AiMT

Advances in Military Technology
Vol. 14, No. 2 (**2019**), pp. 901-917
ISSN 1802-2308, eISSN 2533-4123
DOI 10.3849/aimt.01260

Analysis of Engine Surges in Military Jet Aircraft in Czechoslovakia and the Czech Republic

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The manuscript was received on 10 July 2018 and was accepted
after revision for publication on 27 December 2018.

Abstract:

The article deals with the statistics, causes and consequences of aviation accidents and preconditions for aviation accidents linked causally to jet engine surge events in military jet fighter, fighter-trainer and trainer aircraft in the service of Czechoslovakia and the Czech Republic from 1960 until the end of 2016. It presents a complete list of such aviation emergencies on a timeline, as well as technical contexts and facts of interest (for example, hazardous flight stages, hazardous aircraft types prone to engine surges or possibilities and developments in anti-surge systems). The role of human, technical and environmental factors in the occurrence of these air emergency events is also analyzed. The study is complemented by an overview of information sources on the subject that are currently still accessible.

Keywords:

aviation accident, cause, fire, jet aircraft, jet engine surge, precondition for aviation accident, statistics

1. Introduction

Compressor surge or an instable operation of a jet engine compressor is a phenomenon occurring at off-design operation of the engine (see Fig. 1) [1, 2]. The compressor surge can be preceded by inlet distortions. Both phenomena are characterized by local periodic fluctuations of velocity and pressure fields (pressure shocks) accompanied by temperature rise of the compressed air within the space. In inlets, the distortions are usually caused by major changes in air flow direction and velocity at the inlet lip causing local or even general decrease in the inducted airflow mass. The compressor surge is caused by air flow disruptions on compressor blades and subsequent off-design

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pressure differences from one compressor stage to another [3]. This can lead to a loss in engine thrust or engine failure, mechanical damage to engine components (in particular gas turbine and compressor blades) or to damage to adjacent systems (fuel, hydraulic, etc.), in some instances the result may be even a fire or destruction of parts of the engine [4]. If primary damage to one of the compressor's functional parts is not the case, the cause is always related to undesirable changes in air or fuel supply to the engine. Circumstances may, however, vary across different types of engines and manners of their use.

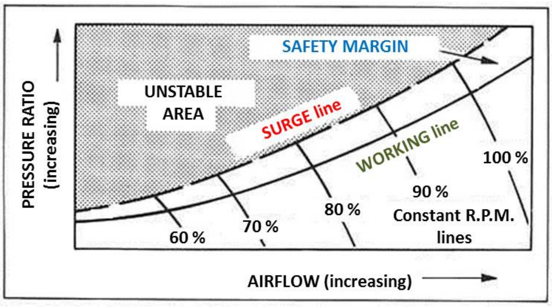

Fig. 1 Airflow limits for stable turbofan engine operation (general principle) [2]

Fig. 2 Examples of surging engines in foreign military jet fighters: (1) F-18 C (2009), (2) F-16 A (2016), (3) F-15 E (2014), (4) Su-57 (2011) [5]

From the pilot's perspective, the surge is manifested by loud bangs, vibrations of the aircraft extending from the engine compartment, fluctuations (sudden increase or decrease) in exhaust gasses temperature and fluctuations in engine speed. An outside observer may see, for example, a flame flared out of the exhaust nozzle (see Fig. 2).

The engine surge is a very dangerous event that has played role in the chain of causes of many aviation accidents (AA) and preconditions for aviation accidents (PAA) in both remote and recent past. It is characteristic particularly for jet engines with axial compressors.

This study aims to give answers to at least four questions: “How many jet engine surge events have been recorded so far in Czechoslovak and Czech military aviation?”, “What were the causes of the engine surges?”, “How and by what means is it possible to avoid engine surges?”, and “Is it a historic problem or is it still a topical flight safety issue?”. The authors will try to give answers to these and other questions in the following paragraphs.

2. Classification of AAs and PAAs

The classification of aviation emergency events used throughout this study is based on the contents of the Všeob-P-10 Flight Safety regulation [6], which was in force between 2006 and June 2016, being replaced by the Order of the Minister of Defence No. 13/2016 Journal – Flight Safety of 15th June 2016 (hereinafter „Order of the Minister of Defence No. 13/2016“) [7]. In this Order of the Minister of Defence No. 13/2016, however, substantial changes in definitions, terminology and classification of emergency occurrences in military aviation were made. Should the emergency events be reclassified in accordance with this document, then all air disasters, crashes and damage events would be merged under one common term “air accident”, PAAs would be replaced by the term “incident”, and serious PAAs would approximate to the term “serious incident”.

