ANALYSIS OF UNSTABLE PHENOMENA IN DIFFERENT PARTS OF THE AVIATION JET ENGINE

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The presented work deals with analysis of unstable phenomena in various parts of the aviation jet engine. It focuses mainly on description of those unstable phenomena and presents the causes of their generation. The work describes mainly those unstable phenomena which threaten the action of the engine safety during different operation modes and which can lead to its destruction and thus to the threat of the flight safety itself. Based on the information and knowledge gained at consultations and available literature sources dealing with the topic, the work deals mainly with jet engine surging, which is presented throughout individual parts of this work. It also describes other unstable phenomena which are equally important in connection with jet engine operation computational mode.

K e y w o r d s: unstable phenomena, surging, vibration, coefficient of excess air

1 INTRODUCTION

It is necessary to take into consideration possible development of undesirable unstable phenomena which can appear during non-computational mode in the operation of the aviation jet engine. The presented work will focus exactly on this issue. This problem has accompanied the development of jet engine since their commissioning. Several aircraft accidents, which resulted even in catastrophes, were caused by the development of such unstable operations of the jet engine and therefore considerable effort is being made to avoid the generation of these events.

2 THE ANALYSIS OF UNSTABLE PHENOMENA OF THE INLET TRACT IN JET ENGINE

In this part unstable events which can develop in the inlet tract at certain conditions will be presented. These unstable phenomena such as surging or vibration are certainly undesirable and therefore an effort is made to avoid the conditions causing their development as they lead to considerable damage, even to destruction of the engine.

2.1 Inlet tract surging in the jet engine

As the engine requires higher airflow rate Q_{air} than the inlet tract is able to provide, vacuum develops in front of the compressor which causes supercritical airflow. At this moment the airflow amount becomes higher than it is necessary for the engine operation and critical and supercritical mode appears. Thus a periodically repeated phenomena - surging – occurs. Unstable operation mode of the inlet tract is inadmissible as:

- it causes mass flow pulsation which can lead to extinction of flame in the combustion chamber
- it increases mechanical stress of all parts affected by surging

To maintain the supersonic inlet tract stable it is required to ensure an adequate shock waves system position. It is also necessary to profile diffuser channels so that they narrow into critical section and then expand again. This means that after the closing perpendicular shock wave the airflow increases its speed into a critical one and then it expands to supersonic speed in the expanding section. Due to the counter pressure expansion at the end of the channel, another perpendicular shock wave occurs in certain part of the channel that limits the supersonic region in the inner diffuser channel (fig. 1).

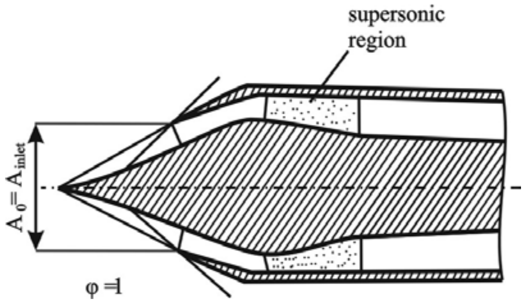

Fig. 1 Diagram of the supersonic air flow in a supersonic inlet tract

Surging in the inlet tract may occur when the amount of airflow in the diffuser is greater than the airflow in the engine. This may result on abrupt reduction in engine speed at an unchanged position of the cone. In this case, the air pressure in front of the compressor will increase [1].

2.1 Aviation jet engine inlet tract vibration

When the compressor speed increases above the computational value, conversely, the vacuum in front of the compressor increases which requires a larger mass flow that the inlet tract can provide at the computational value. Therefore there is a growth of the trailing shock wave intensity which in this case shifts towards the compressor. A relatively large pressure gradient causes the air current tear-off and a decrease of air mass flow intake occurs. This will reduce the vacuum, the trailing shock wave intensity drops, the wave will return towards the front and the air flow detachment disappears. The original conditions are restored immediately and the process repeats. This periodic event is called vibration. Vibrations in the inlet tract are less dangerous than surging in terms of engine work reliability and durability but are equally unacceptable because:

- they also cause mass flow pulsation although with small amplitude and high frequency,
- can lead to dangerous swing of compressor blades.

3 ANALYSIS OF THE UNSTABLE PHENOMENA IN JET ENGINE COMPRESSOR

In this part of the work, compressor surging which occurs in certain non-computational modes of the engine operation will be analyzed. We will focus on axial compressors which are more often used than radial compressors nowadays due to page limitation and vastness of this subject.

