Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2022, 16(1), 62–74
https://doi.org/10.12913/22998624/143290
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Received: 2021.08.26
Accepted: 2021.12.10
Published: 2022.01.01

Areas of Investigation into Air Intake Systems for the Impact on Compressor Performance Stability in Aircraft Turbine Engines

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ABSTRACT

The high demands placed on aircraft turbine engines necessitate the use of the latest engine compressors which must be increasingly efficient and more robust due to the increased loads. The key safety issue in this context is to ensure compressor stability over all engine speed ranges and aircraft flight regimes. This paper presents selected areas of research into surge and stall of axial compressors used in aircraft turbine engines based on scientific publications in recent years. On the basis of the analysed literature the authors defined the main research areas into compressor surge, namely: air intake research, compressor research and combined air intake and compressor system research. On the background of the conducted analysis the authors has presented their own areas of research. The aim of this work is to search for an intake-compressor design more passively resistant to stall or surge phenomena without necessity of implementation of complex control systems to prevent compressor stall.

Keywords: mechanical engineering, aviation, aircraft engines, compressor stall, compressors.

INTRODUCTION

The primary task of an aircraft turbine engine compressor is to force air of specified, optimum characteristics into the engine combustor within a specific unit of time. Unsteady compressor performance or surge is a serious problem in the operation of modern aircraft turbine engines [1, 2].

The causes of compressor stall may include air flow disturbance in the engine's air duct (e.g. due to icing of the engine air intake, flight at high angle of attack), or mechanical failure of the compressor's structural components, which in turn may prevent proper engine operation and consequently become a threat to flight safety. When a compressor begins to stall, it loses its capacity to force the air flow along the engine air duct. Pressure pulsing begins at a low frequency and a high amplitude, with rapid air flow variations. As a result, the accumulated high-pressure air in the engine mid section is ejected simultaneously through the air intake and the exhaust. As the airflow continuity is interrupted in the engine air duct, a phenomenon called 'compressor surge' occurs (Fig. 1).

In the worst case scenario, the compressor surge caused by a significant reduction of the mass flow rate makes the fuel-air mixture rich beyond the allowed range, leading to a risk of fire or permanent damage to engine components from the strong vibrations and overload which accompany the surge. Figure 2 shows the changes of turbine engine parameters during surge.

A compressor stall event may necessitate a forced landing of the aircraft, additional maintenance, and engine repairs. This disrupts the flight connection network of air operators and increases the costs of flight operations.

While compressor surge or stall occurs relatively often during routine operation of aircraft turbine engines, it is thanks to the use of technically advanced engine control systems that the issue is largely reduced in an automatic manner, without any need for the flight crew to intervene.

Fig. 1. Example of engine surge during an aircraft's take-off [source: www.airliners.net]

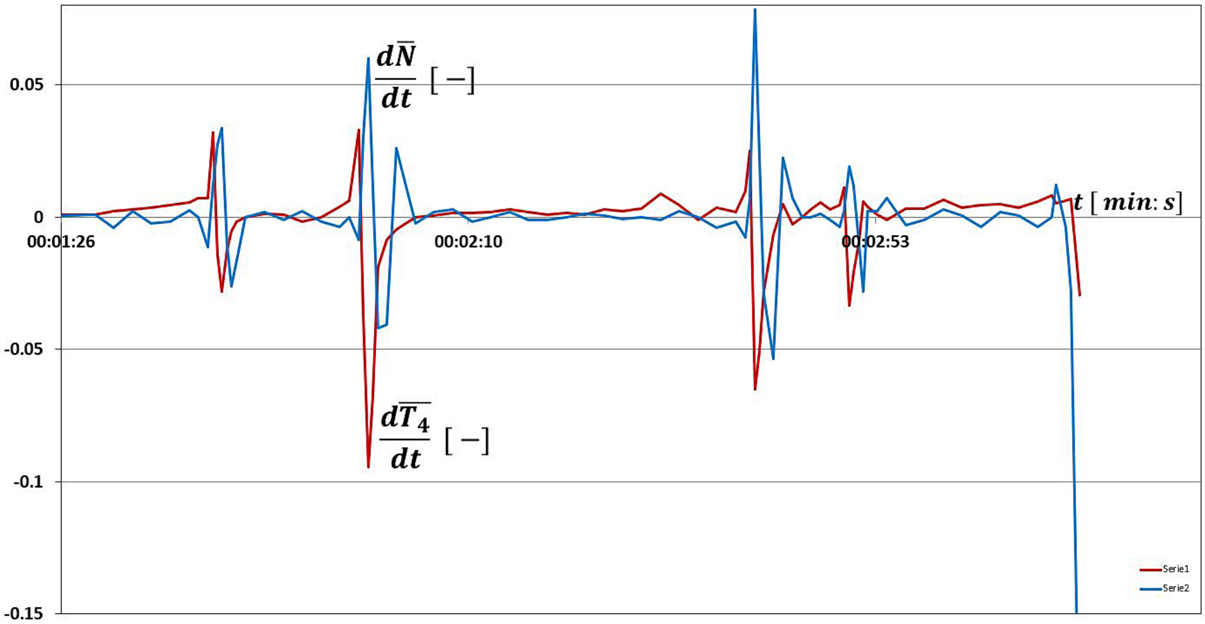

Fig. 2. Dynamics of turbine engine parameters during entry into surge, where: $\bar{N}$ – dimensionless changes in the turbine power; $\bar{T}_4$ – dimensionless changes in the turbine delivery temperature

Nevertheless, aviation incidents occur every year and include emergency landing and return to the airport immediately after take-off due to underperformance of engine compressors (Fig. 3). For example, on 14 January 2019, a Delta Airlines aircraft (flight number DL89) was forced to turn back after take-off the Los Angeles Airport as a result of a compressor stall. As the aircraft was prepared for the emergency landing, it became necessary to dump the fuel, which unfortunately landed on a public building located on the outskirts of Los Angeles. Another example is the crash of a Northrop T-38 Talon training aircraft on 18 June 2019. The root cause of the crash was precisely as a result of a compressor stall during a landing.

