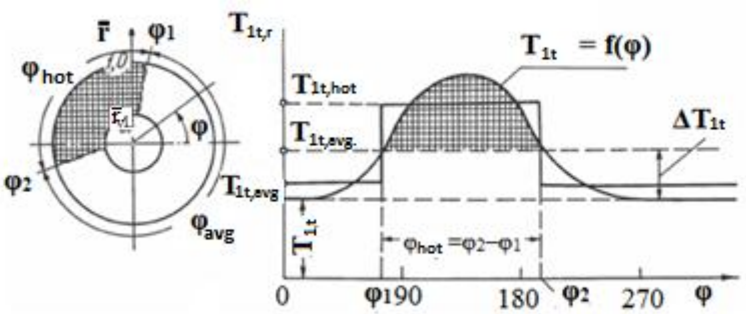

Fig. 1: Determination of thermal non-uniformity

Thermal non-stationery is defined via graph of the functionality of absolute heating $(\Delta T_{1t,i,max})_{max.} = T_{1t,i} - T_{0t}$ on time in the specific point of "hot" zone where is the maximal value of the heating (Fig. 2). This point is evaluated by action duration of the thermal disorder t_m in the field of temperature rise $T_{1t,\,i,\,max.,}$ total time of the temperature operation and also by proportional gradient of the temperature rise in "hot" zone as a function on time $\delta \dot{T}_{1t} = \dot{T}_{1t}/T_{0t}$, where $\dot{T}_{1t} = \dfrac{\partial T_{1t,i,\max.}}{\partial t} \approx \dfrac{(\Delta T_{1t,i,\max.})}{t_m}$ [2]

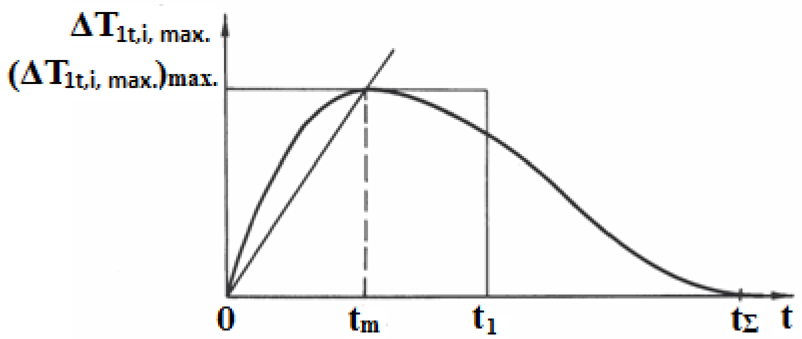

Fig. 2: Determination of thermal non-stationary parameters

The basic quantitative indicator of thermal processes is: intensity of heating δT_{1t}, temperature rise time $\dot{T}_{1c}$, the scope of the "hot" zone φ_{hot} and duration of the thermal disorder t_m. In current practice these indicators during rocket start are changed in successive ranges: δT_{1t} = 0,05 to 0,3; $\delta \dot{T}_{1t} = 1{,}2 \div 7{,}5 s^{-1}$ $(\dot{T}_{1t} = 300 \div 2000 K.s^{-1})$; $\overline{\varphi}_{hot} = 0{,}2 \div 0{,}6$; $t_m = 0{,}01 \div 0{,}2 s$ $(t_\Sigma = 1{,}0 \div 2{,}0 s)$. [2]

Fig. 3 shows the qualitative nature of engine parameters change according to time during suction of hot gasses from rocket engine exhaust system, which in turn causes unstable compressor work.

