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STUDIES ON UNSTEADY OPERATION OF A TURBOJET ENGINE AND AN INTAKE CHANNEL OF A SUPERSONIC AIRCRAFT

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Abstract

The paper explains how to analyse possible disturbances in the intake air stream and their impact on engine operation. The introduction outlines possible reasons that induce disorders in the intake air stream. Then the substantial differences in operational characteristics between a centrifugal and an axial compressor are enlightened. The phenomenon of an unsteady compressor, referred to as the compressor stall, is explained through presentation of the process phases when air stream detaches from the surfaces of the compressor blades. Then the paper presents how disturbances in the air stream propagate down subsequent stages of the engine compressor with the emphasis on the fact that the air stream is not able to affect the full height of blades but usually only a portion of them. In addition, the mechanism of the unsteady operation of the engine (compressor) is presented on the graph that shows fuel consumption Q as a function of the engine rpm n. Attention is drawn to the fact that the phenomenon of the engine unsteady operation is associated with the so called rotating areas of air detachments that revolute in the same direction as the engine rotor itself but their rotation speed is lower than the rotor rpm. Consequently, flame downstream the area of detachment may go out for a moment and then quickly reappear, since air is kept supplied at quite high rates. If the foregoing process fails to go in phase with the rotating areas of air detachment, it may even lead to a total flameout of the engine.

Then the unsteady operation of the intake channel is discussed in details, as it is frequently mismatched with the compressor stall. The mechanism of the phenomenon origination and the consequences it entails is presented with adequate details by means of appropriated graphs. In addition, the paper explains the phenomenon of beats in the intake channel, which is a result of detachment of the wall-adjacent layer of air flow just downstream the perpendicular shock wave in the intake channel. The effect of beats frequency often leads to the engine stall. The paper ends up with conclusions, in which it is emphasized that studies on the phenomenon and familiarity with the process are extremely important for the safety of flights.

Keywords: *stall in the intake channel*

1. Introduction

Rapid development of aviation has induced equally fast advance in design of avionic driving hardware, in particular turbojet engines. In the course of time, designers began implementation of axial compressors to achieve high compression factors for the air stream that is supplied to the combustion chamber with high degree of the engine compaction and less weight per unit of the engine power. Such compressors had many an advantage, but also exhibited a number of drawbacks. The most important weakness is their high vulnerability to disturbances in the stream of intake air and propensity to unsteady operation of the jet engine (commonly referred to as the compressor stall). The air stream that enters the compressor via the intake channel of the engine is subjected to quite significant disturbances that are caused by various factors [4-6]. These factors can be roughly structured into the following groups:

- external (e.g. wind gust, stream of flue gas ejected by another engine, stream of air generated by thrust inverters, spontaneous vortex at the air intake – Fig. 1),
- phenomena associated with acceleration/deceleration of the engine rpm (changes in rotation speed of the compressor rotor),
- changes in flight conditions (flight altitude and speed, attack and planning angles).

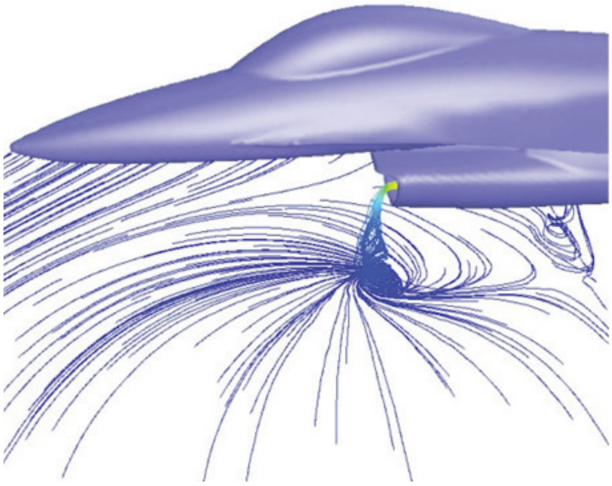

Fig. 1. Model of the an air vortex at the engine inlet produced by a side wind gust [8]

Moreover, particularly in flights with supersonic speed exceeding 1.5 M, disturbances in the stream of inlet air (pulsation of air pressure, drops of air pressure and mass flow rates of air upstream the engine, etc.) may lead to unsteady operation of the intake channel, which is commonly referred to as the stall caused by supersonic intake. Such a stall may, but not necessarily has to lead to a compressor stall [9].