In a bid of clarity of the interpreted results and in order to effectively synchronize data for different periods, the authors chose to use the classification system based on the previous Všeob-P-10 Flight Safety regulation. Most available technical literature and archival records are based on the contents of this Všeob-P-10 Flight Safety regulation, including the information base from the Information System for Logistics [8], a part of which has been used by the Air Forces of the Army of the Czech Republic (AF ACR) to keep records of emergency occurrences since 1985 to the present day.

3. Statistics, Causes and Consequences of Engine Surge Events

During the 68 years’ history of military jet flying in Czechoslovakia and the Czech Republic (1948–2016), 14 AAs and 57 PAAs linked causally to jet engine surge occurred. They represent 2.2 % of all 647 AAs (sum of disasters, air crashes and damage events according to the classification contained in the Všeob-P-10 regulation) and 1.2 % of all 4807 PAAs that could be tracked down. A more detailed analysis, broken down by topics, is given below (see Sections 3.1 to 3.4).

3.1. Statistics of Jet Engine Surge Event

In the “jet era” (from 1948 until now) of military aviation in the former Czechoslovakia and the present Czech Republic, a total of 71 AAs and PAAs whose chain of causes included jet engine surge were recorded, including 1 disaster AA, 12 air crash AAs, 1 damage AA and 57 PAAs (see Tab. 1 and Fig. 3).

In these events, 13 aircraft were destroyed and 1 damaged. 15 crew members ejected from the aircraft they lost control over (14 successfully – the crew members survived, 1 unsuccessfully – the crew member was killed). The engine surge events were recorded in 17 versions of 8 jet fighter, fighter-trainer and trainer aircraft types (see Tab. 1).

The largest number of these cases took place in the period from the mid-1960s to the early 1990s, mostly in MiG-21s (46.5 % of cases), MiG-23s (28.2 % of cases) and Su-7s (14.1 % of cases).

Most of the AAs and PAAs (84.5 %) took place under normal weather conditions during the day (NWCD). Only a small portion of them occurred under different weather conditions, that is, under difficult weather conditions during the day (DWCD), normal weather conditions during the night (NWCN), or under difficult weather conditions during the night (DWCN).

Tab. 1 Number of AAs and PAAs linked causally to engine surge in 1960–2016 (arranged by aircraft type and number of AAs and PAAs) [8-15]

Aircraft type and version	**Number of AAs (engine surge)**				**Number of PAAs (engine surge)**		
	Disaster	**Air crash**	**Damage**	**Total**	**PAA**	**PLN - serious**	**Total**
MiG-21							
MiG-21 F	1	0	0	1	6	0	6
MiG-21 PF	0	2	0	2	3	1	4
MiG-21 PFM	0	0	0	0	4	0	4
MiG-21 R	0	0	0	0	0	1	1
MiG-21 MA	0	1	0	1	0	0	0
MiG-21 MF	0	1	0	1	8	3	11
MiG-21 UM	0	1	0	1	1	0	1
Total for aircraft type	**1** **(16.7 %)**	**5** **(83.3 %)**	**0** **(0 %)**	**6** **(100 %)**	**22** **(81.5 %)**	**5** **(18.5 %)**	**27** **(100 %)**
MiG-23							
MiG-23 BN	0	1	0	1	9	2	11
MiG-23 ML	0	0	0	0	3	0	3
MiG-23 MF	0	0	0	0	5	0	5
Total for aircraft type	**0** **(0 %)**	**1** **(100 %)**	**0** **(0 %)**	**1** **(100 %)**	**17** **(89.5 %)**	**2** **(10.5 %)**	**19** **(100 %)**
Su-7							
Su-7 BM	0	3	1	4	3	0	3
Su-7 BKL	0	1	0	1	2	0	2
Total for aircraft type	**0** **(0 %)**	**4** **(80 %)**	**1** **(20 %)**	**5** **(100 %)**	**5** **(100 %)**	**0** **(0 %)**	**5** **(100 %)**
L-159							
L-159	0	0	0	0	1	2	3
Total for aircraft type	**0** **(0 %)**	**0** **(0 %)**	**0** **(0 %)**	**0** **(0 %)**	**1** **(33.3 %)**	**2** **(66.7 %)**	**3** **(100 %)**
L-29							
L-29	0	0	0	0	2	0	2
Total for aircraft type	**0** **(0 %)**	**0** **(0 %)**	**0** **(0 %)**	**0** **(0 %)**	**2** **(100 %)**	**0** **(0 %)**	**2** **(100 %)**
MiG-19							
MiG-19 PM	0	1	0	1	0	0	0
Total for aircraft type	**0** **(0 %)**	**1** **(100 %)**	**0** **(0 %)**	**1** **(100 %)**	**0** **(0 %)**	**0** **(0 %)**	**0** **(0 %)**
L-39							
L-39 C	0	1	0	1	0	0	0
Total for aircraft type	**0** **(0 %)**	**1** **(100 %)**	**0** **(0 %)**	**1** **(100 %)**	**0** **(0 %)**	**0** **(0 %)**	**0** **(0 %)**
JAS-39							
JAS-39 C	0	0	0	0	1	0	1
Total for aircraft type	**0** **(0 %)**	**0** **(0 %)**	**0** **(0 %)**	**0** **(0 %)**	**1** **(100 %)**	**0** **(0 %)**	**1** **(100 %)**
Total for all	**1** **(7.1 %)**	**12** **(85.8 %)**	**1** **(7.1 %)**	**14** **(100 %)**	**48** **(84.2 %)**	**9** **(15.8 %)**	**57** **(100 %)**

