Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 95 **2017**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2017.95.9

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Laskowski P. Factors influencing axial compressor stalls. *Scientific Journal of Silesian University of Technology. Series Transport*. 2017, **95**, 89-96. ISSN: 0209-3324.
DOI: https://doi.org/10.20858/sjsutst.2017.95.9.

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FACTORS INFLUENCING AXIAL COMPRESSOR STALLS

Summary. The article describes the problem regarding stalls in axial compressors, which are widely used in the engines of large and very large transportation aircrafts. The stall phenomenon, unless cleared, poses a major danger to the integrity of a compressor module, which in turn may result in uncontained engine failure and loss of thrust, thereby seriously affecting flight safety. The costs of maintenance to be performed may also be very high, due to irreversible deterioration in some components. A practical assessment of the stall problem and its countermeasures are discussed below.
Keywords: stall; axial compressor; performance.

1. INTRODUCTION

Modern transportation aircraft are powered by dual- or triple-spool gas turbine engines. The purpose of these engines is to deliver thrust or power to the propeller. As such, turbine engines are divided into direct and indirect reaction engines. Direct reaction fully ducted engines produce the thrust force by the significant acceleration of stream flowing through them. To produce a mixture of fuel and air, air must be first compressed. The pressure outlet to pressure inlet value is called the compression ratio. To achieve high compression ratio values, which exceed 30 on modern engines, multiple compressor stages are needed, given that the single-stage axial compression ratio is 1.3...1.5. Radial compressors achieve higher compression ratio values per stage and are more adaptive to harsh operating conditions, which is an important feature when considering foreign object damage resistance. Meanwhile, one disadvantage of

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this type of compressor is that it is composed of no more than two stages, which restricts airflow. Therefore, an axial design is used on fully ducted engines to enable high compression ratio values. This, however, requires hundreds of kilograms per second of the airflow, which in turn requires regulation to keep the airflow stable. The more that air flows through the engine duct(s), the more that regulating methods must be applied. The article below describes other factors that influence the airflow and methods of flow regulation to avoid a stall in the whole compressor working map.

A stall is an unintentional and gas-dynamically unstable condition, caused by airflow disturbance. This disturbance is not necessarily abrupt. A stall poses a danger to safe engine operations, since it may cause engine damage, including uncontained disintegration. Most common stall symptoms are sudden and wide fluctuations in pressure, rotors' rpm, exhaust gas temperature and airflow. Fully ducted engines with a changeable exhaust nozzle throat experience fluctuations in the convergent nozzle area as the first sign of a stall occurrence.

This is caused by the low-pressure compressor rotational speed and engine pressure ratio variation. The convergent nozzle reacts directly to airflow changes, particularly to bypass flow. Most of the thrust produced by a turbofan engine is delivered by the bypass duct. Both high and low pressure rises in the compressors and decreases in turbines, as a result of dependence on stream flow changes. Therefore, a stall also means that these relations have been disturbed.