MAJOR RESEARCH CENTRES WORLDWIDE

The problems of unstable compressor operation (stall) are a focus of interest to many researchers and engineers around the world. These problems are extremely important and continue to remain so because of their impact on the safety of flight operations. Currently, the Massachusetts Institute of Technology (MIT, USA) is the largest research centre working on the issue of unsteady operation of aircraft engine compressors. All of the leading manufacturers of aircraft engines and components – including Pratt & Whitney, General Electric, and Collins Aerospace – are stakeholders in the research

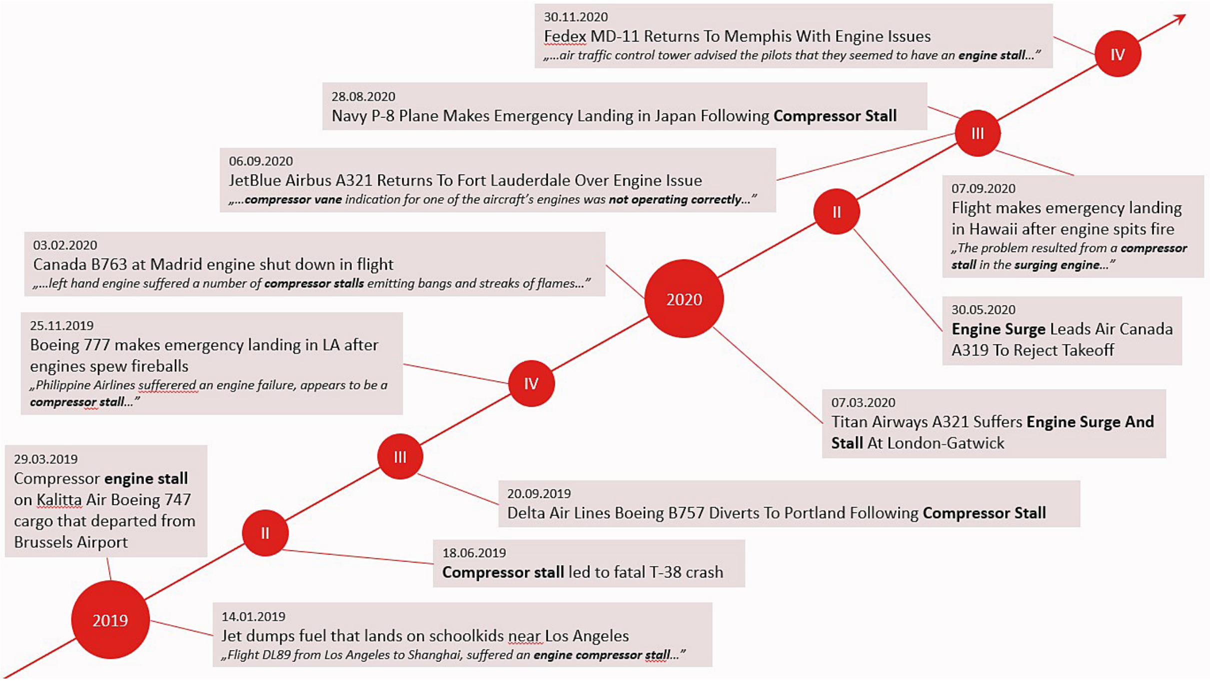

Fig. 3. Aviation incidents caused by compressor stall worldwide in 2019–2020

at MIT. Traditionally, the research carried out at various centres under the aegis of NASA has also been important and very valuable for many years. U.S. facilities employ researchers with the greatest global scientific output on this topic. The research carried in Europe is also significant. The University of Cambridge (in cooperation with MIT) and other research and university centres in the UK, France, Spain, and Italy, boast a large body of work in the field of compressor stall. Joint initiatives are undertaken with the aerospace industry, including Rolls-Royce and the Safran Group.

Far Eastern research centres – including Chinese research institutions (with a dozen universities in total), where work on aircraft compressors is carried out, are now becoming increasingly visible and active in this field of interest [3]. The studies of the authors of this paper [1 ,2, 4, 5] are also part of this research stream.

In recent years, research into compressor stall has been focussed on three main areas. These include air intake research, compressor research and combined air intake and compressor system research. Since the air intake and the compressor operate within the same engine air flow ducting, the parameters of the air flow supplied through the air intake strongly influence the operation of the compressor itself. The current studies on turbine engine air intakes is mainly concerned with their performance characteristics in terms of generated disturbances in different operating conditions. The compressor research focusses on the analysis of compressor performance and stability with the search for new design engineering methods [6, 7, 8] and solutions to improve the performance parameters. On the other hand, new methods are also sought to effectively detect unsteady operation and improve the efficiency of the compressor itself [9]. The research into the combined air intake and compressor system is focussed on acquiring new knowledge on the impact of engine air intake disturbances on compressor performance, in particular on the compressor operating stability.

AIR INTAKE RESEARCH

The primary purpose of the air intake of an aircraft turbine engine is to pre-compress and, most importantly, to deliver a stable and homogeneous air flow in sufficient quantity to the compressor. The research work carried out in this department of engine air intake assemblies varies with the air intake application and design. For the aircraft propulsion systems with axial compressors, two main streams of research are currently apparent, namely: subsonic air intake research for turbofan engines and supersonic air intake research.

The air intake performance is gauged, among others, by the coefficient σ_{wl} of total pressure efficiency (pressure loss) according to the following empirical relations [10]:

$$\sigma_{wl} = \frac{p_2^*}{p_0^*} \text{ for Ma} \leq 1.0 \quad (1)$$

$$\sigma_{wl} = \frac{p_2^*}{p_0^*} = 1 - 0.075\,(\text{Ma} - 1)^{1.35} \quad (2)$$

$$\text{for Ma} > 1.0$$

where: p_0^* – non-turbulent flow total pressure; p_2^* – compressor inlet section total pressure; Ma – Mach number.