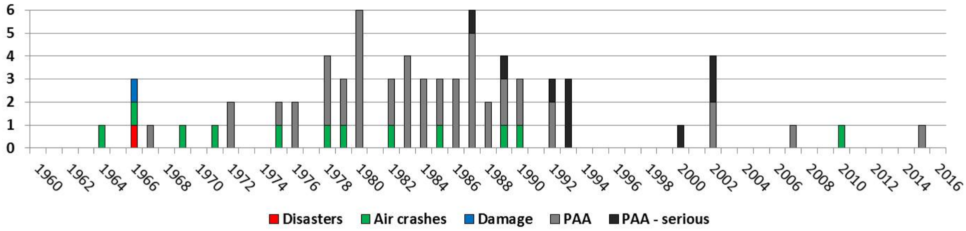

Fig. 3 Graphical overview of numerical representation of AA and PAA types associated with aircraft engine surge in 1960–2016 [8-15]

The most frequent flight stage in which the engine surge events were recorded was the flight task (78.9 % of cases). In other recorded stages of flight (take-off, climb, arrival and approach maneuvering), the engines surged on rare occasions.

The data also show that the incidence of jet engine surges bears no relation to the time of day or the time of year.

3.2. Hazardous Causes

For the purposes of this study, three indicators can be defined for the analysis of the causes of AAs and PAAs in question: the main cause factor (see Tab. 2), the main cause and the specific technical cause (see Tab. 3).

The main cause factor expresses traceable and verifiable origin of the main cause and the specific technical cause. It can be divided into technical factor (TF), human factor (HF), environmental factor (EF) and unknown or not found (N). The human factor can further be subdivided into human factor of the flight personnel (HF-fp) and that of the non-flight personnel (HF-np).

The above table shows (see Tab. 2) that the AAs and PAAs in question were predominantly caused by TF failures (38 cases – 53.5 %) and by HF-fp (16 cases – 22.5 %). In a relatively high number of cases, the cause was never found or established (11 cases – 15.5 %). Other cause factors (LF-np and EF) were represented in smaller numbers (3 cases – 4.2 % for both cause factors).

The main cause can be described in accordance with the Všeob-P-10 regulation [6] by one of the 26 options listed therein. The following 11 main causes were reported in the AAs and PAAs in question: operational degradation (22 cases – 31.0 %), not found (11 cases – 15.5 %), construction design and manufacturing defects (9 cases – 12.7 %), noncompliance with regulations by the crew (8 cases – 11.3 %), piloting (7 cases – 9.9 %), other causes (7 cases – 9.9 %), avian damage management (2 cases – 2.8 %), unit's aviation engineering services (2 cases – 2.8 %), use of aviation equipment (1 case – 1.4 %), poor quality of work in manufacturing or repair plants (1 case – 1.4 %), and foreign object ingestion with no fault of the unit's aviation engineering services (1 case – 1.4 %).

The specific technical cause formulates precise reasons of the occurrence of surge in the aircraft's engine system. The 10 recorded specific technical causes can be divided into three groups, based on the physical nature of the problem caused (see Tab. 3).

Tab. 2 Factors of the main causes of AAs and PAAs linked causally to engine surge and meteorological conditions under which they occurred in 1960–2016 (arranged by aircraft type and number of events) [8-15]

