UNSTABLE OPERATION OF THE TURBINE AIRCRAFT ENGINE

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The article presents reasons for generating a non-uniform field of parameters in the compressor inlet of a turbine aircraft engine and its influence on the air jet kinematics at lowering fatigue strength of the compressor blade. Analysis of the engine torque in function of the engine operation time has been performed. Courses of the basic turbine engine operation parameters during compressor stall have been presented. The significant role of changes of the first torque derivative in relation to variation of the rotor acceleration in that assessment has been determined, which may be an important signal of the compressor surge occurring in the compressor. That parameter may be a signal for the control system to eliminate the negative phenomenon. The engine dynamics during the compressor surge has also been presented by developing the phase images of the engine operation basic parameters. The article includes analysis of dynamical changes in temperature of the combustion gases.

Key words: turbine engine, engine dynamics, compressor stall

1. Introduction

The air jet flowing into a compressor through the inlet duct is perturbed. This process is a result of the influence of various factors which may be divided into three categories:

- external (e.g. wind blow, jet of exhaust gases from another engine, jet of air from the thrust reverser, occurring inlet vortex – Fig. 1)
- connected with changes in the engine operation range (changes of the compressor rotor rotational speed)
- caused by changes in the flight conditions (flight altitude, angle of incidence and planning angle).

The above factors cause the stream flow perturbation in the compressor blade rows inlet, which least to inhomogenity of the jet parameters (speed c, temperature T, and pressure p). This phenomenon may be intensified by structural configuration (positions in relation to each other) of the engine – wing or engine – fuselage. An especially adverse problem is the positioning of engines and their inlets in the wing section, which in such a case are vulnerable to the influence of the vortices flowing off the wings (Szlachtjenko, 1987).

In the case of disturbance, the distribution of parameters in the compressor inlet is two-dimensional (Fig. 2). It causes e.g. changes of speed along the blade and on the circumference $c_{1a} = f(r, \phi)$. The non-uniformity of the field of pressure, temperature and speed leads to the variability of the blades profiles flow round angles (Fig. 3).

It causes the stall phenomenon, which occurs initially on single blades, and then creates separation zones, including a given group of blades (Fig. 4). The consequence is the flow choking in that area. The separation zones spin with the angular speed lower by two up to four times
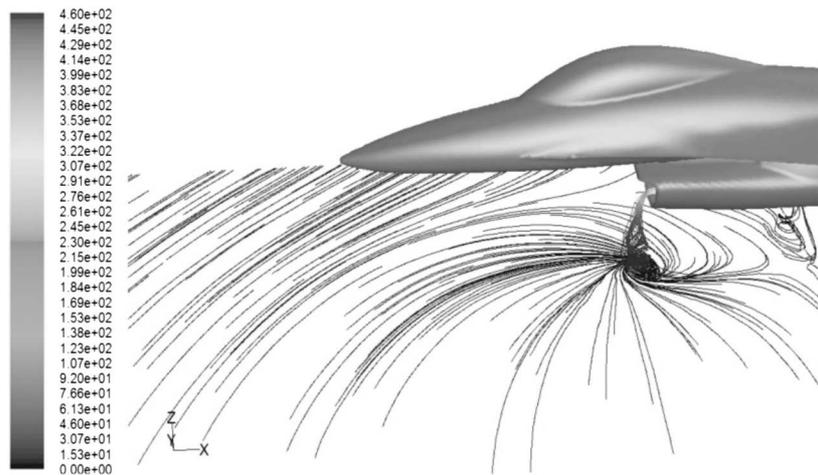
Fig. 1. Model of the inlet vortex occurring at the side blow (Kozakiewicz and Frant, 2011)
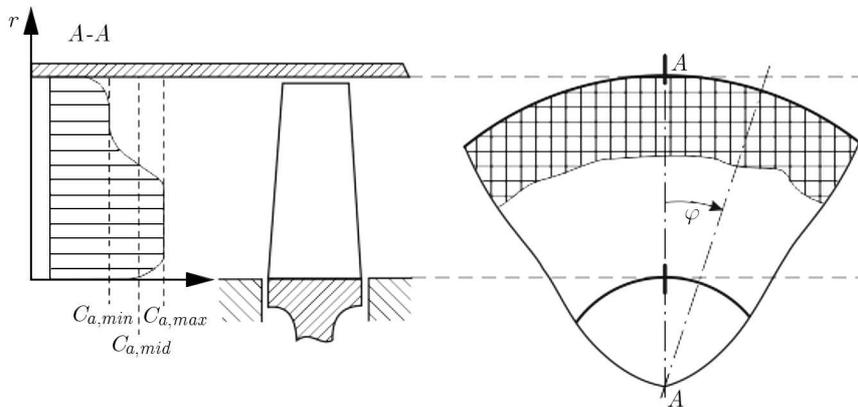