3.1 Axial compressor surging in aviation jet engines

Surging is a phenomenon that occurs at a particular mode of engine work. It is characterized by sudden changes in pressure and air velocity and is accompanied by the characteristic sound effects. Other accompanying phenomena include pulsing pressure and velocity at the outlet of vibration of engine parts, especially blades. These accompanying phenomena may lead to engine interruption, its damage, but also to its destruction.

The surging in the axial compressor arises because of different flow rate at each stage. If at any stage an obstruction occurs and it is unable to release more air, while the previous stages are able to continue to press, an unstable phenomenon, surging, develops. Further, we will explain the formation of axial compressor surging when changing the rotation speed. The axial compressor is schematically shown in fig. 2.

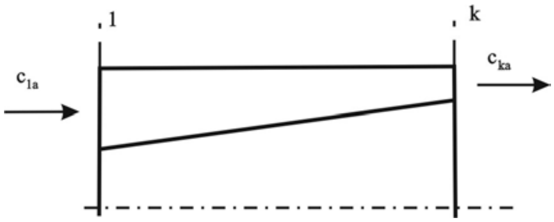

Fig. 2 Schematic representation of axial compressor

Where:

c_{1a} – total velocity which enters the compressor [m.s^{-1}],

c_{ka} – overall rate which exits from the compressor [m.s^{-1}].

The following equation applies to the input and output of the compressor section:

$$c_{1a} \cdot \rho_1 \cdot A_1 = c_{ka} \cdot \rho_k \cdot A_k$$

Where:

ρ_1 – density of air entering the compressor [kg.s^{-1}],

ρ_k – density of air at the outlet of the compressor [kg.s^{-1}].

This can be modified to:

$$\frac{c_{1a}}{c_{ka}} = \frac{A_k}{A_1} \cdot \left(\frac{p_k}{p_1}\right)^{\frac{1}{m}} [1]$$

Where:

p_1 – air pressure at the inlet to the compressor [Pa],

p_k – air pressure at the outlet of the compressor [Pa],

m – polytrope exponent for air [1].

Here we assume that the change in fluid in the compressor can be understood to be polytropic with the exponent polytrope *m*.

$$\frac{\rho_k}{\rho_1} = \left(\frac{p_k}{p_1}\right)^{\frac{1}{m}} [1]$$

Then we can modify the equation for the compressor inlet section:

$$\frac{c_{1a}}{c_{ka}} = const. \cdot \pi_k^{\frac{1}{m}} [1]$$

If we reduce the compressor speed from the computational speed, the value of static compression of fluid in the compressor will decrease. The formula derived above shows that the ratio of c_{1a} / c_{ka} will fall because at reducing the speed c_{1a} drops faster than the c_{ka}. The opposite effect occurs when the compressor speed is greater than the computational value. Because the rotors of all stages are firmly connected, the peripheral speed of all stages will vary with speed as well. Looking at rotor grates wrapping of the first and last stage (fig. 3) we can see that to keep the angles of attack at both stages constant it would be necessary to keep speed triangles similar in spite of the change in speed.

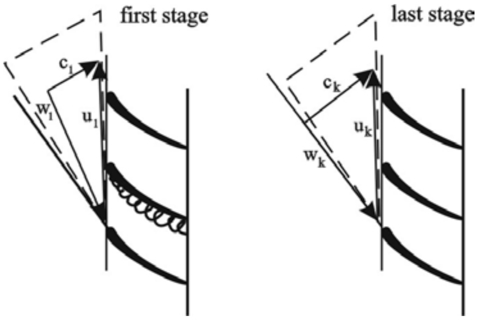

Fig. 3 Wrapping rotor bars of the first and last stage

This would mean that following equations should be applied for each of the stages:

$$\frac{c_{1a}}{u_1} = const. [1] \qquad \frac{c_{ka}}{u_k} = const. [1]$$

In doing so, we know that $u_k \ / \ u_1 = const.$ – a common shaft, therefore, in order not to alter the angle of attack on blades, the ratio of axial speeds should remain fixed as well:

$$\frac{c_{1a}}{c_{ka}} = const. [1]$$

However, as we can see from the relation $c_{1a} / c_{ka} = cons.\pi_k^{1/m}$, with the decrease in speed, c_{1a} decreases faster than c_{ka}, which means that the angle of attack in the first stages will increase. In fig. 3, the dashed lines show the velocity triangles in the computational mode. The increase of the angle of attack at the reduced speed in the first stages causes the surging development. However, if the speed increases, it analogically leads to the increase of the angle of attack in the last stages and thus the surging in the last stages occurs. So we can assume that the decrease of speed in multi-stage axial compressor leads to the surge in the front stages while the increase of speed leads to the surge in the back stages.