2. Unsteady operation of a turbojet engine

The core difference between the operation of a centrifugal and of an axial compressor can be explained by analysis of typical operational characteristic curves for these compressors – Fig. 2. The design operation range for these compressors is marked on the characteristic curves by *a* letter. As one can see in the graph, within vicinity of the design point the operational curve is distant from the stall limit. However, when the operation range of the compressor departs towards the increase of the rotation speed referred (normalized) to the design point (*A*), the allowance for steady operation of the compressor is reduced. Although the phenomenon refers to both types of compressors, the allowance for steady operation is much larger for a centrifugal compressor due to much longer distance between the operational curve and the stall limit. One has to pay attention to the fact that the characteristic curves corresponding to subsequent values of normalized rotation speed are much steeper in case of an axial compressor (Fig. 2) and they may become nearly vertical for an axial compressor with high values of the compression factors. It is an important observation, since in case of axial compressor even slight changes in delivery of air via the intake, while keeping the engine rpm constant at the same time, may lead to a compressor stall.

To explain the stall effect it is necessary to focus on the operation of a single stage of the engine compressor for an undisturbed flow of air stream (Fig. 3a). During flights down a straight line or operation of the engine on the ground, the direction of air inflow (its vector) is nearly parallel to the chord of turbine blades. It is the so-called designed flow of air stream, which is typical for undisturbed operation of the compressor [1, 12]. Analysis of Fig. 3a reveals that no detachments of air stream from the planes (surfaces) of the compressor blades take place.

Under other circumstances, e.g. when the direction of air inflow is not parallel to blade chords, the air stream is deflected towards negative angles of inflow (outwards the concave plane of blades) or positive angles (outwards the convex side of blades – the tail). In such a case, a disturbance in the flow of air stream takes place (Fig. 3b and 3c). When the inflow angle is negative (less than the design one), the delivery of air supplied by the compressor exceeds the design rating, whilst at the positive angle – it is lower.

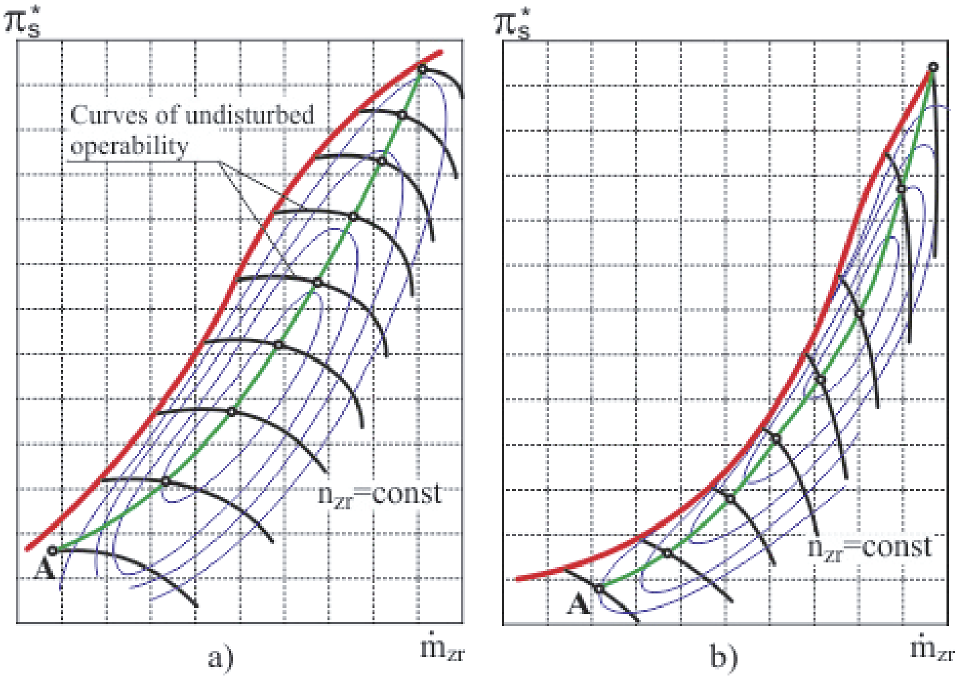

Fig. 2. Mutual positions for operational curves and the boundary of steady operation (stall limit) for (a) centrifugal compressor and (b) axial compressor