Fig. 2. Example of non-uniform distribution of axial speed of the air jet in the compressor inlet
(a) distribution of the axial speed along the blades $C_{1a} = f(r)$, (b) distribution of the axial speed along
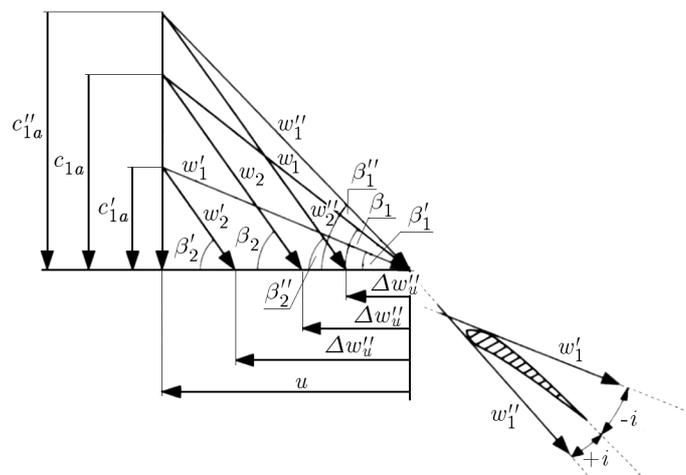the circumference $C_{1a} = f(\phi)$

Fig. 3. Diagram of changes of the flow round the blade profile (changes of the flow angle i) as a result of
variation in the axial component of the jet speed c_{1a} (change in the flow mass intensity) as well as
changes of the component angles and speed on the blade profile

than the compressor rotational speed (Kotlarz, 1973). It causes an illusion of movement of the zones in the direction opposite to the rotating rotor.
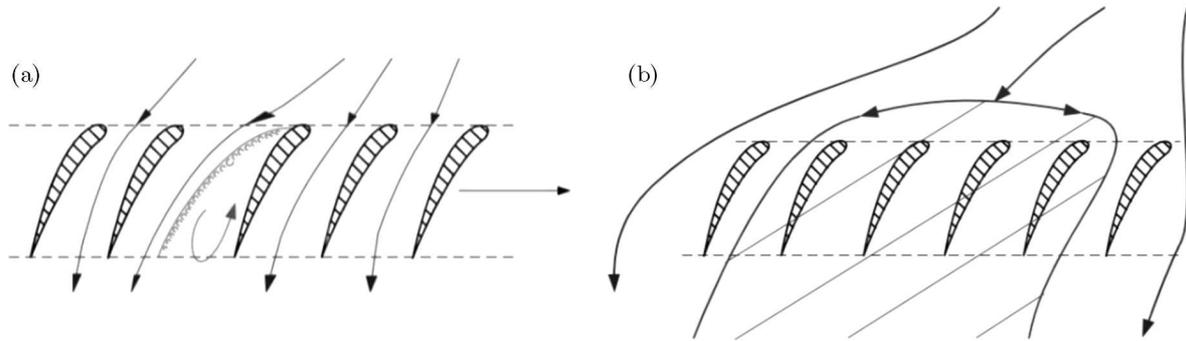