Aircraft type and version	**AA's and PAA's (engines surge) main cause factor**					**Meteorological conditions in AA and PAA**			
	TF	**LF-lp**	**LF-np**	**FP**	**N**	**NWCD**	**DWCD**	**NWCN**	**DWCN**
MiG-21									
MiG-21 F	3	0	1	1	2	6	1	0	0
MiG-21 PF	3	2	0	0	1	5	1	0	0
MiG-21 PFM	3	0	0	1	0	3	0	1	0
MiG-21 R	1	0	0	0	0	1	0	0	0
MiG-21 MA	1	0	0	0	0	1	0	0	0
MiG-21 MF	9	3	0	0	0	11	0	1	0
MiG-21 UM	0	0	1	0	1	2	0	0	0
Total for aircraft type (33 = 100 %)	**20 (60.6 %)**	**5 (15.1 %)**	**2 (6.1 %)**	**2 (6.1 %)**	**4 (12.1 %)**	**29 (87.8 %)**	**2 (6.1 %)**	**2 (6.1 %)**	**0 (0 %)**
MiG-23									
MiG-23 BN	5	5	0	0	2	11	0	0	1
MiG-23 ML	1	2	0	0	0	3	0	0	0
MiG-23 MF	4	1	0	0	0	1	3	1	0
Total for aircraft type (20 = 100 %)	**10 (50 %)**	**8 (40 %)**	**0 (0 %)**	**0 (0 %)**	**2 (10 %)**	**15 (75 %)**	**3 (15 %)**	**1 (5 %)**	**1 (5 %)**
Su-7									
Su-7 BM	3	1	0	0	3	7	0	0	0
Su-7 BKL	1	1	0	1	0	3	0	0	0
Total for aircraft type (10 = 100 %)	**4 (40 %)**	**2 (20 %)**	**0 (0 %)**	**1 (10 %)**	**3 (30 %)**	**10 (100 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**
L-159									
L-159	2	1	0	0	0	3	0	0	0
Total for aircraft type (3 = 100 %)	**2 (66.7 %)**	**1 (33.3 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**3 (100 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**
L-29									
L-29	1	0	1	0	0	2	0	0	0
Total for aircraft type (2 = 100 %)	**1 (50 %)**	**0 (0 %)**	**1 (50 %)**	**0 (0 %)**	**0 (0 %)**	**2 (100 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**
MiG-19									
MiG-19 PM	0	0	0	0	1	0	0	0	1
Total for aircraft type (1 = 100 %)	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**1 (100 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**1 (100 %)**
L-39									
L-39 C	1	0	0	0	0	1	0	0	0
Total for aircraft type (1 = 100 %)	**1 (100 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**1 (100 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**
JAS-39									
JAS-39 C	0	0	0	0	1	0	0	0	1
Total for aircraft type (1 = 100 %)	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**1 (100 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**1 (100 %)**
Total for all (71 = 100 %)	**38 (53.6 %)**	**16 (22.5 %)**	**3 (4.2 %)**	**3 (4.2 %)**	**11 (15.5 %)**	**60 (84.5 %)**	**5 (7.1 %)**	**3 (4.2 %)**	**3 (4.2 %)**

Under certain circumstances, all causes of engine surges without exception can be fatal for the aircraft crew members. It is, however, possible to statistically evaluate which of them have caused so far the greatest damage or the most serious consequences.

The most hazardous causes of engine surge for aircraft are definitely those that lead to engine failure or damage (mechanical or thermal) in flight. In the Czech Republic, past experience indicates that this applies mostly to the cases when animals or foreign objects (including blades of the compressor itself, shed by force or by fatigue and not contained) are sucked into the engine.

Other hazards include damage to compressor blades due to dust erosion that takes place near the earth's surface (mostly on the ground, in very low or low altitudes). In the course of time, dust particles abrade the compressor blades changing not only their mechanical properties (strength) but also their aerodynamic properties resulting in a significant reduction in engine performance and service life (evidenced, for example, by the experience of the United States Army or the former Soviet Union from wars in Afghanistan) [16, 17]. In volcanically active zones, there is a risk of volcanic ash ingestion and its burning onto the surface of compressor blades leading to changes in their aerodynamic properties or even to a compressor halt (engine failure in flight). In the proximity of saline water bodies, the salt may cause corrosive wear to the compressor blades affecting adversely their mechanical properties (strength), as well as their aerodynamic characteristics [18].

Tab. 3 Overview of specific technical causes of AAs and PAAs linked causally to jet engine surge in 1960–2016 (arranged by number of cases) [8-15]

Group of specific technical causes	Specific technical cause	Number of cases (percentage)
Undesirable changes in the amount of air supplied to the engine *(Total: 41 cases – 68.3 %)*	Off-design changes in air flow at inlets (at flights in stratospheric altitudes or aerobatics)	17 (28.3 %)
	Inlet malfunctions	15 (25.0 %)
	Inspiration of exhaust gases from another aircraft's engine, or combustion products from a launched rocket, or inspiration of hot gases from a shooting cannon	7 (11.6 %)
	Spontaneous rearrangement of compressor vanes	1 (1.7 %)
	Compressor inspection cover fall-off causing a change in the amount of supply air	1 (1.7 %)
Undesirable changes in the quantity of fuel supplied to the engine *(Total: 10 cases – 16.7 %)*	Incorrect engine control procedure by the crew (causing improper control of the fuel supply to the engine, especially in stratospheric altitudes)	6 (10.0 %)
	Faults in the system of automatic regulation of fuel supply to the engine	4 (6.7 %)
Foreign object ingestion *(Total: 9 cases – 15 %)*	Blade non-containment	5 (8.3 %)
	Bird or foreign object ingestion	3 (5.0 %)
	Ingestion of pieces of prematurely exploding rocket	1 (1.7 %)
Total		**60 (100 %)***

*Note: In 11 out of total 71 recorded compressor surge events the causes were not found; therefore, the percentage shown in the table refers to the 60 cases with known causes.