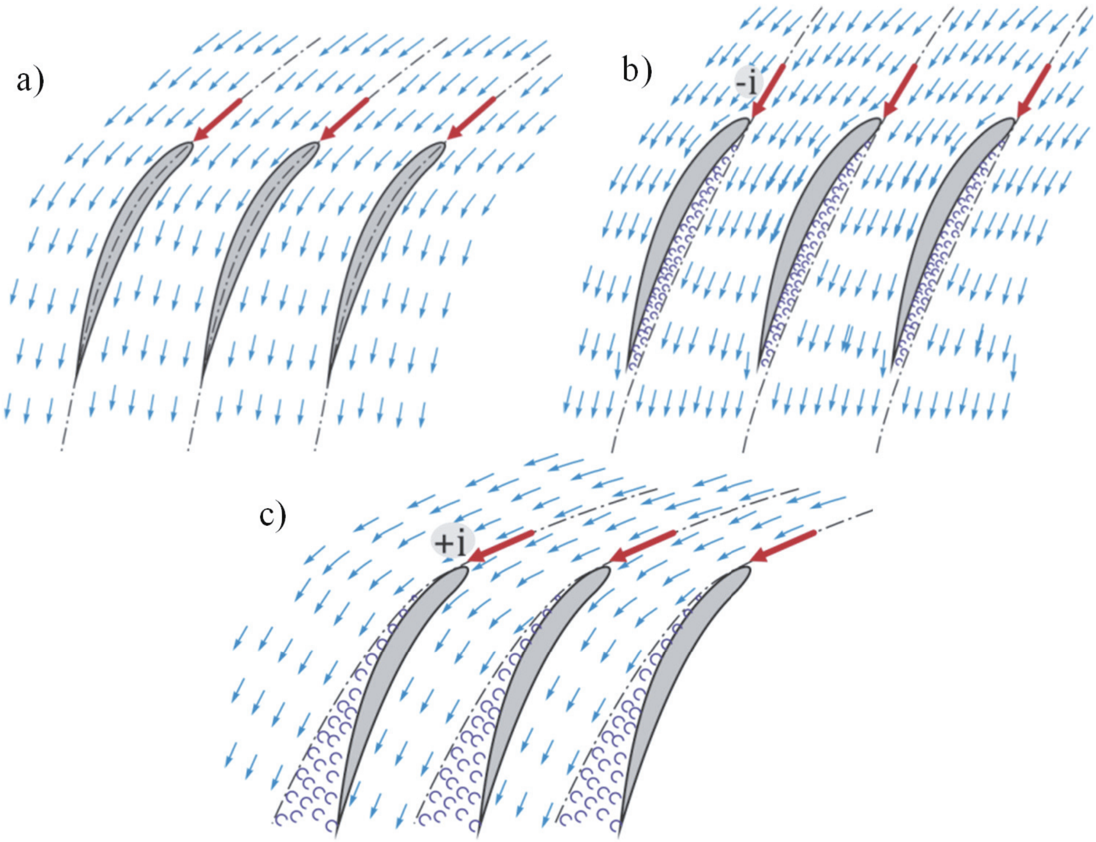

Fig. 3. Options of air stream inflow onto blades of the compressor rotor: a) design conditions; b) negative angle of air flow; c) positive angle of air flow

Such disturbances of air flow may propagate to the subsequent stages of the compressor. They do not affect the entire height of the blades but usually only their part, as is shown in simplification in Fig. 4.

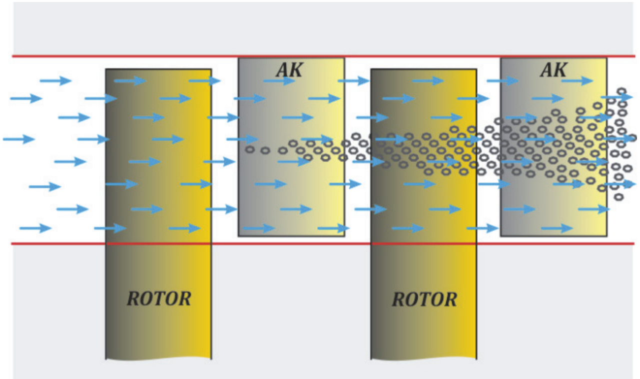

Fig. 4. Propagation of disturbances of the air stream on subsequent stages of the compressor