Fig. 4. Creation of the separation zones: (a) creation of stall on a single blade, (b) rotating stall zone on a group of blades

A change of the angles of incidence of individual groups of blades causes, besides the flow round kinematics, a change of the blades load, which results from the Eulerian flow equation

$$\mathbf{F} = \sum_i \mathbf{F}_i = \sum_i \dot{m}(\mathbf{w}_2 - \mathbf{w}_1)_i \qquad (1.1)$$

where $\dot{m}$ is the intensity of the mass flow, $\mathbf{w}_1$, $\mathbf{w}_2$ – relative velocity of the flow upstream and downstream the compressor, respectively.

The resultant of external forces $\mathbf{F}$, influencing the separated jet volume in the steady state, equals to the increment of amount of jet mass during its flow through that volume in a time unit. It allows evaluation of the forces acting upon the compressor rotor blades only with known jet parameters on the boundaries of its separated volume, without investigating the nature of the processes taking place inside that volume. A change of the blades loads varies the fatigue strength (Fig. 5), which is additionally conditional upon the number of cycles and the engine operation time.
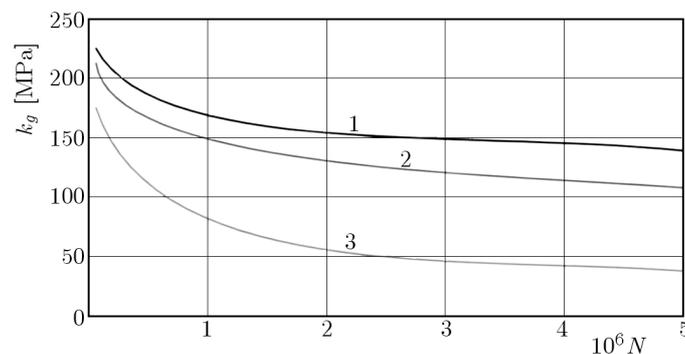

Fig. 5. Change of the blade fatigue strength in function of the number of cycles of experienced loads in the case of operation time: 1 – 0 h, 2 – 100 h, 3 – 200 h (Movikov, 2007)

Changes of kinematics of the air jet flow makes the load of the blades vary in form of pulsating forces. It is very unfavourable, especially due to the fatigue strength of the blades (it decreases the blade strength even by 40-50%, Fig. 5).

2. Dynamical analysis of operation of the turbine aircraft engine

A change of the engine operation range is a result of changing the fuel flow to the combustor, which increases or drops the engine rotational speed.

The essence of engine operation is best shown by the change of the first derivative of the rotational speed dn/dt in function of time (Fig. 6 – prepared upon the basis of studies included in Kowalski *et al.* (2010)).
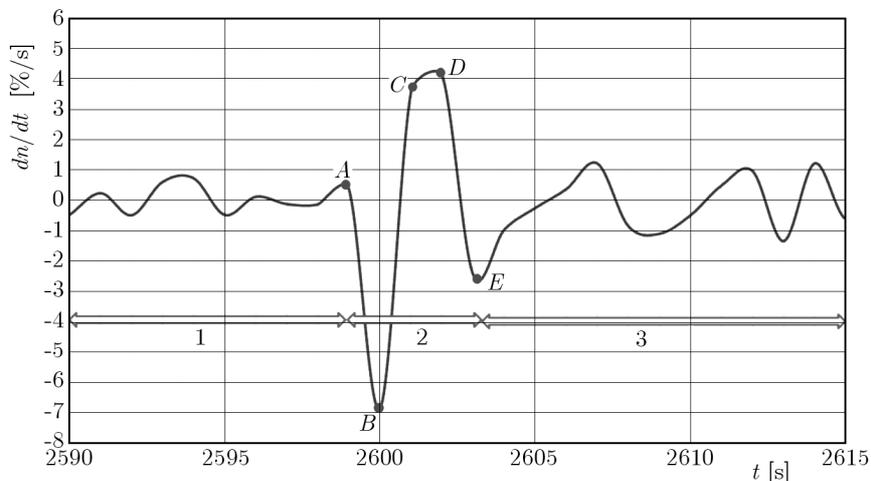
Fig. 6. Time history of the first derivative of the rotational speed dn/dt in the turbine engine