Surging in multistage compressors with variable speed can also be clarified by the characteristics of stages where it can be demonstrated that with the decrease of speed the operating point of the first stages characteristics shifts towards the surging limit. The characteristics of multi-stage axial compressor are steeper than single stage characteristics. The reason for this is the fact that the change in the front compression changes are reflected in the shift of the operating point at last the curve of the last stages, narrows the range of stable compressor operation and pressure changes are accentuated. The pressure change, in which surging can occur, can appear when there is a temperature change T_{1c}, where the velocity triangles have a different shape but the surging process is of a similar character.

At the end of the surging analysis we can assume several conclusions:

- surging in fact is a back flow of the tear-off air from the blades and its regressive intake,
- the tear-off occurs only at some parts of the blades, not the entire length,
- the tear-off is affected by irregularities in air flow as well as production and assembly irregularities,
- there may be several tear-off ranges and they may move in the direction of the wheel rotation, but with lower angular velocity,
- surging has its own vibration character and is affected by the entire system of the compressor operation; it occurs mainly in the front stages of axial compressors with higher pressure values and it s necessary to prevent its occurrence by the means of suitable anti-surge device [4, 5].

4 THE ANALYSIS OF UNSTABLE COMBUSTION OF FUELS IN THE COMBUSTION CHAMBERS OF THE JET ENGINE

Unstable combustion in the combustion chamber of the jet engine may occur for several reasons. Coefficient of excess air is the main parameter which determines stable combustion, therefore we will observe the results of the change of this air excess coefficient depending on the altitude and rotations speed changes as well as its effect on the combustion process itself. Coefficient of the excess air α_0 can be expressed as the ratio of air that actually supplies the combustion of 1 kg of fuel Q_s to the theoretically necessary amount of air necessary for combustion of 1 kg of air Q_0.

$$\alpha_0 = \frac{Q_s}{Q_0} [1]$$

If:

$\alpha_0 = 1$, mixture is „theoretical“,
$\alpha_0 < 1$, mixture is „rich“,
$\alpha_0 > 1$, mixture is „poor“.

4.1 The effect of external conditions on the stable operation of the combustion chamber in jet engines

The stable operation of the combustion chamber is considerably influenced by the external conditions such as the pressure and ambient temperature. If the pressure and temperature of air entering the combustion chamber decreases, fuel ignition conditions worsen. In addition, there is an unstable burning and under certain conditions it can lead to tearing off the flame.

With the increasing altitude, the temperature and pressure decreases. As the altitude increases, the oxygen content attributable to 1 kg of air decreases as well as the value of air excess ratio α_0 , which gives rise to a spontaneous combustion of fuel mixture and air and thus the stable work of the combustion (fig. 4a).

The pressure value and air temperature decreases when the engine speed is reduced. Therefore the boundary air excess ratio α_0 reduces (fig. 4b). If the reduction in spontaneous ignition of fuel mixture and air at the rise of the height level as well as at reduced speed occurs, the formation of unstable combustion work follows and thus it makes the engine start after its discontinuation difficult. If the engine stops at high altitudes, it is possible to restart it if it is equipped with a system of starting engine in flight. If it is not equipped with this system, the restart is difficult because the air flowing into the combustion chambers of non-operating engine is cold and has a low pressure and velocity. Under these conditions the flame is torn off. In this case it is necessary to reduce the flight altitude to more acceptable conditions to enable the engine restart.

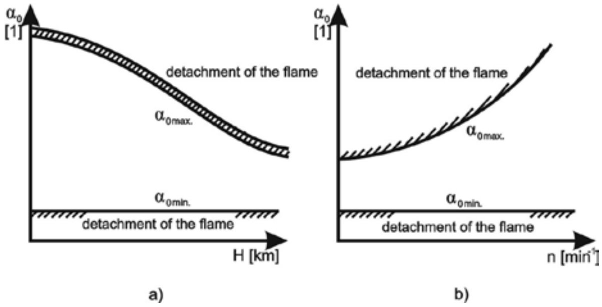

Fig. 4 Nature of change borders steady burn, depending on a) the altitude, b) speed

Fig. 5 shows the characteristics of a stable work in the combustion chamber, which points out how, depending on the air excess ratio, the airflow rate varies. After exceeding $\alpha_{0crit.}$ fuel and air mixture in the combustion chamber loses its stability and the flame is extinguished. The part of the curve between the points $\alpha_{0crit.}$ presents a stable area of combustion in the combustion chamber [2, 3, and 5].