Such a phenomenon is extremely hazardous, since it leads to the effect of an engine stall (unsteady operation of the engine compressor) that is manifested by "ejection" of partly compressed air from the area downstream the compressor and towards the compressor inlet. In case of a really "deep" stall, it is even possible to see flames that appear at the end of the engine inlet, which is a symptom of a very violent degree of the phenomenon, strong enough for partly drag flames from the combustion chamber towards the engine intake. It if why one has to remember that excessively violent movements of the engine control lever (DSS), in particular during engine acceleration (excessively fast acceleration from the idle run to the range near the maximum and then maximum rpm) may lead to disturbances in flow of air stream. It is extremely hazardous during flights performed at low altitudes, when each spontaneous flameout of the engine (that frequently follows the moments when the engine works in an unsteady manner) is an immediate danger to life for the plane craft.

The process of an unsteady operation of an aircraft engine can be traced on the diagram of fuel consumption Q as a function of the engine rpm n. When the engine control lever (DSS) is repositioned towards growth of the engine speed, the amount of fuel supplied to the combustion chamber increases as well (the green line in Fig. 5). However, such a curve is rather unlikely, since it takes place only when the engine control lever is moved very slowly from the rotation speed of the idle run to the maximum rpm. In practice, movements of the engine control lever are more or less violent, which leads to the acceleration or deceleration of the engine shafting rotation. It is why the green line (in particular in the initial phase of accelerations) approaches the boundary of steady operation that is referred for as the stall limit (the red line in Fig. 5-7) [3, 12].

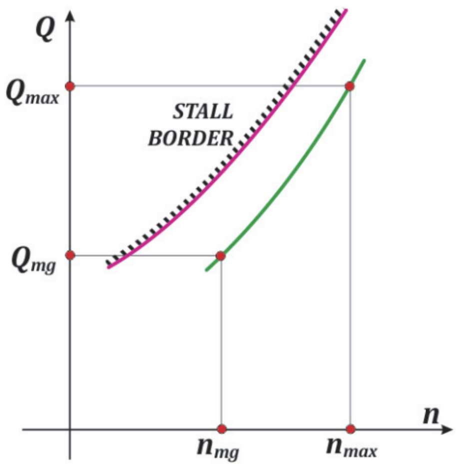

Fig. 5. Nature of fuel consumption Q as a function of the engine rpm n for slow acceleration of the engine

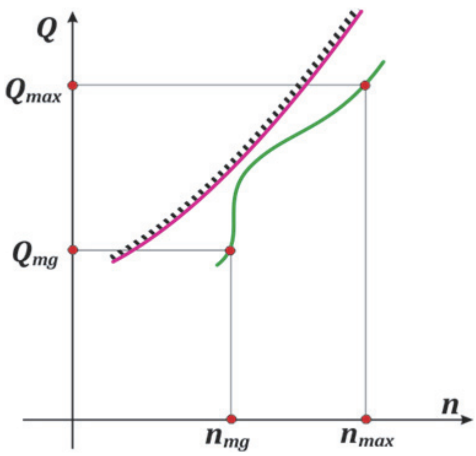

Fig 6. Approaching of the fuel consumption curve to the stall limit during engine acceleration

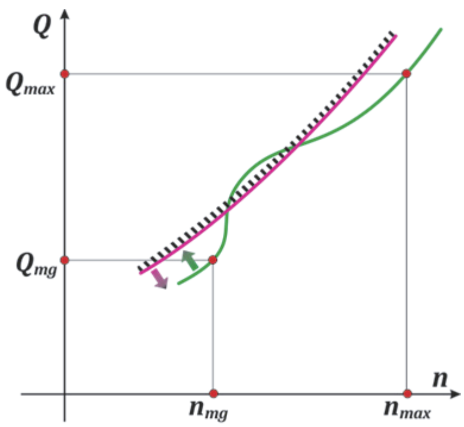

Fig. 7. Intersection of the stall limit during engine acceleration

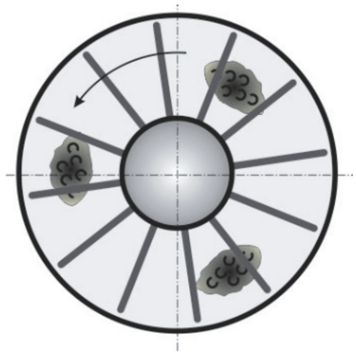

Fig. 8. Rotating areas of detached air stream when the effect of a compressor stall takes place