Analysis of Fig. 6 allows determination of three quite characteristic ranges of the engine operation:

- range 1 (to point A), corresponding to the quasi-steady range
- range 2 (from point A to point E), characterized by a sudden drop and a quick increase in the rotational speed (from point B to point C – typical course during temporary compressor stall)
- range 3 (from point E), connected with leaving the range of sudden changes of the rotational speed and gradual periodical limiting changes of the derivative dn/dt – typical for entering the steady states of the engine operation.
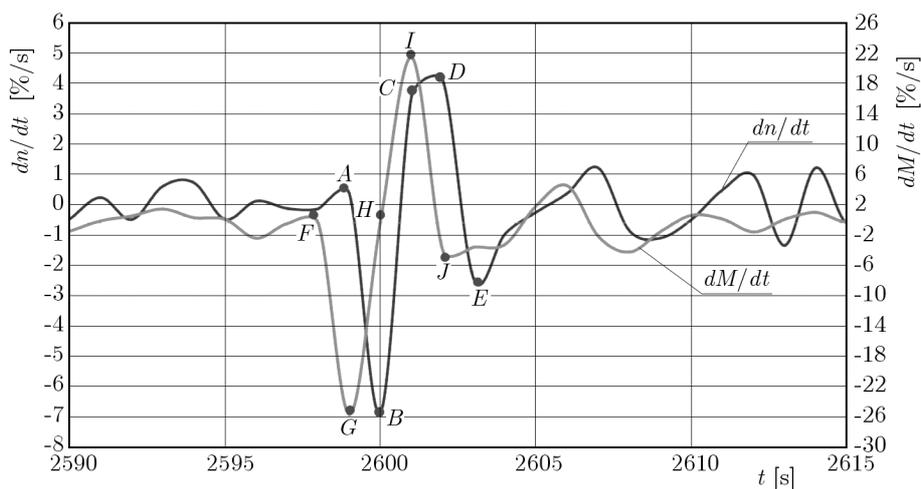
Fig. 7. Time history of the derivative of torque on the shaft during compressor surge compared with the derivative of the rotational speed

Changes of the engine rotational speed in function of time (Fig. 6) illustrate the phenomena taking place in the flow duct of the turbine engine during temporary compressor surge. However, they do not give a clear signal determining the moment before entering the stall range by the engine. It turns out that such information may be obtained from analysis of changes of other engine operation parameters, like torque for example (Fig. 7).

The comparison of changes in the torque with changes in the rotational speed may give information for determining the exact moment of entering of the compressor surge.

To do this, it is required to analyse the locations of extrema of the first derivative of the engine operation parameters. The comparison of point F in Fig. 7 with point A shows the relevance of simultaneous tracking of changes in the first derivative of torque dM/dt and rotational speed dn/dt. They provide quicker information about degradation of the parameters connected with the compressor surge.

When the rotor is still accelerating $(dn/dt > 0)$, the torque is already dropping. The time shift between the extrema of those parameters is approx. 1.2 s. In the engine operation point where the torque derivative has the minimum value, point G, the acceleration of the engine rotational speed reaches zero. Then there is a quite sudden increase in the torque, see segment G-H. Behind point H, the values of acceleration of the rotational speed (dn/dt) become positive, which causes the acceleration process, see segment B-C. The acceleration drop (segment C-D) is caused by a quite sudden drop in the torque increase (segment I-J). Such intensive changes of the torque and the rotational speed lead to a significant load of the engine rotor, which lowers the fatigue strength of the compressor elements.