Subsonic air intake assemblies

In typical turbine engines which feature a high mass flow ratio and find applications as powerplant systems for passenger and cargo aircraft (e.g. the Trent 1000 engine for the Boeing 787 Dreamliner or the Trent XWB engine for the Airbus A350), the disturbances generated by the air intake occur most frequently in two cases. The first case is the taxiing of an aircraft on the tarmac, during which the phenomenon of air intake vortex may occur (Fig. 4). In addition, during taxiing or take-off, air flow disturbance may occur due to crosswinds (the horizontal deviation of the airflow incoming at the engine air intake).

The second case occurs when the aircraft operates at high angles of attack.

The current tendency to strive for continuous improvement in engine performance, including above all the fuel economy and efficiency of turbine engines with a large mass flow ratio, leads to the engineering of fans with increasingly larger diameters, which consequently reduces their operating stability and increases the generated disturbances.

The research of Harjesn et al. [11] of the air intakes of this type of engine has shown that there is a significant disturbance of the air flow supplied into the engine in the presence of crosswinds. The high dependence and sensitivity of these air intake assemblies to the speed and incidence angle of crosswinds was also demonstrated. The higher the wind speed or the greater the entrance angle, the stronger the disturbance, manifested primarily by an increase in the local Mach number at the edge of the engine nacelle (Fig. 5).

As a result of the asymmetrical air entrance at the engine air intake, the sound barrier can be locally exceeded, especially during crosswind take-off or climbing at a high angle of attack. The air intake assemblies in passenger aircraft engines are characterised by a significant edge curvature, which is supposed to ensure laminar airflow under design conditions. However, this curvature causes the sound barrier to be exceeded locally and the formation of a lambda-form shock wave. The resulting disturbance in the form of distortion of the airflow spreading deep into the air flow duct of the turbine engine may lead to unsteady operation of the fan and – in extreme cases – failure of the fan blades, which has been presented by Kalsi and Tucker [12].

In response to the operational problems of passenger aircraft engine air intake assembles described above, Wakelam et al. [13] carried out work to stabilise the air flow under off-design

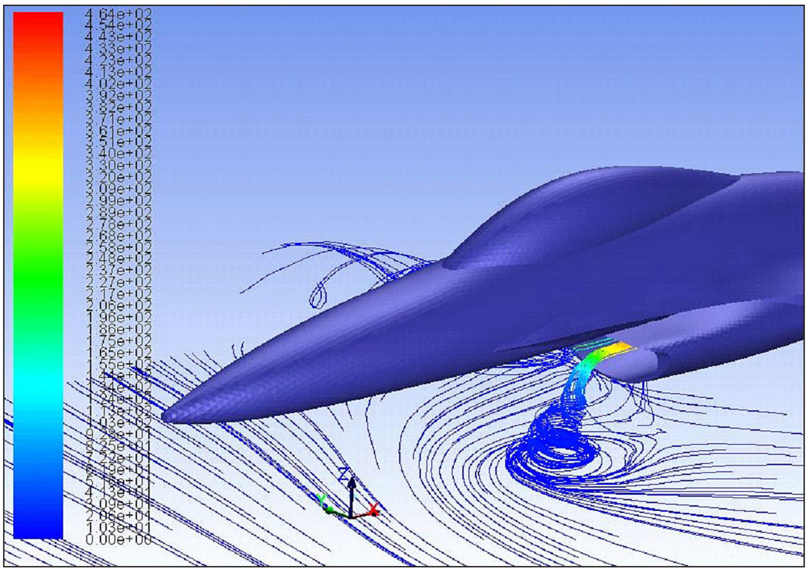

Fig. 4. Simulation of an intake vortex generated on the air intake section of an F-16 aircraft. Raster scale shows velocity magnitude in [m/s] [4]

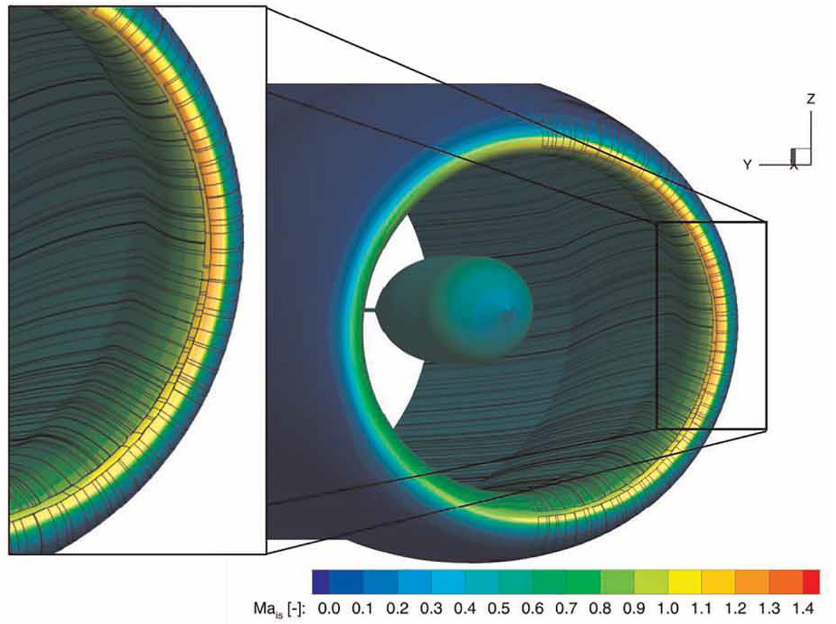

Fig. 5. Simulated air intake operation at Ma = 0.45 and a crosswind of 11.3 [m/s] [11]

(permissible) conditions. An example of a solution to the problem is the proposal to use turbulators (turbulence simulators or vortex generators) on the inner part of the air intake duct, which reduce the intensity of the manifested disturbances by generating a turbulent boundary layer.