Designers of turbojet engines tend to apply devices (subassemblies) that are called acceleration automates. The purpose of these devices is to disable excessive fast growth of fuel amount that is supplied to the combustion chamber when movements of the engine control lever are too fast. It slows down the excessively rapid growth of the engine rpm, which might lead to the intersection of both lines and the occurrence of engine unsteadiness (Fig. 7).

The effect of engine unsteadiness is associated with the so-called areas of detached air stream (Fig. 8) that rotate in the same direction as the engine rotor but at a lower speed. Flames downstream such areas are put out for a moment (deficiency of air as compared to the amount of fuel) and then reappear due to quite fast supplying of air. If that process is not in phase with rotation of areas with detached air stream, the effect of engine flameout may take place.

3. Unsteady operation of the engine intake channel

The stream of inlet air (Fig. 9) includes:

– stream of free flow that is formed in the ambient atmosphere right upstream the intake;
– air stream that is confined within walls of the intake channel.

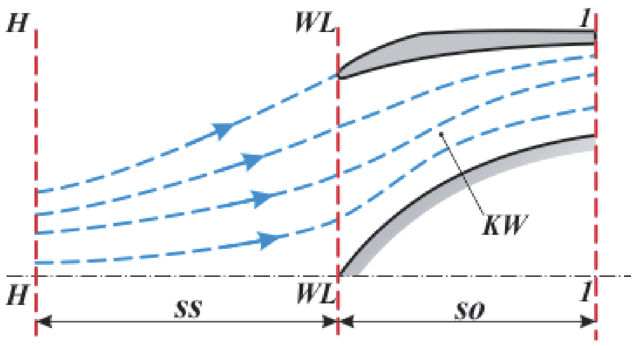

Fig. 9. Diagram of air suction with indication of characteristic cross-sections: H-H – cross-section of undisturbed air stream, WL-WL – cross-section of the air inlet, 1-1 – cross-section of the air outlet (upstream the compressor), KW – flow channel of the intake, SS – section of free flow of air, SO – section of a confined air stream 12]

Operation of aircrafts in flight may lead to some disturbances in the inlet air stream. It is particularly important for flights with speed that significantly exceeds the speed of sound when application of supersonic intakes is required. The key task of supersonic intakes is to reduce losses that are associated with crossing of the sound barrier, i.e. transition from supersonic flight speed to subsonic speed in flow channels of compressors. The overall compression achievable for the engine can be noted in the following way [12]:

$$\pi^* = \frac{p_2^*}{p_H} = \frac{p_2^*}{p_1^*} \cdot \frac{p_1^*}{p_H} = \pi_S^* \cdot \pi_{WL}^*, \tag{1}$$

where:

p_H – pressure of air flow upstream the inlet,
p_1^* – pressure of air flow upstream the compressor,
p_2^* – pressure of air flow downstream the compressor,
π_S^* – compression capacity of the compressor,
π_{WL}^* – compression capacity of the intake.

Compression capacity of the intake π_{WL}^* is directly proportional to the factor of pressure loss due to pressure build-up at the inlet and to the dynamic compression that defines the maximum possible gain of compression when the inlet stream is fully decelerated to zero velocity. The dynamic compression is the function of flight speed determined by the Mach number. It results from the following relationship [12]:

$$\pi_{WL}^* = \frac{p_1^*}{p_H} = \frac{p_1^*}{p_H^*} \cdot \frac{p_H^*}{p_H} = \sigma_{WL}^* \cdot \pi_{dyn} = \sigma_{WL}^* \left(1 + \frac{k-1}{2} Ma^2\right)^{\frac{k}{k-1}}, \tag{2}$$

where:

σ_{WL}^* – factor of pressure loss due to pressure build-up at the inlet,
$\pi_{dyn} = f(Ma)$ dynamic compression (depends on the flight speed expressed by the Mach number),
k – exponent of isentropic curve for air ($k=1.4$).

Disturbances of air flow at the air intake may lead to unsteady operation of the intake channel, also referred for as the inlet stall (Fig. 10) [3, 11].