The obtained results are consistent with the references data, which confirm the relationship between the torque and power – Fig. 8.
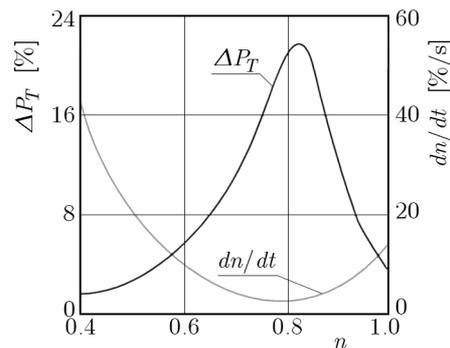

Fig. 8. Turbine excess power and rotational acceleration in with respect to rotational speed (Szlachtjenko, 1987)

The acceleration process takes place when the power increment is positive, , $\Delta P_T > 0$, and the deceleration process takes place when the power increment is negative, $\Delta P_T < 0$. The higher the turbine excess power and the lower the moment of inertia, the higher rotor accelerations dn/dt are obtained (Szczepanik, 2003). The dynamics of the acceleration and deceleration process is best shown with the use of the so called phase portrait. It shows the relationship between the rate of change of a selected parameter and that parameter – Fig. 9. The advantage of that method is the possibility of detecting "hidden" defects of an object (engine and its modules) and the engine operation in actual operating conditions.

The turbine torque M_T and power P_T is connected with the work done by the medium whose parameters, especially the exhaust gas temperature, enable their determination through the following relationships

$$P_T = \eta_T \Delta h_T \dot{m} \qquad M_T = \frac{\dot{m}}{\omega} \eta_T \Delta h_T \qquad (2.1)$$

where the enthalpy drop is function of the temperature drop $\Delta h_T = f(\Delta T^*)$, η_T is the turbine efficiency, $\dot{m}$ – rate of the mass flow, ω – angular velocity of the vector.
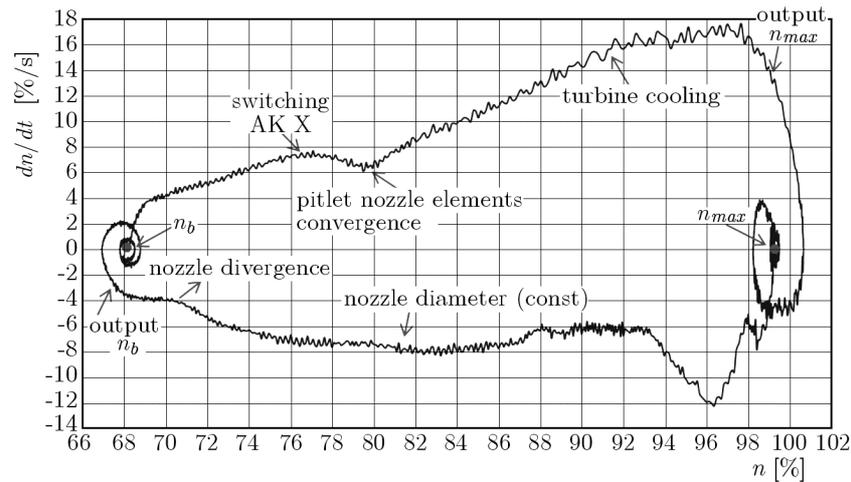
Fig. 9. Phase portrait of the rotational speed of the turbine engine during acceleration and deceleration
(*AK* of blade *X* in *X* stage of the stator rows) (Szczepanik, 2003)

Due to problems with the temperature measurement upstream the turbine, it is measured downstream the turbine. Changes in the derivative of the exhaust gas temperature downstream the turbine (T_4) withrespect to time (Fig. 10) may be a signal preceding the phenomenon of compressor surge.