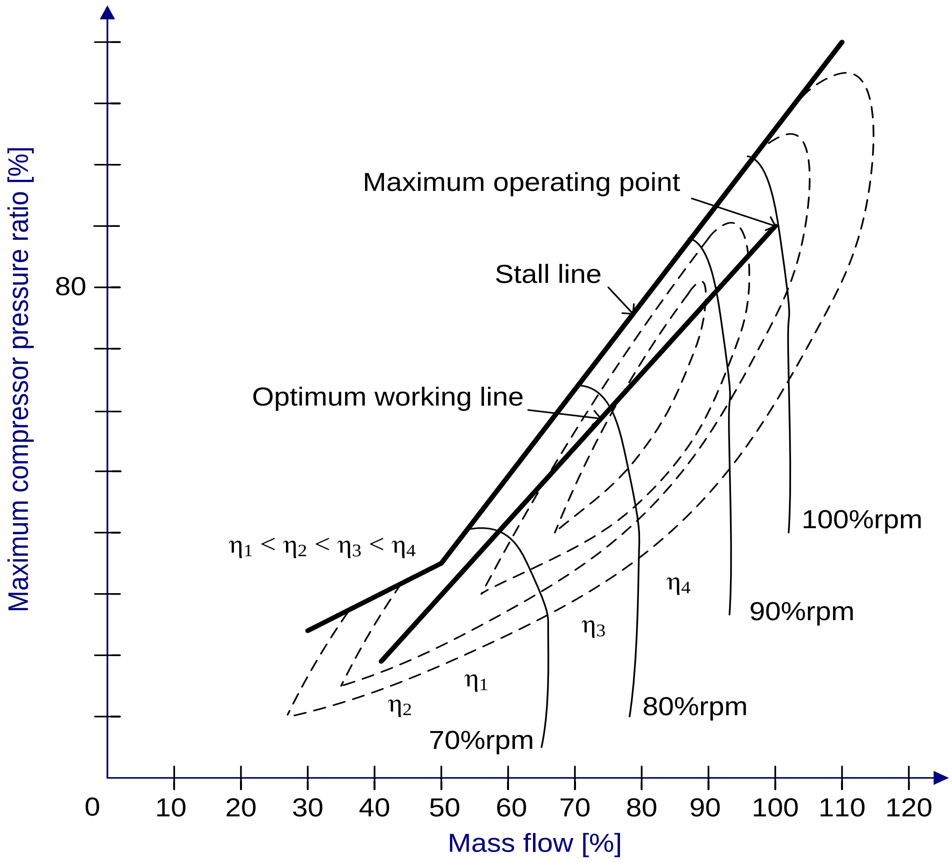

Fig. 1. Compressor map

2. STALL OCCURRENCE ORIGIN

In order to achieve a high compression ratio, the axial compressor consists of several (up to 17) stages, with the compression ratio at each stage being no more than 1.5. In modern turbofan engines, the compression ratio of the engine reaches 52 (Trent 1000). When producing such a pressure increase in a compressor, the main challenge is to ensure its safe operation with an appropriate stall margin, alongside the high compression ratio itself. Each stage of the axial compressor consists of one rotor stage and one stator stage. Both the rotor and stator form a divergent channel to enable a pressure rise; however, the compressor duct is generally convergent in order to maintain the required axial velocity of the airflow. The turbine delivers power to the rotor stages of the compressor, which converts kinetic energy into potential energy, thereby decreasing volume and axial velocity. In turn, a stall may occur due to a change in airflow parameters, such as mass airflow, pressure, temperature or power delivered from the turbine in the form of the rotational movement of the rotor.

With the fall in rpm, the first compressor stages deliver the uncompressed stream to the latter stages. The air volume and axial velocity exceed limits, which, alongside a decrease in the cross section of the compressor duct, causes clogging of the latter stages. The stream of air flows to the airfoils of blades and vanes at higher and higher angles of incidence. When the critical value of the angle is exceeded, the stream separates from the airfoil, which protrudes downstream, while air from the latter stages moves back through those areas of lower pressure in a chaotic way. When this phenomenon propagates through the adjoining stages, while applied regulation methods fail to restore stabilized airflow, this situation is referred to as stagnation.

The velocity of the stream is tangential to the camber line of the airfoil under optimum working conditions. Stalling conditions (i.e., when the airflow separates from the airfoil) may occur both on its concave and its convex sides. A stall on the convex side is more dangerous to the compressor and engine operation, being more difficult to restore. In the latter stages of the compressor, the stream may flow into airfoil at negative angles, which results in separation on the concave side. However, this neither causes it to stall, nor protrude through the compressor because the separation is neutralized by the movement of the rotating airfoils.

Since the stall is caused by inappropriate operations by the compressor, the likelihood of stall occurrence increases with the compression ratio, in terms of its scope and rate of change. The likelihood of stall is influenced by design parameters, the most significant of which are as follows:

- Compressor’s sizes and weight of its elements
- Angle of incidence, angle of discharge of the blade, and their variation along the airfoil
- Axial and radial variation in the parameters
- Minimum and maximum air discharge of the stage

Rotor speed, engine pressure ratio and mass airflow, as well as their mutual relations, directly influence the stable compressor’s workings. The higher the rotor speeds, the faster the axial velocity decreases, which practically means that more compressor regulation methods should be applied, given the wide scope of the rotor speed and engine pressure ratio. Furthermore, the applied methods should be more precise.

Stall occurrence is also influenced by the compressor’s aerodynamic characteristics, as well as additionally inhibited by the engine inlet (with its equipment), the volume of the combustion chamber and the engine exhaust nozzle surface.

3. STALL CAUSES

A stall is initiated by one of the events specified below.

3.1. Uncontrolled change in rotor speed

This phenomenon changes the angle of incidence between the stream and the airfoil. The rpm fall causes the axial velocity decrease, but in uncontrolled way since, in the first stages, it falls more rapidly than in the latter stages. Therefore, the angle of incidence in the first stages increases faster than in the latter stages in order to reach critical value. As such, a stall takes place in the first stages during deceleration and in the latter stage during acceleration in the compressor.