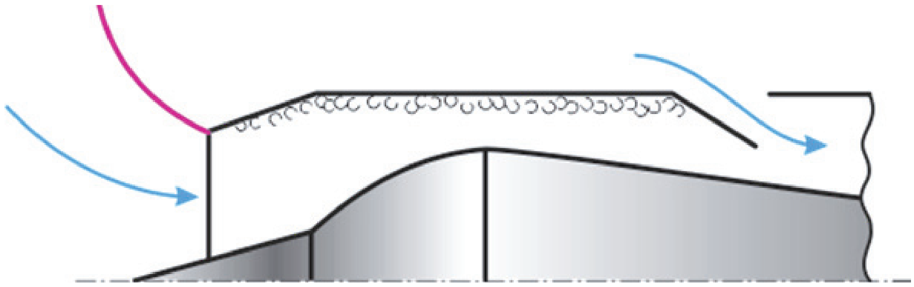

Fig. 10. Abruption of air stream at sharp edges of the intake channel at high values of the attack angles

Unsteady operation of the intake channel may take place at supersonic speed of a flight, usually when the Mach number exceeds 1.5. Under such circumstances, a system of skewed waves and a crosswise shock wave may be formed on the surface of the inlet cone (Fig. 11).

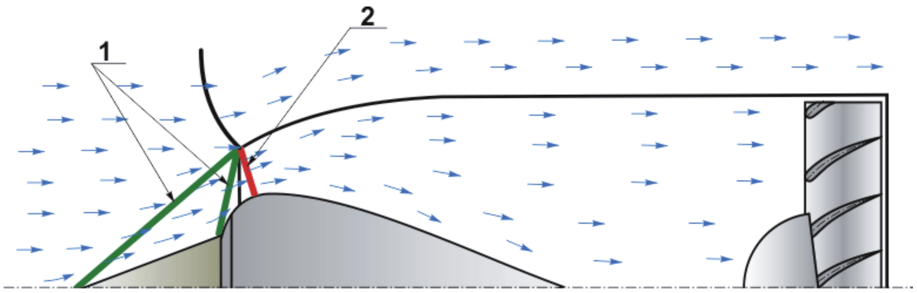

Fig. 11. Formation of shock waves: 1 – skewed, 2 – crosswise one

In addition, a crosswise shock wave appears in the diffuser parts of the intake, where supersonic velocity of air stream is lower than the speed of sound. It corresponds to the state of equilibrium between the intensity of mass flow across the intake and the engine (Fig. 12) [9, 11].

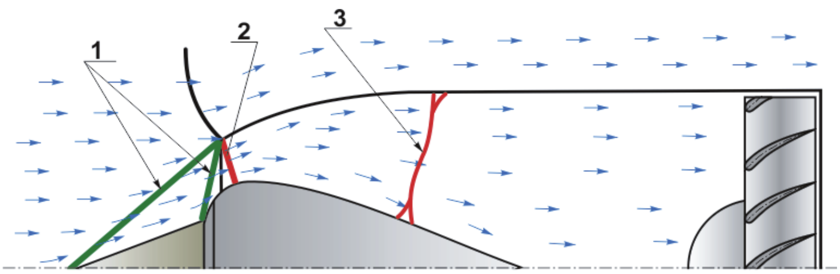

Fig. 12. Formation of shock waves: 1 – skewed, 2 – crosswise one at the edge of the air intake, 3 – crosswise one in the intake diffuser

In pace with deceleration of the engine rpm, the mass flow intensity of air stream is reduced as well. Under such circumstances, the aforementioned equilibrium state is distorted with simultaneous build-up of pressure right upstream the engine and translocation of the crosswise shock wave down the intake channel (No. 3 in Fig. 12) towards the input of the intake channel. As a consequence, the system of shock waves nearby the inlet cone moves outwards of the input edge of the intake and excess of air is ejected from the intake channel to the outer space (Fig. 13). Such a process leads to a drop of air pressure in the intake channel and the system of shock waves system begins to move back into its interior.