The process of a sudden drop in the rotational speed, presented in Fig. 10, see segment *A-B*, is preceded by a quite sudden increase in the exhaust gas temperature (segment *K-L*), which almost coincides in time with the torque drop (segment *F-G*). Then a temperature drop (segment *L-M*) takes place with a simultaneous drop in the rotational speed (segment *A-B*) and with removing of the quite sudden drop in the torque (segment *G-H*). Therefore, it can be seen that thorough observation of the individual parameters of the turbine operation of aircraft engines may give signals preceding the occurrence of the unfavourable phenomenon of compressor surge. In the future, it will be possible to develop methods preventing the occurrence of such phenomena, however today, with the use of available technology (and due to quite short preceding time – approx. 1 s) it is very difficult to achieve.
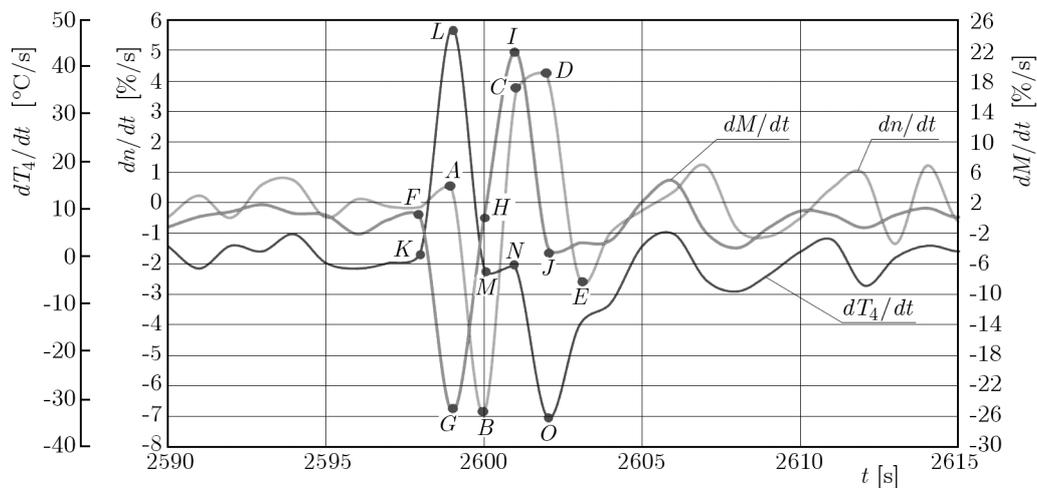

Fig. 10. Dynamics of changes of the exhaust gas temperature downstream the turbine compared with
changes of the rotational speed and torque

3. Ranges of unstable operation

The process of compressor entering the unstable operation range, called the compressor surge, has been described above. It allows the working medium to accumulate itself in some volume V of the engine (it may be e.g. the combustor volume). The accumulation of air in some area is a result of diversified jet output, e.g. during flow through the compressor $(\dot{m}_S)$ and turbine $(\dot{m}_T)$. This process may be also described with the use of continuity equation in the following form

$$V\frac{d\rho_S}{dt} = \dot{m}_S - \dot{m}_T \tag{3.1}$$

where V is the combustor volume, ρ_S – air density, $\dot{m}_S$, $\dot{m}_T$ – mass flow rates through the comressor and turbine, respectively.

The process of the occurrence of compressor surge is shown in Fig. 11, where the change in the pressure coefficient $\Delta\widetilde{p}_S$ is presented in relation to the air output coefficient olc_a in the characteristic range of its value

$$\Delta\widetilde{p}_S = \frac{\Delta p_S}{\frac{1}{2}\rho u^2} \qquad \overline{c}_a = \frac{c_a}{u} \tag{3.2}$$

where $\Delta p_S = p - p_{max}$ is the pressure change, u – circumferential component of the air jet speed, c_a – stream velocity in the axial direction.