Work is also under way to optimise the geometry of the air intake and engine nacelle itself. Savelyevn et al. [14] proved that optimisation of the air intake geometry contributes to stable engine performance in 10 degree crosswinds of up to 20 m/s, significantly reducing the local Mach number at the edge of the air intake. This has the effect of reducing the overall aerodynamic drag of the engine nacelle by approximately 10%.

The reviewed publications (cited in the reference literature) and the research specified in them prove that the these adverse phenomena occurring in taxiing, take-off and climbing conditions are complex issues, and a more accurate estimation of the results depends on many different variables, including, for example, consideration of the design of the engine fan itself and its rotational speed.

Supersonic air intake assemblies

In the area of supersonic air intakes, the fulfilment of their basic function of delivering a homogeneous air flow to the compressor has been a perennial challenge in their design due to the impact of shock waves. Research into supersonic air intakes gained momentum with NASA's project to develop the Lockheed Martin X-59 experimental aircraft – a 'silent' (low-sonic boom) supersonic jet that would usher in a return to supersonic flight in civil (commercial) aviation. In this area, the search began for new and improved air intake geometries that would better suit the imposed requirements.

In this context, the development of new and improved air intake geometries that provide lower pressure losses, less air flow disturbance generated and quieter operation in supersonic flow conditions – such as the SPIKE air intake; and a lower aerodynamic drag coefficient providing improved aircraft performance – such as the STEX air intake (Fig. 6) – has been a success.

Nevertheless, reconciling these diverse parameters and developing an optimal design remains a challenge.

In defence aviation, due to the changing tactics and the nature of air combat, the demands placed on modern combat aircraft are evolving. In the designs of successive generations of multi-role fighters, increasing emphasis is being placed on the manoeuvrability of the aircraft over a wide range of Mach numbers including subsonic speeds.

Diverterless Supersonic Inlets (DSI) are still an important innovation. Their concept was originally developed by NASA and has become a major trend in the design of combat aircraft air intakes. The geometry of the DSI is integrated into the aircraft fuselage and consists of a bump area upstream of the air intake and an forward swept cowl.

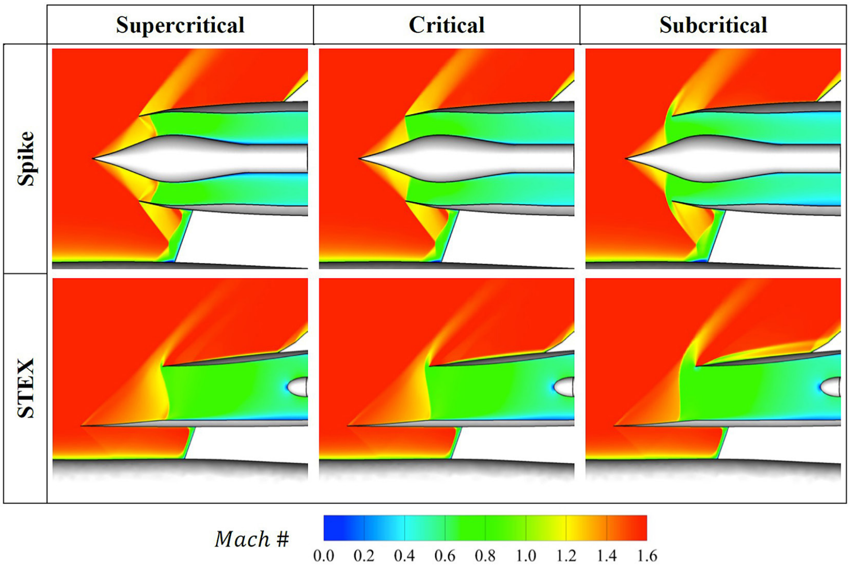

Fig. 6. Mach number in the flow around the SPIKE and STEX air intakes [15]

The combination of these two shapes diverts the air flow boundary layer to the outside of the engine air intake duct, which improves overall air intake performance, reduces aerodynamic drag and ensures effective deceleration of the air flow from supersonic to subsonic speeds with low pressure losses and high air flow uniformity and stability over a wide range of flight conditions. Improving these parameters also benefits the overall performance of the entire powerplant. The DSI was first used on the Lockheed Martin F-35 Joint Fighter aircraft (Fig. 7).

Afzal et al. [16] carried out numerical and experimental studies that confirm the most significant advantage of the DSIs, which is their wide range of stable operation at flight speeds with a Mach number of about 0.70–1.80 and angles of attack from 2 to 6°. Despite the obvious decrease in air intake performance, including in particular the pressure loss coefficient and increased air flow disturbances at supersonic speeds and high angles of attack, they maintain satisfactory parameters for stable engine operation.

Simultaneous work is also being carried out to improve the existing DSI designs. Montes and Chandler [17] attempted to use a different shapes of bump surface ahead of the air intake, with early work already eliminating an elliptical form. An example of simulated DSI performance is shown in Figure 8.

Air intake ducts for combat aircraft are of particular interest to researchers. In a typical jet fighter, the air intake duct is long due to the installation of the turbine engine in the aft section of the fuselage; due to the expected low-radar cross-section of the craft, a bend is used (to conceal the engine fan inside of the fuselage). An additional challenge in the design engineering of air intake ducts is usually the need to

Fig. 7. Comparison of the air intake on the F-22 fighter (Fig. 7a) and its successor, the F-35 to a DSI-type design (Fig. 7b) [source : www.aviationweek.com, www.airman.dodlive.mil]