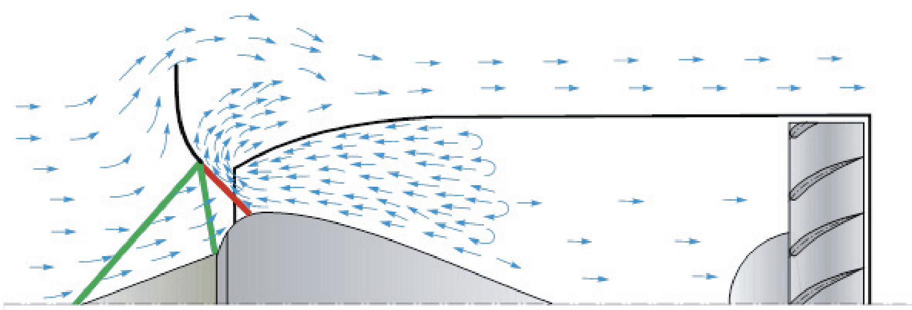

Fig. 13. Ejection of air from the intake channel as a result of the pressure build-up

Pressure of air in the intake channel starts to build-up again and the process is repeated (usually with the frequency from 5 to 8 times per second). The phenomenon is associated with the emission of an unpleasant sound. In addition, a strong vibration of the aircraft may appear. Unsteady operation of the intake channel usually leads to the unsteady operation of the engine. It is why the stall effect at the intake channel must be eliminated and only then the unsteady operation of the engine can be remedied or the engine can be restarted if its flameout occurred beforehand. Aircrafts that operate at high (supersonic) speed are furnished with the so-called automatic anti-stall flaps that are designed to secure reliable operation of the engine intake (Fig. 14). These flaps open when excessive pressure build-up occurs upstream of the engine and release (depressurize) excess of air to the ambient space.

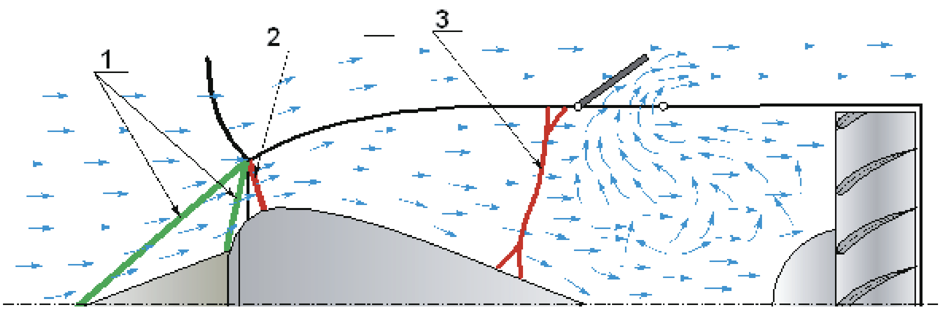

Fig. 14. Depressurizing by releasing air via anti-stall flaps

The analysis of the foregoing phenomenon demonstrates that the direct reason for the unsteady operation of the engine intake is the build-up of pressure upstream the engine, which leads to movements of a crosswise shock wave towards the input to the intake channel. Therefore, the anti-stall flaps can be opened to balance pressure upstream the compressor, to disable translocation of shock waves towards the input of the intake channel and to prevent from ejection of air from the intake channel.

Another very interesting effect that may also occur during supersonic flights are the so-called beats [3, 9, 11], which are frequently mismatched with the stall in the intake channel. The direct cause of this effect is the detachment of the enclosure-adjacent layer of air rights downstream the crosswise shock wave in the intake channel (Fig. 15). Beats never lead to unsteady operation of aircraft engines and are not considered as an immediate hazard for the safety of flights. To get rid of that effect, it is enough to reduce the flight speed and slightly retract the inlet cone.

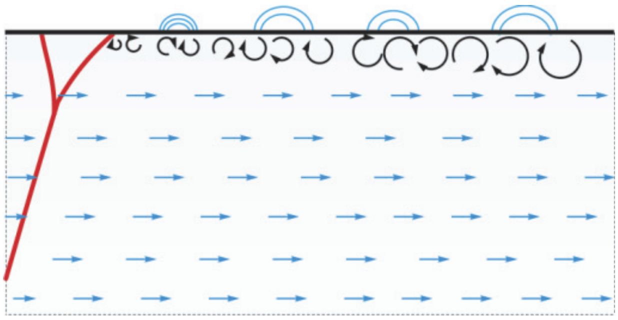

Fig. 15. The detachment process of enclosure-adjacent layers leading to the effect of beats

Therefore, it is necessary to have a system of preventive trainings in place, in particular for aircraft crews, to make them familiar with possible disturbances in flow of the intake air stream with the aim to improve safety of flights.