The process taking place during compressor surge may be divided into the following stages (Fig. 11):

- operation range BC – the process of stall development (increase in losses), it is a non-stationary process characterized by a quick and significant drop in the speed component $\overline{c}_a$ (accordingly, also the air output in the compressor), and as a result – an increase in the dimension of stalled zones;

- operation range CD – weak variability of the air flow intensity $(c_a \approx \text{const})$ through the compressor, with occurring stalls (Fig. 4) on the blades, which is accompanied by a drop in the pressure coefficient $\Delta\widetilde{p}_S$ (connected with the surge), until point D, which is the surge exit point;

- operation range DA – quick restoration of the air output with the pressure increase. This causes a reduction in the stall zones. It is the process of non-stationary exit of the compressor from the stalls.
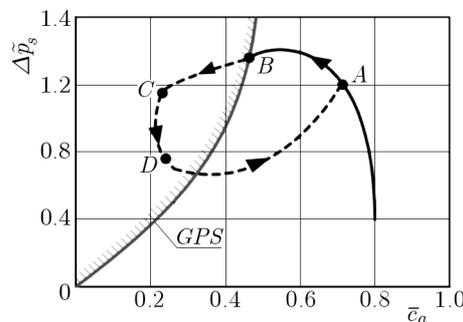

Fig. 11. Course of the compression surge (Kozakiewicz, 2011): GPS – boundary of stable operation, A, B, C, D – limit points of the compressor operation in the transient states of insufficient operation

The process is terminated with the exit to the characteristic branch AB of compression (steady state range – no stalls). The dynamic stability boundary is located in point B. The dislocation of the operation point up the AB line is conditional on the presence of an increased

air output, which supports the flow through the compressor to the turbine. In the presence of positive air output in point B, that point continues dislocation up to the stall area. Therefore, the new cycle of self-inducing jet pulsations is initiated. Interruption of the compressor surge in the stable flow area may be achieved only when the compressor and turbine cooperation is balanced, and the choking line crosses the stability boundary curve (GPS line). The possibility of lowering the choking line may be gained in that process with full cut-off of the fuel output to the combustor, and where the condition of maximum compression $\pi_{S_{max}} < \pi_S(B)$ is fulfilled. The consequence of compressor operation in the unsteady state (compressor surge) is the occurrence of pressure pulsation.

4.   Summary

The above analysis confirms the complexity of cooperation between the compressor and the turbine, especially in transient ranges. The compressor operation should assure the maximum pressure ratio at the maximum mass flow intensity, which is possible to execute at the design stage of that unit. The operating conditions force the compressor (engine) operation range to change, which is caused by a change in the rotor rotational speed, flight speed and altitude as well as air parameters (T_H and p_H). The inlet air jet perturbations lead to the occurrence of stall zones on the blades, which may lead to compressor surge. The symptom of entering that operation range is pulsation of the engine operational parameters (pressure, rotational speed and temperature), which causes vibrations of the compressor and turbine blade grids. Such compressor operation conditions are very dangerous.

A very important problem in terms of protecting the engine against compressor surge effects is finding the parameters which might be (for the control system) an appropriate signal of the possibility of entering that operation range. From the performed analysis, it appears that the significant signals are the torque change dM/dt and the derivative of temperature of exhaust gases dT_4/dt. The analysis of these parameters allows quick reaction of the engine system to protect it from the occurrence of compressor surge. Modern control systems do not allow, in such a case, entering the diving (increasing the speed component C_a) with the lowering of the rotational speed (decreasing the speed component C_u), which was the method of exiting that range in the initial period of exploitation of turbine aircraft engines (Balicki *et al.*, 2009; Szczeciński, 1955).

The analysis of gas-dynamic processes is an important element of calculations dedicated to any engine and one of the most difficult issues connected with modelling of the engine phenomena.

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