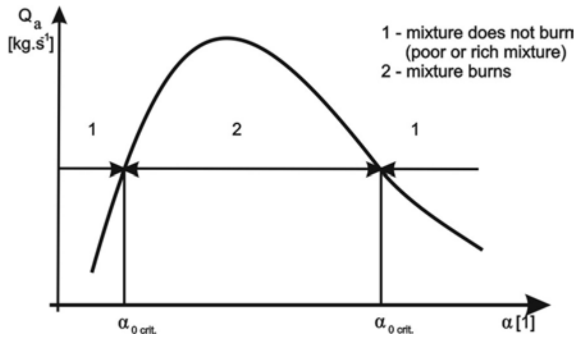

Fig. 5 Nature of change borders steady burn, depending on the air excess ratio α_0 and air flow rate Q_{air} [8, 10].

5 THE ANALYSIS OF UNSTABLE WORK OF GAS TURBINES IN THE JET ENGINE

The instability phenomena may also develop in gas turbines of turbo engines due to unstable airflow. The gas turbine is kinematically linked to the turbocharged engine and therefore the unstable phenomenon occurs here especially when there is an unstable flow in the turbo compressor. The stable gas turbine work is also considerably affected by the work mode of the main combustion chamber (the coefficient of excess air, whipping flames, etc.) [6].

5.1 Unstable flow in the profile turbine lattice in the jet engine

Fig. 6 shows a sectional turbine lattice where the angle of attack is defined by the difference $\varphi_1 - \beta_1$.

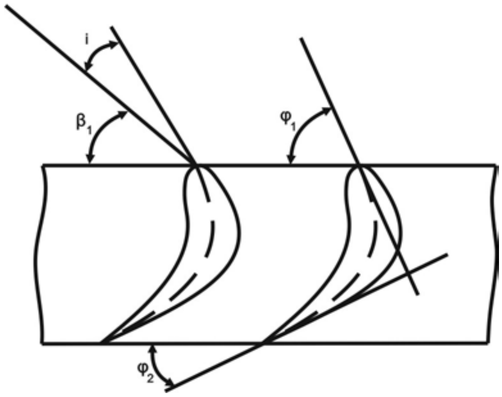

Fig. 6 Profile turbine lattice of gas turbine

Where:

φ_1 – tangent angle to the middle curve profile on the leading edge of the gas turbine blade [°],

φ_2 – tangent angle to the middle curve profile on the drain edge of the gas turbine blade [°],

β_1 – relative speed angle [°],

i – attack angle [°].

In each profile lattice the pressure gradient on the back of the blade increases in connection with the angle of attack as well as the thickness of boundary layer which increases the probability of the airflow tear-off on the gas turbine blade. At certain value of the angle of attack the back blade causes the partition of the gas flow. The angle of attack, in which the flow is torn off, is called positive critical angle of attack and is referred to as i_s.

Fig. 7 shows an example of gas flow in a multi-stage gas turbine. This particular case points out the formation of unstable flow in low pressure gas turbines. The formation of this unstable flow can be already seen in the first stage. However, the gas flow tear-off can be best seen on the back of the blade in the last rotor stage [7].

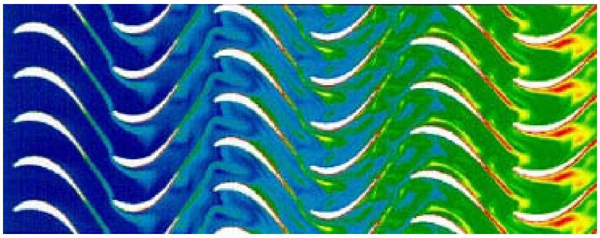

Fig. 7 Visualized unstable nature of gas flow through a multi-stage gas turbine

6 THE ANALYSIS OF UNSTABLE OPERATION OF THE NOZZLE EXIT IN JET ENGINE

To ensure the axially directed motion of the gas output from the output system, expansion in the output tract must develop to the pressure which is equal to ambient pressure or near. For these reasons, the system output must be correspondingly shaped. In practice, there may be three forms of flow in the exhaust system, characterized by pressure gradient that are unstable in the context of critical work.