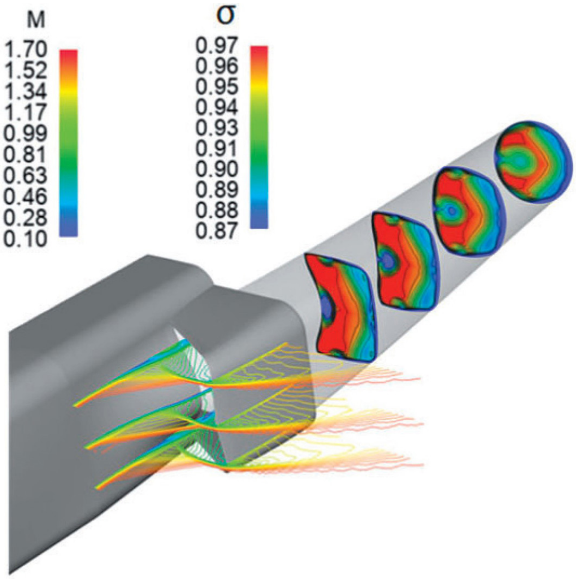

Fig. 8. Simulation of DSI performance, where: M – Mach number, -pressure coefficient [18]

switch from a quadrilateral to a circular cross-section and to merge two ducts into one (forming Y-ducts).

Currently, much research is being done to optimise the air intake duct geometries to generate as little air flow disturbance as possible. Both numerical and experimental studies are being carried out (Fig. 9).

Tanguy et al. [20] shows that the disturbances generated are strongly dependent on geometrical parameters, mainly the bend and length of the air intake duct. The shape of duct inlet cross-section used is also an important factor. The interaction of these components with the entire aircraft fuselage also remains an extremely important issue in the research into the air intakes and intake ducts. The results of the analyses of Bravo-Mosquera et al. [21] show a significant influence of the aircraft aerodynamic system and airframe geometry on the performance of the air intake system, which cannot be neglected in the final considerations.

COMPRESSOR RESEARCH

In general, the research into axial compressors has focussed for many decades on finding ways to better stabilise the operation of these assemblies and improve their efficiency.

In recent studies of the operating stability of axial compressors, there has been significant focus on the issues of blade tip clearance and the resulting leakage. The clearance between the blade on the rotor and the compressor casing has a significant impact on the formation of turbulence and flow disturbances, which are a source of pressure losses and have a negative impact on the overall compressor performance stability.

When the clearance between the blade and the casing is small, the dominant disturbance phenomenon is the separation of the boundary layer at the blade tip and the chocking of the flow by the vortex formed in this area. As the blade tip clearance increases, the phenomenon of flow leakage through the compressor blade tip plays an increasingly important role, as there is a local increase in flow velocity in this area (Fig. 10).

This can lead to Spike-type disturbances, i.e. a strong longitudinal vortex originating at the point of separation at the leading edge. The research of Hewkin-Smith et al. [22] shows that for each rotor, there is a certain optimum value of blade tip clearance that ensures a relative balance of disturbances, which ultimately leads to more stable compressor performance. It is estimated that the optimum blade tip clearance is about 0.5% of the chord of the rotor blade.

One method of reducing the blade tip clearance losses, and thus improving compressor stability, is to increase the load on the blades near their tips. This leads to a local increase in the

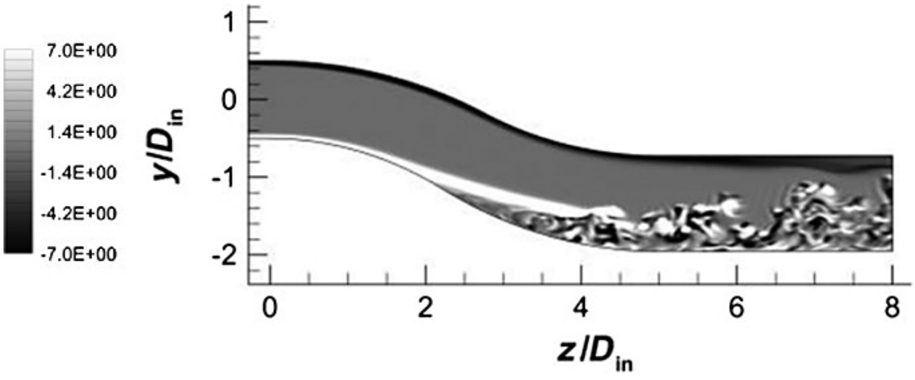

Fig. 9. Vorticity of x and z on the z-y plane in an example air intake duct [19]

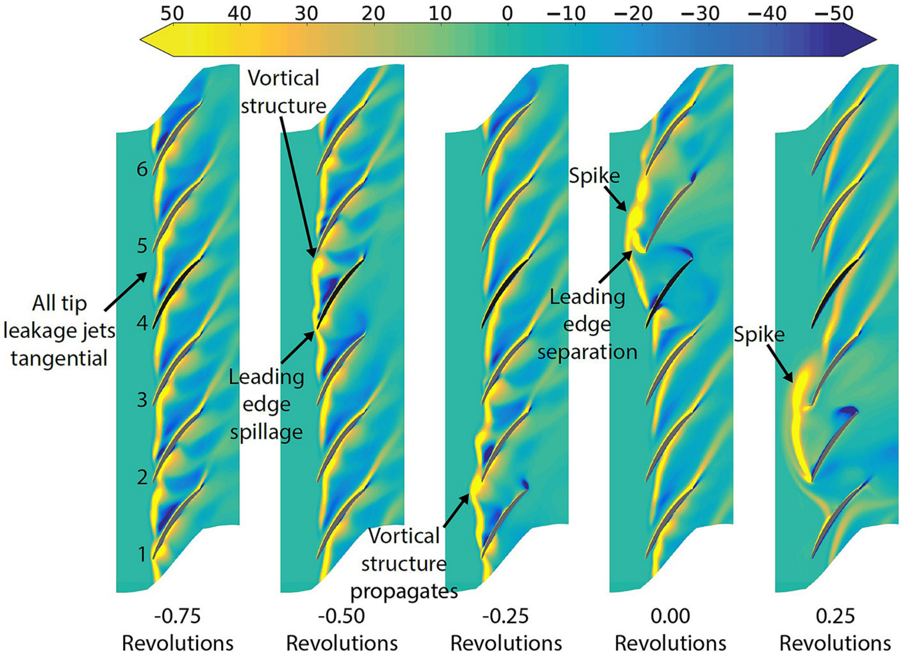

Fig. 10. Flow disturbance phenomena on the blade rotor for outer diameter (95%) and tip clearance of 1.8% of the chord [22]

mass flow rate, which in turn has a positive effect on the limit of steady operation.