3.2. Uncontrolled change in airflow

This may be the result of the unintended opening or closing of the compressor bleed, particularly during its latter stages. Air from these stages is used in systems where high pressure and high temperature are needed. Such systems include the following: anti-ice, environmental control or exhaust nozzle steering/control. The temperature of the compressor outflow air reaches 500°C, while its pressure is a dozen times higher than the ambient pressure. Such values impose stringent conditions on compressor regulation. Under specific engine operating conditions, such as engine start or take-off, bleed is restrained. However, bleed-off operations enable maximum thrust and reduce the stall margin.

3.3. Temperature and/or pressure change at the compressor inlet

A temperature rise results in an axial velocity fall, causing a tendency towards increasing the angle of incidence. This is true, when assuming a constant rotor speed; however, the engine control system is designed to adjust the rotor operation to variable ambient conditions. Rotor speed rises under higher temperatures, since more power is required from the turbine to achieve the expected compression ratio and adequate combustion. The rotor speed may vary up to 10% rpm in conditions between -30 and +30°C at the same engine operating level. Due to variable and various operation conditions, the engine control system uses rotor speed signals corrected to the inlet temperature.

3.4. Fuel flow scheduling and duct contamination

Contaminated compressor duct elements have a minor influence on stall occurrence. But, as contamination has more adverse effects on specific fuel consumption rises, periodical engine cleaning is necessary to reduce the risk of stalls.

Stalls may be caused by an abrupt change in fuel flow scheduling, particularly in the fuel governor, which directly regulates the fuel pressure in fuel nozzles. Another important factor is when an engine operates below or above the scheduled minimum or maximum level. This may cause unpredicted effects, which exceed the compressor operating diagram.

3.5. Influence of the engine control system on safe compressor operations

This system controls not only fuel scheduling, but also systems and components, such as variable guide vanes or the exhaust nozzle. A stall may be caused by inappropriate parameter signals (command or feedback) or false conditions while computing command signals. The most important control signal with an influence on stall margin are rotor(s) speed(s), compressor inlet pressure (station 2), exhaust nozzle inlet pressure (station 6, on turbofan engines with a common exhaust nozzle), compressor inlet temperature, low-pressure turbine inlet temperature and gas generator fuel flow.

4. STALL SYMPTOMS

Stall symptoms may include one or more of the phenomena listed below:

- Low- and/or high-pressure rotor speed fluctuation - This is a reaction of the rotor to a chaotically changing airflow.
- Low-pressure turbine inlet temperature and/or exhaust gas temperature fluctuation with a strong tendency to increase rapidly - A decrease in compressor outlet pressure will cause an increase in turbine workload, caused by a rich fuel mixture, and therefore a rise in temperature. This relation is primary. The turbine’s direct reaction will occur sooner than the adjusted fuel flow scheduling by the fuel governor, which may mean that it is not practically possible to respond to such abrupt variations in stream flow. Furthermore, due to the compressor stalling, less air is directed to the turbine(s) for cooling purposes because the compressor bleed is most often the source of cooling air.
- Abrupt change in the exhaust nozzle area - If the engine is equipped with an exhaust convergent nozzle with a variable area, unstable area fluctuations will be the first observed symptom of a stall by the engine operator, since this is a direct regulator of the bypass airflow, which reacts immediately to low-pressure rotor speed changes and fan air discharge.
- Rumbling
- Strong vibrations
- “Bang” – This is caused by an intermittent air flow in the forward direction.

5. CONCLUSIONS

To ensure the compressor’s safe operation with a sufficient stall margin, the following systems should be used.

5.1. Variable stator vanes

Variable stator vanes are positioned upstream of the stage, where stalling is most possible due to the direct stream at the optimum angle of incidence in relation to the following rotor stage at a low rotor speed. During low rotor speed operations, the value of the angle is no more than -30° for high-pressure compressor variable vanes, and approximately -20° for low-pressure compressor variable vanes. This position is called the cambered position. With rotor speed acceleration, slightly above idle speed, the vanes’ axial position starts to change. Before maximum speed is achieved, they reach the final “axial” position, which is in fact up to 50° above the cambered position. Variable stator vanes are operated by a fuel subsystem, but controlled by an engine control system. Typically, in a low-pressure rotor, only inlet guide vanes are variable (actually, inlet guide vanes are part of a fan module, but not the fan itself), while the amount of regulated stages in a high-pressure compressor is at least two or three, or even six or seven in older designs; this is also the case in which other regulating systems are not applied or not enough. More stages are regulated in high-pressure compressors because of their bigger influence on the stall margin. Furthermore, variable stator vanes operate actively while accelerating, decelerating and performing other specific flight phases to increase the stall margin and enable smooth airflow adjustment, before the fuel flow schedule is regulated. For example, when the throttle is rapidly retarded from the maximum detent to the idle position, this feature will “camber” vanes to allow a high-speed rotor to maintain high rpm, thereby avoiding abrupt changes in airflow. This enables quick acceleration and deceleration. Only the first or final stages of each compressor are regulated.