3.3. Hazardous Flight Phases

The danger of a flight phase in relation to the risk of the occurrence and consequences of the jet engine surge is determined primarily by flight height, flight speed and flight mode.

For the purposes of investigations of AAs and PAAs, 6 flight height intervals are distinguished: on the ground (0 m), very low (0-200 m), low (200-1000 m), medium (1 000-4 000 m), high (4 000-12 000 m) and stratospheric (over 12 000 m) [6]. If flight height is the only factor taken into account, then the risk of surge occurrence in jet aircraft engines increases with higher altitudes. It is usually the highest in stratospheric altitudes close to the aircraft's ceiling. This is due to the technical limits of the particular inlet system for the intake of air into the engine compressor, as well as to the technical design of the compressor itself regarding its capability to inspire and compress enough air to generate ideal air-fuel mixture in combustion chambers. It is, however, necessary to distinguish between safety risks for the engine and safety risks for the crew. While the safety risk for the engine increases with increasing flight height, for the crew it is quite the opposite. The lower the flight height, the higher the risk of disastrous consequences for the crew if an engine surge actually occurs. In low heights there is usually very little time – if any – to successfully resolve such type of in-flight emergency.

The flight speed in jet aircraft can be basically divided into three ranges: subsonic (Mach number $Ma < 0.8$), transonic (Mach number $Ma = 0.8$ to 1.2) and supersonic (Mach number $Ma > 1.2$). If flight speed is the only factor taken into account, then the risk of surge occurrence in jet aircraft engines increases with higher speeds. Again, this is due to the technical limits of the particular inlet system for the intake of air into the engine compressor, as well as to the technical design of the compressor itself regarding its capability to inspire and compress enough air to generate ideal air-fuel mixture in combustion chambers. The physical problem lies in the capability of these technical systems to cope with changes in airflow pressure and velocity field when the supersonic shock wave passes through the inlet. In this case, the safety risks for the engine and for the crew are consistent: The higher the flight speed, the higher the risk of both serious consequences for the engine and the catastrophic consequences for the crew if the engine surge actually occurs. The danger to aircraft crews arises from technical limitations in guaranteed functionality of ejection seats. Ejection seats can be safely used only at a limited flight speed range, usually at subsonic speeds.

Flight mode can be defined as the aircraft's motion state determined by its position in space, the speed of motion and angular speeds around aircraft's principal axes (longitudinal, transverse and vertical). Flight modes can be divided into rectilinear and curvilinear, and into steady and unsteady. With regard to the risk of engine surge, the flight mode affects the way the air flows around the aircraft's air inlets. Under certain conditions in specific aircraft types, the air flow through the inlet can be restricted due to an excessive change in the flow direction around the inlet lip at a given speed. Generally, the surge risk increases with the degree of curvilinearity (i.e., with the maneuver dynamics and reached g-force) and unsteadiness (e.g., in spins or dives) of the flight mode. The risk further increases for the engine with increasing flight height (maneuvering in stratospheric altitudes) and for the crew with decreasing flight height and speed (risk of diving or spinning at heights where there is insufficient time to successfully resolve the situation). Unfortunately, it is not possible to define exact rules in this respect, because resilience to these phenomena depends on the technical and aerodynamic design of an aircraft that can vary greatly between individual types of aircraft or even between versions of the same type of aircraft. However, some aircraft types are known to have been more susceptible to these phenomena (see below).

In the context of the above, regarding the possibility of occurrence of a jet engine surge and its consequences, the most hazardous flight phases can be regarded those that take place in low heights in the second flight mode (i.e., in low-speed flights with a high angle of attack of the wings) or, on the contrary, in supersonic speeds. In addition, in very low and low heights the bird strike (bird ingestion) risk is increased, as well as erosive effects of dust particles that gradually upset the compressor blades aerodynamics or even cause shedding of blades due to changes in their mechanical properties. Engine rundown or failure in such situations means an immediate emergency or a disastrous scenario for the crew with the need to abandon the aircraft (eject). This is evidenced by the fact, that almost all AAs (disasters, crashes, damage) linked causally to jet engine surge resulted from in-flight emergencies occurring at low (200-1 000 m above ground) or very low (less than 200 m above ground) flight heights. It is obvious that at such heights the crew members usually have not enough time to address the situation successfully. When similar situations took place in higher altitudes, they were often resolved with success and classified just as PAAs.