Another very interesting proposal for minimising losses and leakages is the use of recirculation channels integrated into the compressor casing (Fig. 11).

Preliminary work of Kawase and Rona [23] in this area confirms that the use of recirculation channels reduces losses in the blade tip area and has a positive effect on compressor stability. This is done mainly by mitigating the flow leakage between the concave and convex sides of the airfoil. This application of recirculation channels and several related solutions has been covered by international patent applications.

Analogous work on blade tip clearance is being carried out for stators. It has been shown by Liu et al. [24] that, although stators are not rotating components, the phenomena occurring in the area of the blade tip of the stators are the same as those for rotor blades. Experimental testing has shown that clearances smaller than approximately 0.5% of the blade chord is also not optimal for compressor stability.

Prolonged operation of the powerplants, especially in a harsh environment (e.g. with increased dust concentrations), causes degradation of the compressor blades. This phenomenon occurs most intensively at the tips of the rotor blades (Fig. 12), causing a decrease in their chord and an increase in the clearance between the blade and the compressor casing.

Changing the geometrical parameters of the blade leads to a decrease in the efficiency of

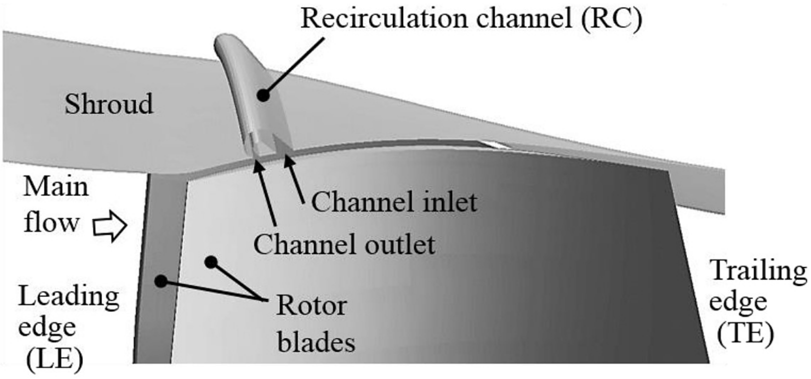

Fig. 11. Structural diagram of a recirculation channels [23]

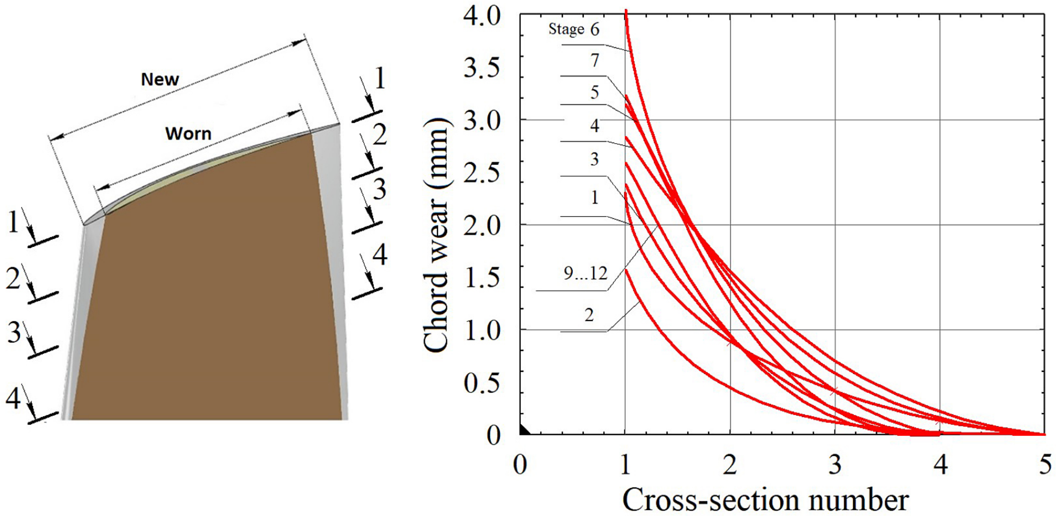

Fig. 12. Rotor blade wear diagram [25]

the entire axial compressor and also reduces its steady-state operating limit which has been a subject of research of Dvirnyk et al. [25].

An important part of the research into axial compressors is currently devoted to exploring optimisation issues. New algorithms are being developed that optimise compressor blade geometry (e.g. waisting, twist, and profile) usually to maximise the efficiency of the entire component. In papers of Popov et al. [26] it has been proven that the implementation of these algorithms can provide an improvement in compressor efficiency of about 0.3 to 1.3%, and an increase in compression ratio approximately up to 4.0%.

Another important area on which modern compressor research is focussed is the search for new and improved methods for the early detection of compressor instability or stalling. In modern aircraft turbine engines, performance instability prevention systems are typically based on measuring the compressor inlet and outlet pressure. The difference between these two values is used by the control systems to set the bleed valves and the variable stator vanes, respectively. The disadvantage of this method is the strong effect of potential disturbances emerging at the compressor inlet on the performance of the whole system (Fig. 13).