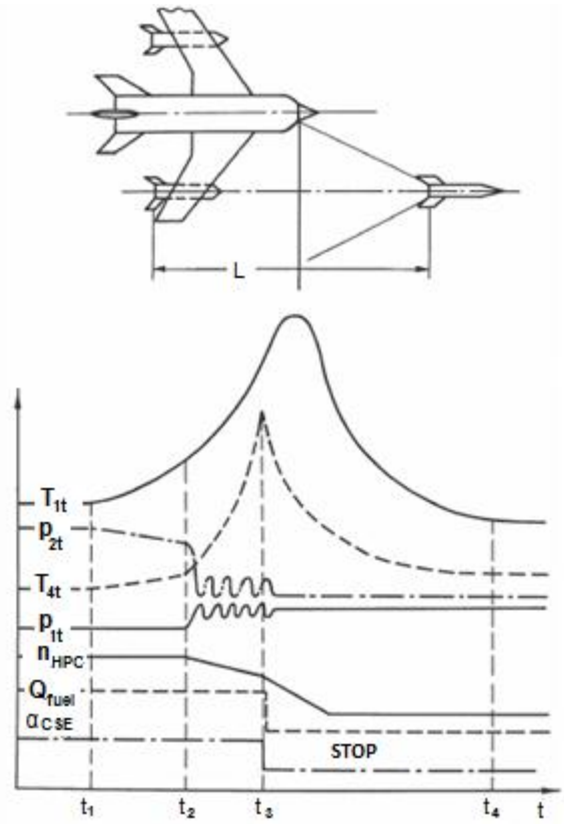

Fig. 3: Qualitative engine parameters change during suction of gasses from rocket engine
T_{1t} – air total temperature on compressor intake, p_{1t} – air total pressure before compressor, p_{2t} – air total pressure behind compressor, T_{4t} – gas total temperature behind turbine, n_{HPC} – high pressure rotor's RPMs, Q_{fuel} – fuel flow rate, α_{CSE} – control stick engine lever angle adjustment

Time t_1 in graph (Fig.3) determines beginning of thermal action of hot gasses, and t_4 determines end of action of hot gasses.

Graph shows (Fig.3) some obvious facts. In the initial stage of the process (in the time interval from to), the high pressure rotor's RPMs n_{HPC} and fuel flow rate Q_{fuel} have no enough time to change and the temperature behind turbine T_{4t} is increased and in same time total pressure behind compressor is slightly decreased p_{2t}. At the time at given levels of thermal disorder arises unstable compressor work (rotating air flow separation). From this moment, the total temperature behind turbine T_{4t} is rapidly increased and the high pressure rotor's RPMs n_{HPC} are decreased (checked by pilot). To protect gas turbines engine blades prior to thermal damage is required by engine control anti-stall system (or by pilot) turn-off the engine (time t_3) and then turn-on the engine and make normal starting procedure until the engine will works in normal mode.

The intensity of thermal exposure of the aircraft on-board equipment to engine depends on:

- The location of the missiles deployment due to an engine intake
- Number and performance of missiles
- Chemical composition of the fuel components
- Missiles flight trajectory
- The aircraft speed and altitude during rocket start
- Engine mode

Given by mentioned facts, ensuring gas-dynamic stability of power units at missiles launch should be considered as a complex issue that affect aircraft, equipment and powerplant constructors.

In accordance with the safety standards, there are define three levels of permissible failures:

At the first level must be maintained without loss gas-dynamic stability at the expense of existing stock of stability and compressor inlet system.

The second level need not lead to loss of gas-dynamics stability in cases when the anti-stall system devices are turned on and the stock stability rise.

At the third level, the engine does not directly protected prior to unstable work but the unstable work is eliminated directly by system to avoid compressor unstable work, which are on the plane.

During the engine testing, the gas-dynamic stability is tested by special stands, which are able to simulate different level of external disorders. [2]