3.4. "Hazardous Aircraft" – Aircraft with Increased Surge Risk

In order to assess the hazard of an individual type of aircraft poses in terms of possible occurrence of engine surge, at least 5 aspects must be considered: predestination of the aircraft, the aircraft's engine generation, the level of anti-surge protection of the engine, aircraft's design and aerodynamics (especially those of air inlet), and reliability of specific airborne systems of the aircraft (especially reliability of regulated or unregulated inlet and fuel supply systems).

The predestination of different types of aircraft characterizes the primary purpose for which they were designed. This purpose varied from type to type and also had its own history. To a great extent, it also determined the level of risk to the crew. There are single-purpose and multi-purpose aircraft; the former ones include fighter, bomber and attack aircraft, while the latter ones include fighter-bomber, bomber-attack, trainer-reconnaissance, trainer-fighter-attack and fighter-attack-reconnaissance aircraft. The highest safety risks for the crew are in fighter aircraft (especially in supersonic fighters), as they operate in the widest range of altitudes, speed and flight modes; therefore, the possibilities for the generation of in-flight emergencies are also wide-ranged.

The engine generation (from the first to the current fifth generation of engines) indicates a set of typical design features and performance parameters for the given engine, including those that influence the likelihood of engine surge occurrence and elimination. The more recent the generation of engines which the aircraft is equipped with, the better performance parameters of the engine for higher speeds are, and hence the more complex the anti-surge design is [19, 20].

The level of anti-surge protection of the engine reflects the capability to prevent or eliminate engine surges in the most rapid and efficient way without the risk of subsequent mechanical or thermal damage to the engine.

Fig. 4 Examples of various inlet designs: (1) MiG-21, (2) MiG-23, (3) MiG-29 [5]

The aircraft's design and aerodynamic features influence the capability to inspire enough air into the compressor under different conditions and flight modes. For examples of various air inlet designs, see Fig. 4.

The reliability of specific airborne systems in this case refers, to failure incidence in systems that affect air and fuel supply to the engine.

In the context of the above mentioned facts, in terms of possible occurrence and consequences of engine surges, the following aircraft can be regarded as hazardous:

A. aircraft designed (predestined) to fly in limit conditions and flight modes that can induce surging in engines (stratospheric altitudes, aerobatics, etc.);
B. suffering from design and aerodynamic deficiencies (especially in air inlets);
C. aircraft which are not equipped with anti-surge systems to prevent surges or suppress those that have already occurred; or
D. suffering from failures of airborne air and fuel supply systems.

Aircraft with a combination of more of the above factors can be regarded as the most hazardous, i.e. aircraft susceptible to compressor surging in low flight heights, with a low level of anti-surge protection of the engine and above-average failure rate of key technical systems that have dominant influence on the occurrence of engine surges (in particular, air inlet systems and automatic fuel supply regulation systems).

4. Current Engine Surge Hazards

For the purposes of current flight safety practice, it is necessary to differentiate causes of engine surges that are no longer valid from those that may still apply (for a comprehensive overview see Tab. 3 above). Many engine surge causes are of the past thanks to advances in technology and aircraft design. Apart from them, some causes are present and can still be a threat to air traffic. The question is, if and how they can be dealt with. The statistics of AAs and PAAs of aircraft types that are still in active service in the AF ACR show that the current causes of jet engine surges include:

A. Inspiration of exhaust gases from another aircraft's engine or a rocket, or inspiration of exhaust gases from cannon shooting.
B. Fuel supply system malfunctions.
C. Non-containment (ingestion) of a compressor blade.
D. Bird or foreign object ingestion.
E. Unpredictable airflow changes at the inlet (wind gusts, maneuvering).

Fortunately, the risks arising from these causes can now be greatly reduced.

The risk of inspiration of exhaust gases from another aircraft's engine, launched rocket or shooting cannon can be reduced by observing separation in formation flights and, in case of any firing, by choosing adequate shooting profiles and avoidance maneuvers. The risk of malfunction of fuel supply to the engine can be reduced by rigorous maintenance and inspections of aircraft, as well as by monitoring the fuel quality. The risk of shedding and non-containment of a compressor blade can be reduced by additional surface treatment of blades which increases the blades' abrasion resistance from dust particles and corrosion resistance from salt and humidity. For example, abrasion, corrosion and high temperature resistant titanium-zirconium nitride coating, in a thin layer of several micrometers (2-3 μm), extends the life of a blade by two to three times (for details, see [17]). The risk of bird or foreign object ingestion can be reduced, for instance, by a suitable camouflage of the aircraft (for bird strike and ingestion) or by air inlet guards (for foreign object strike and ingestion). The experience gained in the past shows that metallic glistening gray color camouflage greatly reduces the likelihood of a bird strike. An aircraft of this color and gloss is for most birds in wildlife a foreign element visible over long distances which they tend to keep away from. Another type of ingestion protection is, for example, closable inlet grates that only open at a certain stage of flight (for example, see the MiG-29 inlet design in Fig. 4 above).