Current research work proposes the use of Fourier transform to measure the pressure signal [27]. Improved methods of detecting performance instability are also based on measuring the pressure in the area of the rotor blade tip or between the rotor and stator. Numerous experimental studies conducted by Kim et al. [28] as well as Margalida

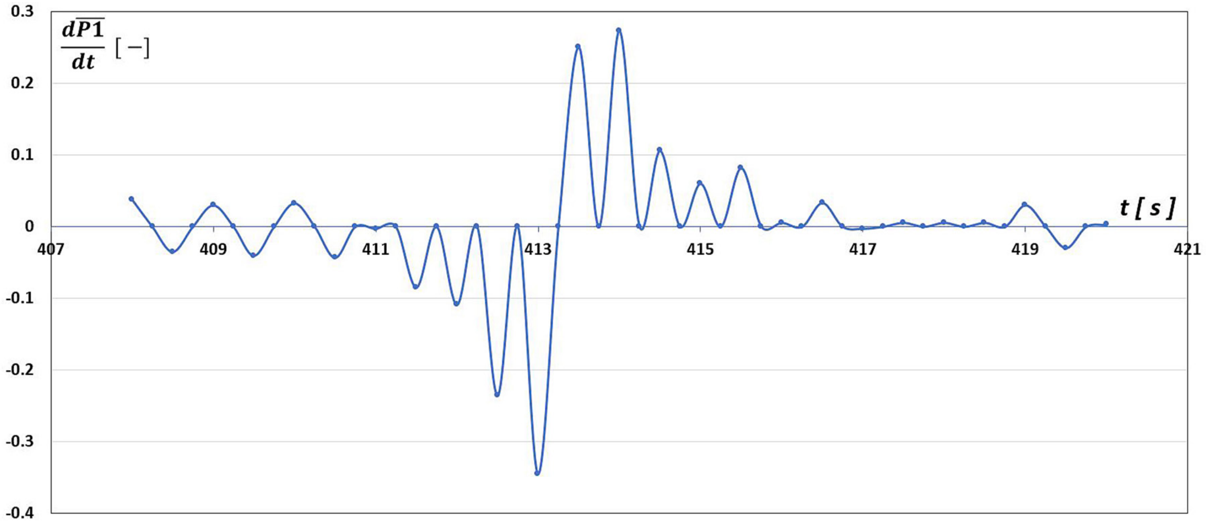

Fig. 13. Dynamics of pressure changes at the turbine engine intake during acceleration and deceleration, where: pressure changes in dimensionless quantities

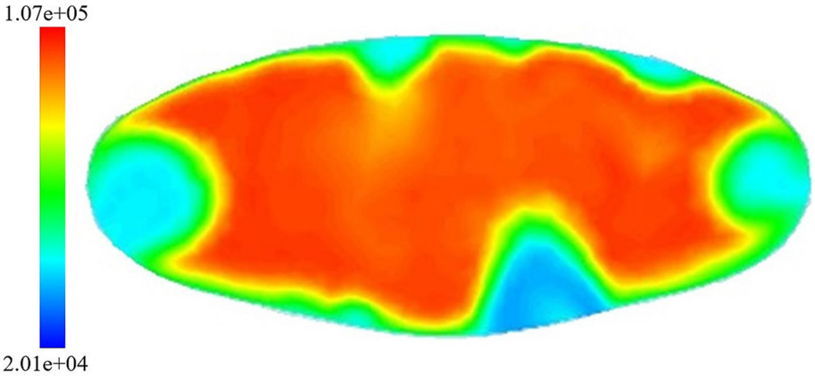

Fig. 14. Distribution of total pressure [Pa] in the engine air intake cross-section [6]

et al. [29], show that new methods of performance instability detection are more effective than those currently used. The location of the pressure sensors in the area of the rotor provides more information and allows more precise detection of early symptoms of unstable component operation.

COMBINED AIR INTAKE AND COMPRESSOR SYSTEM RESEARCH

The research into the combined air intake and compressor systems are based on attempts to combine the two issues discussed here so far. The individual components of a turbine engine are part of a single flow duct. The parameters of the flow exiting an upstream component have a significant impact on the performance of the next component; hence, a natural research question is how the components cooperate.

Flow disturbances emerging at the air intake generally lead to a deterioration in compressor performance. In most cases, the consequences of heterogeneous intake flow (Fig. 14) are a reduction in the compressor steady-state operating limit, a decrease in compressor efficiency, and an increase in stresses on the rotor blades.

However, results from independent studies show that the effect of flow disturbance does not always have such obvious consequences on compressor performance. A lot of work is currently being carried out to understand this issue in depth. Both numerical and experimental research have shown that the location of disturbance, its magnitude, and type are important.

An example of ongoing research work in the field of unstable compressor performance can be found in the numerical calculations of a cascade of flat airfoils in a high mass flow ratio engine compressor, carried out by the authors of this paper (Fig. 15).

In the model developed for one compressor stage at the medium radius, the air flow rate through the cascade was gradually reduced. This situation may occur while the aircraft is manoeuvring or climbing, or for any other reason stemming from a disturbance in the flow duct or engine air intake.

First, a simulation was performed for the engine design conditions and then the mass flow rate was reduced (by changing the axial velocity vector) by 20% and 40%, respectively. At a 20% decrease in mass flow rate, the first disturbances were observed on the inner side of the rotor blades with turbulence events at the stator blades. The resulting disturbance causes the compressor stage compression ratio to drop from a value of 1.65 at design conditions to a value of 1.11.

When the mass flow rate is reduced, successively by 40%, stronger turbulence events are observed on both the rotor and the stator , on the convex side of the blades. In this case, the compression ratio falls below unity to a value of around 0.92. The flow separation events are already so pronounced that the stage practically stops forcing pressure deeper into the compressor duct. This type of simulation can be successfully used to determine the range of stable compressor operation in an aircraft turbine engine.

In the case of both subsonic and supersonic stages, it has been proven by Li et al. [30] that disturbances arising on the outer side of the flow duct diameter (on the casing side) have a negative impact on compressor stability. For disturbances filling approximately 8.0 to 15.0% of the duct, an approximate reduction in the steady-state operating limit of 5.0% was detected. The disturbances formed in this way contribute to an increase in flow turbulence in the blade tip area and consequently to a faster transition of the compressor into unsteady operation.