4. Conclusions

The completed analysis of an unsteady operation of a compressor of a turbojet engine made it possible to find out that it is a rather common phenomenon, which affects all turbojet engines furnished with an axial compressor. In spite of many advantages, such a compressor is very vulnerable to distortions of its intake air stream, due to which it requires numerous actions to improve its operation and a thorough expertise of both aircraft crews and ground personnel. The scope of knowledge revealed in this paper is sufficient to get familiar with the phenomenon and for correctly identify the effect of the engine stall.

The analysis of the phenomena associated with unsteady operation of the engine inlet (stall at the engine intake) that may happen when aircrafts fly at very high speeds (above 1.5 Ma), for instance at the end of the nose diving, provides a substantial amount of accurate information. It enables the aircraft crew to identify the phenomenon, distinguish it from the engine stall (flameout) and timely undertake adequate corrective actions. One has to keep in mind that the stall effect at the engine intake usually leads to the engine stall that may finally end up with the engine flameout, which, in turn, makes the stall effect at the engine intake even deeper. It is why the stall effect at the engine intake must be eliminated in the first place and only then, the crew should proceed to the rectification of the engine stall.

Finally, the conclusion can be drawn that familiarity with all the mentioned phenomena, i.e. the unsteady operation of the engine (compressor stall), the unsteady operation of the engine intake (stall at the intake) and the process of beats at the intake is indispensable to correctly identify these phenomena during flights and to undertake appropriate corrective actions.

References

[1] Balicki, W., Chachurski, R., Kawalec, K., Kozakiewicz, A., Szczeciński, S., *Unsteady operation of turbojet engines – reasons of occurrence and preventive precautions,* Transactions of the Institute of Aviation, Scientific quarterly, 4, (199), Warszawa 2009.

[2] Dzierżanowski, P., Kordziński, W., Łyżwiński, M., Otyś, J., Szczeciński, A., Wiatrek, R., *Turbojet engines,* WKŁ Edition House, Warsaw 1983.

[3] Kowalski, M., *Issues related to troubleshooting of turbojet avionic engines with use of information from on-board recorders of flight parameters,* ITWL Scientific Journals, No. 31, Warsaw 2013.

[4] Kowalski, M., *Adaptive Jet Engines Work Analysis and Control,* Journal of KONES Powertrain and Transport, Vol. 18, No. 2, pp. 225-234, 2011.

[5] Kowalski, M., *Noise Emission Level versus the Structure of the Aircraft Turbine Engine,* Journal of KONES Powertrain and Transport, Vol. 19, No. 4, pp. 325-332, 2012.

[6] Kowalski, M., Odwzorowanie fazowe prędkości obrotowej w procesie eksploatacji turbinowych silników odrzutowych, Logistyka nr 6/2009. (*Phase imaging of rotation speed during the operation of turbojet engines. Logistics, No. 6/2009*).

[7] Kowalski, M., *Use of Data From on-Board Data Recorders for Acceptance Tests of Avionic Driving Units,* Journal of KONES Powertrain and Transport, Vol. 20, No. 2 , pp. 201-206, 2013.

[8] Kozakiewicz, A., Kowalski, M., *Unstable operation of the turbine aircraft engine*, Journal of Theoretical and Applied Mechanics, Vol. 51, No. 3, pp. 719-727, 2013.

[9] Szczeciński, S., *Air intakes of turbojet avionic engines and their effect on flying characteristics of aircrafts and hazards to safety of flights,* Issues of avionic driving systems, Transactions of the Institute of Aviation, No. 4, 2009.

[10] Szczepanik, R., *Investigation of the Dynamic Properties of Engine Fan Titanium Rotor Blades in a High Manoeuvrability Aircraft in FOD Aspect,* Journal of KONES Powertrain and Transport, Vol. 20, No. 2, pp. 371-376, 2013.

[11] Szczepanik, R., *Collaboration between a jet engine and its supersonic inlet at the end of the nosediving operation,* Safety of flights, Warsaw 1979.

[12] Wiatrek, R., *Theory of avionic engines,* Military Institute of Technology (WAT), Warsaw 1983.