Transformation of the heat gas content to kinetic energy in the outlet tract is accompanied by the gas pressure drop and increase of the gas volume in its expansion. The size of the pressure drop in the exhaust tract is characterized by the ratio of adiabatic pressure of restricted gas flow at the inlet to the outlet system to the static pressure in the outlet section. This ratio is called the degree of expansion or expansion pressure drop in the nozzle exit.

$$\pi_{NE} = \frac{p_{4c}}{p_0} [1]$$

6.1 Pressure drop in the nozzle exit

The pressure drop processed in a tightened nozzle exit is divided into subcritical, critical and supercritical, which is reflected by the corresponding work of the output system. Value $(\pi_{NE})_{cr}$ is the critical pressure gradient, which is according to the Poisson gas constant κ '= 1.33, equal to the value 1.85.

Subcritical pressure drop occurs when the expansion pressure drop π_{NE} at the subcritical flow is less than $(\pi_{NE})_{cr.}$. The gas velocity at the exit section is subsonic. The gas in the exhaust tract expands to atmospheric pressure (perfect expansion). Gas flow in the output section narrows smoothly. Losses in the output tract are small.

$$\pi_{NE} < (\pi_{NE})_{cr} [1]$$

At the critical flow, the exhaust gas velocity is equal to the critical or the sonic velocity. The pressure in this section is equal to the critical pressure $p_{5,kr.}$.

$$\pi_{NE} = (\pi_{NE})_{cr} [1]$$

From the moment of a critical pressure drop in the nozzle exit, we can say that the nozzle exit is blocked aerodynamically. In physics it means that in case of constant parameter values of the gas flow in front of the outlet tract and the further reduction of pressure p_0, the gas flow rate is not changed by the outlet tract $Q_{gas.}$.

In supercritical flow, the pressure drop expansion π_{NE} is greater than $(\pi_{NE})_{cr.}$. In the subsonic nozzle exit, the pressure drop is processed only to the value of critical pressure drop $(\pi_{NE})_{cr.}$, The gas expands to a critical pressure p_{5kr}. Other changes in the flow occur behind the outlet tract taking place in areas of expansion, culminating by compression of shock waves. Gas flow behind the outlet tract has a periodic "barrel" structure (fig. 8a).These changes are accompanied by losses and decrease of thrust. With further increasing, the intensity of the shock wave increases (fig. 8b) and a shock wave arises in the form of a "bridge" behind the outlet tract, thus losses continue to grow. With the further increase of pressure drop, the set of shock waves is gradually transformed (fig. 8c). Under these conditions, a practically perpendicular shock wave arises from the expansion area, the total pressure losses are so large that the flow velocity behind the wave is already subsonic. The gas flow loses the periodic structure. The losses and thrust decrease are therefore very significant. For example, when the flight Mach number is M_0 = 2,5 a π_{NE} = 20, the thrust decrease can drop by about 15% compared to the thrust perfect expansion. In such cases, the use of supersonic outlet system is a necessity [13].

$$\pi_{NE} > (\pi_{NE})_{cr.} [1]$$

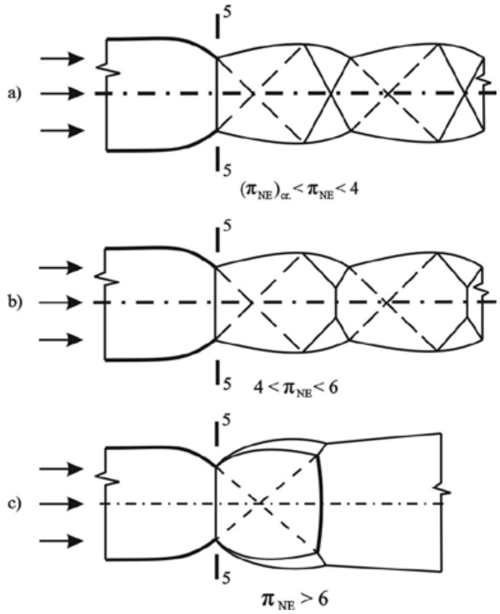

Fig. 8 The structure of free gas flow behind the subsonic nozzle exit for different values of supercritical pressure drop

The character of the nozzle exit operation is further generated by these modes [5, 13].

7 CONCLUSIONS

A constantly increasing security is a tendency in the air transport, therefore this issue is given considerable attention by the designers of aircraft engines. The contribution of new knowledge, introducing the use of new materials and the use of constantly improving programs used at the construction, dramatically reduce the risk of imminent danger of unstable work although it cannot be completely prevented. The possibilities are increasing by the improvements which might extend the use of the jet engine, therefore the issue of the aviation jet engine instability, although undesirable, will still constantly accompany their development.

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