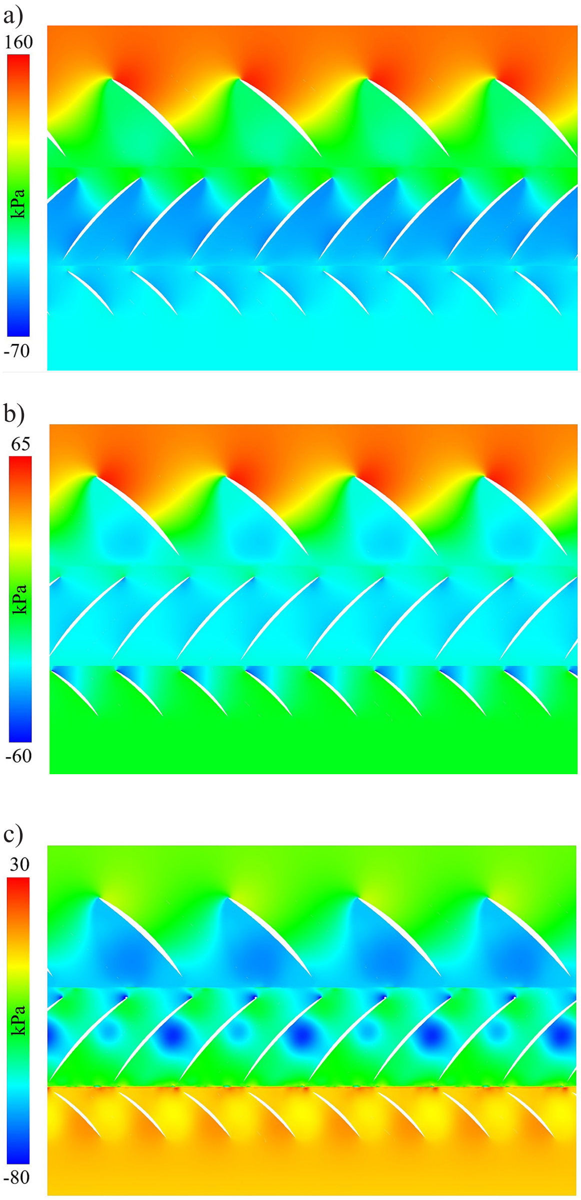

Fig. 15. Static pressure distribution for one compressor stage of a turbofan engine (Fig. 15a) at a mass flow rate decrease by 20% (Fig. 15b) and 40% relative to the design point (Fig. 15c)

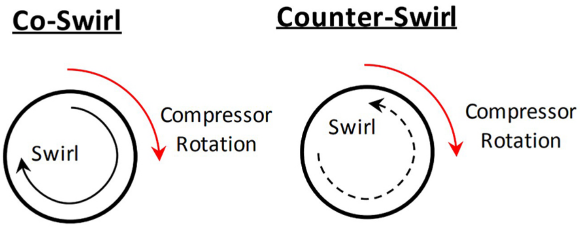

Fig. 16. Diagram of the direction of rotation of the disturbance [32]

An opposite phenomenon is observed in the case of disturbances generated from the inner diameter of the rotor blades (from the rotor hub side). The turbulence created in this way causes a delay in the stalling of the rotor blade tips and the subsequent entry of the compressor into unsteady operation. For disturbances filling approximately 8.0 to 15.0% of the duct, a higher steady-state operating limit of up to 10.0% was recorded.

Another interesting issue is the effect of the direction of rotation of the resulting disturbance on the performance of the compressor blades. If the disturbance follows the rotor's direction of rotation, it is better for the compressor operating stability. When the disturbance moves opposite to the direction of rotation of the rotor, it results in reduction of the steady-state operating limit. The counter-swirl disturbance also increases the Mach number in the blade tip area and increases the load on the entire compressor stage (Fig. 16) [31, 32].

In the context of the variety of these phenomena and their impact on compressor operation, NASA and MIT are now jointly investigating the concept of an engine operating entirely in a disturbed flow (e.g. a separated flow off the wings or fuselage), which could find application in passenger aviation (Fig. 17).

Fig. 17. Disturbed flow engine aircraft concept [33]

The rationale for this work is based on preliminary results obtained by e.g. Hall et al. [34] as well as Kim et al. [35], which indicate a several percent decrease in thrust and efficiency of this engine type, but at the same, a reduction of fuel consumption by more than ten percent, which would make this solution particularly suitable for use in commercial aircraft. Thus, it is easy to see that research is now being undertaken not only in the context of the operation of the whole aircraft engine, but especially in the operation of its compressor and fan under highly disturbed flow conditions.

CONCLUSION

Analysis of recently published scientific papers in area of compressor stall and surge shows that they focus on three topics: air intake research, compressor research, and combined air intake and compressor system research. The knowledge gained in this area allows the development of new design concepts for both aircraft powerplants and new concepts for the aerodynamic systems of the aircraft themselves. The recent trends in compressors stall research seem to evolve into search and design of more stable constructions itself rather than development of complex control systems to prevent the phenomenon. In the recent studies more attention is focused on intake research and in particular influence of flow disturbance generated by them on the compressor stability. This is exemplified by the work carried our by the authors in this area. The analysis of inlet vortices is an important premise of uneven flux parameter field in the intake duct and additionally these phenomena have a dynamic character. This leads to disturbances in compressor operation resulting in problems with operation of entire engine (including engine shutdown) in case of engine surge. The work carried out by the authors is part of the gaining new knowledge about various of factors affecting stall and surge along with development of new methods for their measurement and detection. The subject matter related to the emergence of unsteady operation of axial compressors in aircraft powerplants is extremely important and topical because of the safety and cost efficiency of flight operations. For this reason, it makes perfect sense to undertake and carry out research focussed on these issues, and their practical application certainly contributes to the development of better, more efficient, more capable and – above all – safer turbine engines propelling modern aircraft.

Acknowledgments

This work was financed by Military University of Technology in Warsaw, Poland under research project UGB 898/2021.

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