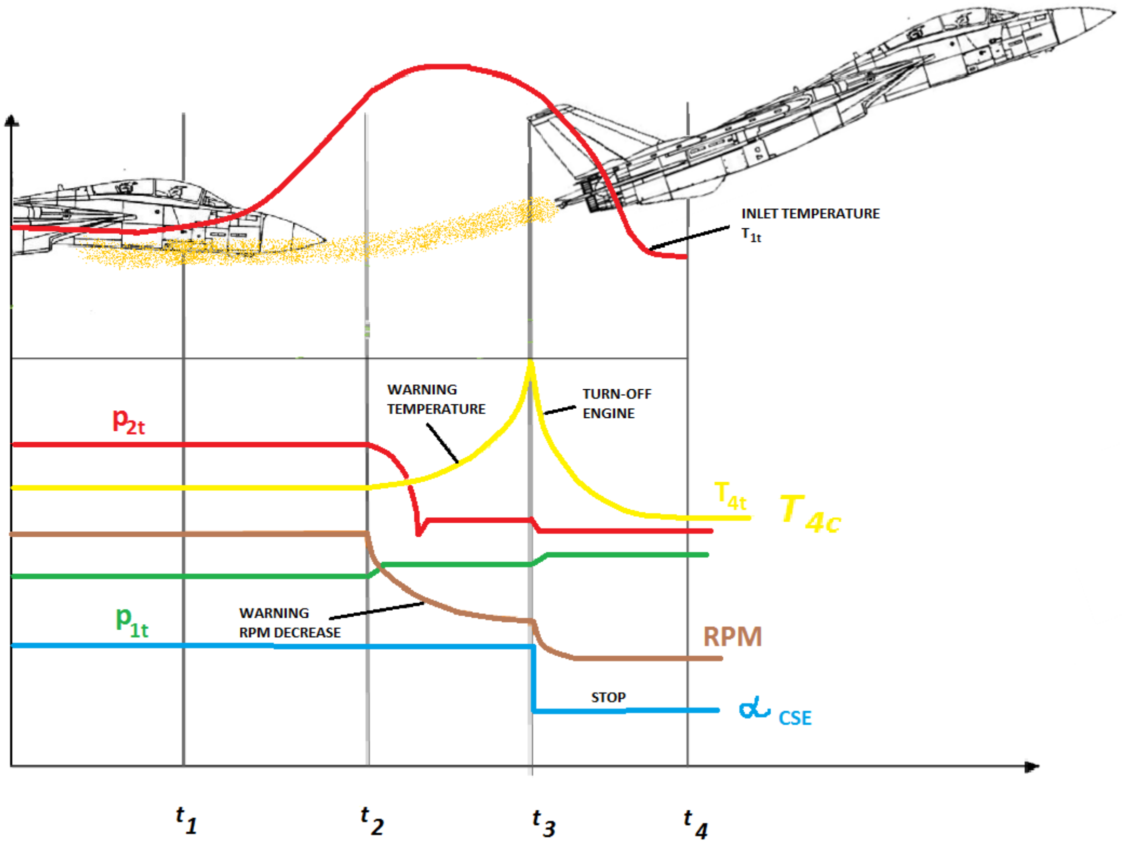

Fig. 4: Qualitative engine parameters change during suction of gasses from another aircraft during formation flight

In case of formation flight could be happened similar situation as mentioned above, when compressor unstable work is caused by hot gasses from an exhaust system of an another aircraft (Fig. 4). In this case is not possible to solve this problem instantly by engine control system as in case of missiles start or in case of on-board cannon. To avoid the compressor or the turbine destruction, the engine control system works on “unstable work liquidation” mode. At this mode engine control system is interrupting fuel flow to main combustion chamber and turning-off the engine. At same time is the engine starting system is turning-on. System of unstable work liquidation is blocked and stay turned-off until aircraft achieving a certain height and airspeed. This situation was artistic performances in the motion picture TOP GUN [4, 5].

3. The phenomena of the flow temperature non-uniformity and non-stationarity at engine inlet to gas-dynamic stability.

3.1 Effect of circumferential non-uniformity of temperature field.

Effect of circumferential non-uniformity of temperature field could be qualitatively described by hypothesis of "parallel compressors", which works for one combustion chamber. In this model, are "cold zone" 1 and "hot zone" 2 are theoretically displaced by compressors, which work with cold and hot air with same physical RPM values. In this case parallel compressors modes are different. There are different calculated RPM values when $n_{cal.hot.} < n_{cal.,cold.}$. The case where each compressor should have their own combustion chamber and turbine is described by points 1 and 2 of characteristics (Fig.5), which are on same line. Pressure on output and pressure ratio π_{Ct} should be different ($\pi_{Ct,cold.} > \pi_{Ct,hot.}$). However, both compressors in the observation scheme operate with the common volume; the pressure in the common combustion chamber is the constant. For this reason, the two compressors have the equal total pressure ratio $\pi_{C,t}$. Figure 5 shows that under these conditions the "cold" compressor has less reserve of stable work ΔK_y. Physical background of this phenomenon is described via pressures in combustion chamber. The mean pressure in the combustion chamber is higher than pressure at "hot" zone and that causes higher throttling effect.