5.2. Variable inlet guide vanes

Inlet guide vanes serve an identical purpose to that described above. But, contrary to other variable vanes, they may form a convergent duct. This will not cause a pressure increase, but will allow an undisturbed stream to form, which is directed to the first-stage fan rotor blades. Given the bigger values of stream velocities at the inlet, inlet guide vanes may have variable arms attached. Like other compressor variables, they are operated by a fuel-fed subsystem, which controls servomechanisms. Servomechanisms receive a command signal from the engine control system, sending out feedback on the current position. In modern designs, these signals are electrical, and sent and received by a “full authority digital engine control” system.

Contrary to high-pressure compressor variable vanes, inlet variable vanes can only offer a dual position, which is cambered from start-up, through idle, and then mild transition, starting from above-idle speed.

The moment of position change depends on the low-pressure compressor rotor speed, which is corrected with regard to the compressor inlet temperature. Above the mid-range power setting, when the position of the vanes is axially fixed, it is not adjusted until spool-down time.

5.3. Exhaust nozzle area control

It is necessary to control the area of the exhaust nozzle if the engine is equipped with an afterburner. This control only has an effect on engines with a chocked nozzle. The controlled area is the end of the convergent section of the exhaust, while the divergent section may remain as free-floating. Nozzle steering is not used on civilian engines, since the velocity of the exhaust stream does not reach the sound barrier level.

5.4. Compressor bleeds

Compressor bleeds, as stall prevention systems, are used on various power settings, especially under transient conditions. The air taken away from the compressor is regulated, depending on the engine operating level, the flight envelope, the bleed interfaces requests etc. The bleed is reduced while the engine is running at maximum rotor speed. The bleed allows for the removal of “unwanted” (uncompressed) air in the stages after the stall occurs, thereby re-establishing the pressure ratio across the stage, as well as “requiring” more outflow from the preceding stage and an increase in axial speed. During deceleration, for example, with a fall in rotor speed, uncompressed air gathers at the latter stages of the compressor, disturbing the airflow. The removal of air, in this case, allows for the axial velocity to increase, which rectifies the stall phenomenon and prevents stagnation. Bleeds from the compressors require more power delivery from the turbine in order to realize the scheduled compression ratio, which results in higher fuel consumption and higher turbine temperatures. Since bleeds are considered as a loss in thermal cycles, efforts are needed to replace them with another source of hot and high-pressure air. Compressor bleeds are opened during the engine start to allow for smooth acceleration and ensure a sufficient stall margin, as well as removing excess compressed air from specific stages.

5.5. Multirotor designs and active clearance control

Since the 1960s, dual-spool constructions have superseded single-spool designs. The original reason for this was to reduce specific fuel consumption, but it also resulted in increased stall margins, as well as rotors spool with different speeds that were not connected mechanically. This also led to higher compression ratios in modern engines, and a reduction in the number of compressor stages and overall engine length. To achieve high compression in single-spool aircraft, more and more compressor stages were required, resulting in aerodynamic problems that involved the mutual relation between axial and rotational velocities.

Indeed, the rotational speed of low-pressure spools causes changes to a greater extent than high-pressure spool changes during engine operations, which in turn facilitate quick and adequate air delivery to the gas generator. For example, during deceleration, a low-pressure compressor spools down more quickly than a high-pressure compressor, which prevents air build-up during subsequent stages. The major disadvantage of multi-spool designs is the requirement for more bearings, when compared to single-spool designs. This means that the former designs are more complex. This however has not stopped engine manufacturers from designing triple-spool or free turbine constructions.

In terms of active clearance control, radial clearance minimization not only increases compressor efficiency, but also enables the adequate control of airflow throughout the rotor stage.

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Received 13.02.2017; accepted in revised form 01.05.2017