5. Means of Engine Surge Control

Aircraft engine surge control consists in applying technical and practice measures. Technical measures involve mostly fundamental engine design concept characteristics and compressor and inlet anti-surge equipment and devices (see below). Practice measures include adherence to aircraft operation and maintenance principles by both flight and non-flight personnel, i.e. by aircraft crews and by ground air maintenance staff.

However, there are factors that cannot be entirely eliminated by any of the above measures (air flow dynamics in the atmosphere, bird strikes, etc.). Therefore, in general, the surge risk can only be reduced (see Sections 5.1 to 5.3 below), but not completely removed.

5.1. Anti-surge Systems – General

Engine surge can generally be avoided by controlling the amount of air entering the engine compressor (by regulating the air flow rate at the inlet) or quantity of fuel supplied into the engine combustion chambers.

The control of intake air is provided by a controllable inlet (if equipped), which is a part of the airframe (see Fig. 4 for an example), and works in relation to the quantity of fuel supplied to the engine. The optimal amount of inlet air is primarily calculated for the actual flight speed, altitude and engine speed (mode). The inlet control system can secondarily respond to, for example, excessive elevator tilt (change in inclination of the aircraft to the airflow leads to a change in how the air flows around the inlet), attaining the limit altitude which the engine is designed for (especially near the aircraft's flight ceiling), or to auto activation of surge suppression elements and systems [21, 22].

The control of fuel flow rate is provided by automatic control system of fuel supply to the engine. Its function is to deliver a continuous supply of fuel to the engine under all design operational conditions according to the specified control program (e.g., the engine speed determines the quantity of fuel supplied into the combustion chamber, etc.). In older jet aircraft, the system was controlled by an "engine controller" operated by pilot through the engine control lever. In present-day jet aircraft in the AF ACR (that is, the Aero L-159 ALCA and the Saab JAS 39 Gripen), the system is tied with the FADEC (Full Authority Digital Electronic Control) computer that processes a variety of data coming from engine and aircraft sensors, signals from autopilot and autothrottle, as well as requirements from the pilot exercised through the engine control lever. Based on these signals and data, the airborne computer controls the optimal fuel supply to the engine in order to avoid its operation in off-design conditions. If there are any indications that an engine surge may arise, the computer shuts off the fuel supply to the engine, the engine itself, and subsequently relights the engine in flight. This is a procedure by which the conditions for surge generation vanish usually. In different aircraft types these systems can be set up and synchronized differently.

Anti-surge system of an aircraft is a technical system designed to prevent surge from occurrence or to recover from the existing one. Therefore, two sub-systems of anti-surge system can be identified:

A. Surge prevention sub-system.
B. Surge suppression sub-system.

The objective of the surge prevention sub-system is to eliminate in advance physical conditions in the engine, in which the occurrence of surge can be envisaged by design (by controlling the air or fuel supply to the engine). This subsystem first appeared in the former Czechoslovakia with the MiG-19 being introduced into service. The MiG-19's RD-9b engine was equipped with an air bleed band located behind the 5th axial compressor stage; its function was controlled by engine speed. Later on, aircraft were equipped with more surge control features, such as air bleed valves, compressor casing treatment – circumferential grooves, stator vanes adjustment mechanisms, multi-spool design of compressors, suction relief doors, or spill doors (see Section 5.2 below). The MiG-23s [23], Su-22s [24] and MiG-29s [25] were equipped with a surge control function activated when armament was used. It automatically reduced fuel flow into the engine while the button for firing was pressed as a possibility of inspiration of hot exhaust gases released during cannon shooting and rocket launching was envisaged. The MiG-21 in version MF was retrofitted with this surge control feature later during its service [21].

The objective of the surge suppression subsystem is to respond to physical conditions detected by airborne sensors by automatically shutting off the fuel supply to the engine, shutting off the engine and its subsequent relighting in flight. This subsystem first appeared in the former Czechoslovakia with the MiG-23 [23] being introduced into service. The R-29B-300 engine, as well as the MiG-23's R-35-300 engine later, was equipped, among other protection features, by this anti-surge system (known as SSP) to facilitate this function in a range of defined flight heights and speeds. Later, in aircraft with axial compressor engines, a similar system was deployed routinely (for example, the current FADEC system).

Inlet distortions and compressor surges can be removed using:

I. Controllable anti-surge devices.
II. Self-actuating anti-surge elements.

Controllable anti-surge devices include, among others, devices for bleeding excess air from compressor middle stages, mechanisms for pivoting stator vanes in the first or several front compressor stages, or inlet regulation mechanisms (inlet doors, retractable inlet cones, etc.).