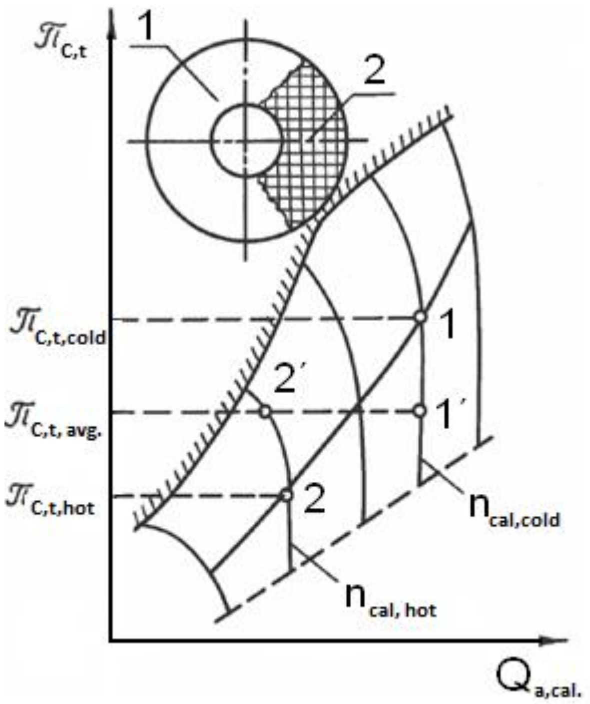

Fig. 5: Effect of circumferential non-uniformity of thermal field to the working point in compressor characteristic

3.2 Effect of total temperature field non-stationary before compressor

If the temperature increasing before compressor T_{1t} is slight (the speed is lower than 50 - 500 $K.s^{-1}$), e.g. rapid increase of aircraft speed causes that the working point starts moving down in the compressor characteristics along to working line (1-2) due to the calculated RPMs (Fig. 6). Total air temperature behind compressor T_{2t} is increasing and total temperature behind turbine T_{3t} is determined by total temperature before engine T_{1t} according to the engine control system mode whereas the fuel control system are able to set fuel supply to the combustion chamber. Decreasing of calculated RPMs is accompanied with decreasing of pressure ration sum $\pi_{Tc,,\Sigma}$.

In case of rapid temperature rise at engine inlet with speed around 1500-2000 K.s-1, the fuel supply to combustion chamber and the revolution have no time to respond to this change and consequently of this phenomena the flow rate rapidly decrease (density and calculated RPM decrease as well). The temperature before turbine is decrease in consideration of engine steady state mode and occurs compressor's "thermal choking". This fact causes that the working point move towards to the surge line (1-2' or 1-2''). The speed of this phenomenon depends on the speed of the temperature increase before engine T_{1t}. This effect could be explained by the total pressure decrease behind compressor p_{2t} (and π_{Ct} as well) delays behind calculated air flow decrease $Q_{a,cal.}$, due to the inertia of gas enclosed in the volume of main combustion chamber.

The value of the total temperature behind compressor T_{2t} could be changed just in case, when the outlet flow intensity from combustion chamber through the gas turbine is changed as well. As a result of higher pressure in combustion chamber, which is higher than pressure behind compressor, the flow through the compressor is braked and the stock of stable work is decrease.

The higher value of δT_{1t} and bigger volume of combustion chamber at same calculated volume of the flow $Q_{a,cal.}$ means worse conditions to secure pressure ratio increase. In these cases is working point moving much faster towards to surge line and it is difficult to secure gas-dynamic stability of the jet engine (Fig.5).

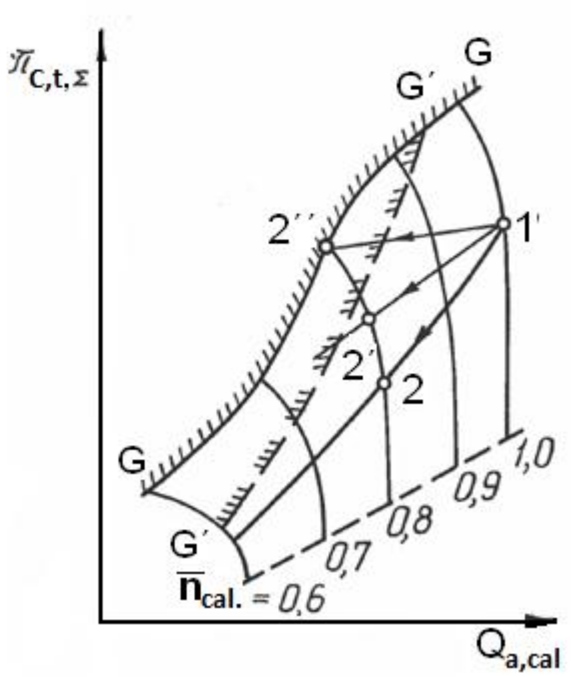

Fig. 6: Effect of circumferential non-stationary of thermal field to the working point in compressor characteristic

Another factor which causes loss of the stable work stock in cases when the temperature is increasing before engine T_{1t} is fact that the compressor control system is not able to respond on time (e.g. by turning blades). Non-controlled compressor at high values of total pressure ratio is moved surge line to right (from position G-G to position G'-G') at the expense of worse stability of working (Fig. 6). [2, 3]

If the intensity of temperature rise in front of engine is higher than 2000 $K.s^{-1}$, the line becomes horizontal. This phenomenon is accompanied by expressions of the inertia of the unstable phenomena (flow separation). The temperature increase gradient in front of engine T1t (e.g. $\dot{T}_{1t}$) causes the compressor gas-dynamic stability decrease.

Whereas the thermal changes at engine inlet causes moving of the surge line in compressor characteristics, the coefficient ΔK_y, losses its validity. For this reason, the stable work stock is defined as a function of the thermal change at engine inlet:

$$\delta T_{1t,kr.} = \frac{T_{1t,crit.} - T_{0t}}{T_{0t}} = \frac{\Delta T_{1t.crit.}}{T_{0t}}$$

i.e. value of proportional heating, which causes loosing of gas-dynamic stability of the engine. To secure stable work of the engine have to be satisfied $\delta T_{1t} < \delta T_{1t,crit.}$

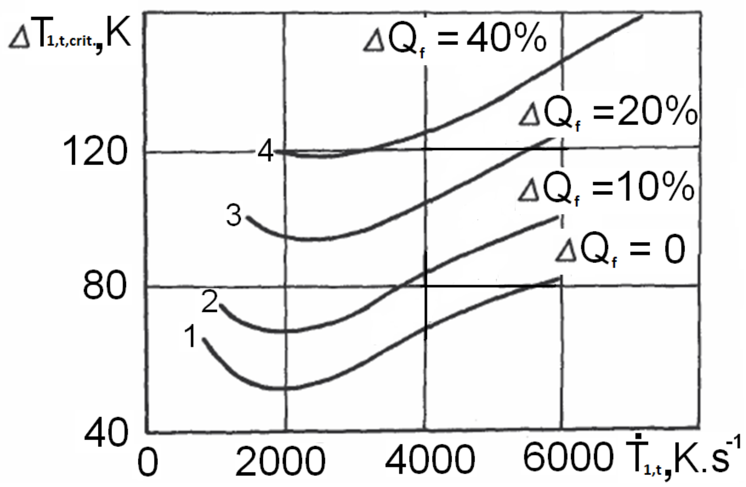

Fig. 7: Function of $\delta T_{1t,crit.}$ on $\delta\dot{T}_{1t}$ pri 1 – Q_{fuel} = const., 2 – rapid decrease of Q_{fuel} by 10%, 3 – rapid decrease Q_{fuel} by 20%, – rapid decrease Q_{fuel} by. o 40%

In real combat conditions the value of critical heating depends on aircraft flight mode, engine working mode, δT_{1t} and φ_{hot}. Figure 7 shows experimental function of $\Delta T_{1t,crit.}$ on speed of temperature increase ΔT_{1t} at constant fuel supply Q_{fuel}=const. and for cases when the thermal disorder is connected with the rapid fuel supply decrease to the combustion chamber. The figure 7 also shows that at constant fuel supply Q_{fuel}=const., the value of critical heating $\Delta T_{1t,crit.}$ by action of temperature change before engine ΔT_{1t} initially decrease and nearby temperature gradient 2000 $K.s^{-1}$ is going to increase. Rapid decrease of fuel supply to the combustion chamber before the effects of heat disorders at engine intake causes reducing of the compressor throttle, increasing of the air flow though the compressor, decrease of angles of attack and increase the stable work stock which allows increasing a value of $\Delta T_{1t,crit.}$ two to three times. This kind of solution is used on engine control system used by Russian aircrafts [4, 5].

Conclusion

The engine stable working conditions in operating and combat condition are achieved by normalization of the compressor stable work stock, the inlet systems, and also disorders which the engine have to handle during operation. For securing these actions the engine control systems are equipped by systems to prevent the engine unstable work and by system to eliminate unstable work.

Although gas-turbines used for energetic purposes and for transportation working significantly more stable than aircraft engines, they can also occur phenomena that have been described in the article. For this reason it is necessary in the engine control system take measures to prevent these unstable phenomena.

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