Self-actuating anti-surge elements include, among others, multi-spool design of compressors (compressor protection), compressor casing treatment – circumferential grooves (compressor protection), spill doors (inlet protection), or suction relief doors (inlet protection).

Air bleeding is performed using air bleed bands (e.g., in the MiG-19's RD-9B engine and in the Su-7's AL-7F-1 engines) or air bleed valves (e.g., in the L-39's AI-25TL engine) that release the excess air from a slot formed around the circumference of the compressor stage outside the engine (controlled by engine speed). In terms of design, this is the simplest method that was applied in the oldest jet engines and in combination with other anti-surge protection features, it is applied even today. In turbojets it was less energy-efficient, because the bleed air was removed completely off the engine, which reduced the amount of air available for engine thrust. In turbofans, this is no longer an issue as the bleed air is released from the compressor into the bypass air stream.

Pivoting of stator vanes influences the intake air flow rate (intake air quantity) and pressure conditions in different compressor stages (controlled by engine speed). Although this solution is more energy efficient, it is also more difficult to design and manufacture than the former one. Nonetheless, it is applied in almost all jet engines of the latest generations.

Multi-spool design of compressors allows the air compression to proceed stepwise in parts while each part (each rotor) operates at different speed, optimal for achieving the desired compression. This is the most efficient, but also the most complicated solution in terms of structural design [1].

5.2. Anti-surge Systems in Selected Aircraft

During the jet era in the former Czechoslovakia and the present Czech Republic, engine surge events have been recorded in 17 versions of 8 jet fighter, fighter-trainer and trainer aircraft types (see Tab. 1 and Tab. 2 above).

The aircraft were equipped with the total of 10 types of air-breathing jet engines in 14 versions. Their list, together with aircraft types and versions they were used in and their protection against surge is shown in Tab. 4. Detailed information on specific surge protection features can be found, for example, in [1, 3, 19, 20].

Tab. 4 List of engine types, in which engine surge events were recorded in 1960–2016 (arranged in descending order of number of cases) and their protection against surge [3, 8-15]*: (1) air bleed bands, (2) air bleed valves, (3) compressor casing treatment – circumferential grooves, (4) spill doors, (5) suction relief doors, (6) inlet guide vanes, (7) multi-spool design of the compressor, (8) anti-surge system – airborne computer system (e.g., SPP or FADEC)*

Aircraft type and version	Engine type and version	Protection against engine surge	Number of surge events
MiG-21 MF, UM	Tumansky R-13-300	(2), (3), (4), (5), (7), (8)*	14 (19.7 %)
MiG-23 BN	Khatchaturov R-29B-300	(3), (7), (8)	12 (16.9 %)
Su-7 BM	Lyulka Al-7F-1-100	(1), (3), (4), (6)	7 (9.9 %)
MiG-21 F	Tumansky R-11F-300	(2), (4), (5), (7)	7 (9.9 %)
MiG-21 PF	Tumansky R-11F2-300	(2), (4), (5), (7)	6 (8.5 %)
MiG-21 PFM, MA, R	Tumansky R-11F2S-300	(2), (4), (5), (7)	6 (8.5 %)
MiG-23 MF	Khatchaturov R-29-300	(3), (7), (8)	5 (7.0 %)
MiG-23 ML	Khatchaturov R-35-300	(3), (7), (8)	3 (4.2 %)
Su-7 BKL	Lyulka Al-7F-1-200U	(1), (3), (4), (6)	3 (4.2 %)
L-159	Honeywell/ITEC F124GA-100	(1), (6), (7), (8)	3 (4.2 %)
L-29	Motorlet M-701	-	2 (2.8 %)
MiG-19 PM	Mikulin RD-9b	(1)	1 (1.4 %)
L-39 C	ZMBD Progress (Ivchenko) AI-25TL	(2), (6), (7)	1 (1.4 %)
JAS-39 C	Volvo Aero RM12UP	(6), (7), (8)	1 (1.4 %)
Total			**71 (100 %)**

*Note: The anti-surge system with the subsystem for surge prevention at armament firing was retrofitted to MiG-21 MFs and was not present in other versions of the aircraft.

5.3. Anti-Surge Systems – Current Development Trends

Taking a long-term perspective of the use of air-breathing jet engines in military aviation, not only in Czechoslovakia and the Czech Republic, the following development trends in anti-surge protection of aircraft engines have been formulated; the list can be divided into two groups: anti-surge protection in inlets (inlet distortions can cause the engine compressor to surge) and anti-surge protection of compressors themselves.

Development trends in anti-surge protection in inlets can be formulated as a shift:

1. from long and narrow inlets to shorter and broader ones (the inlet length-width ratio has changed);
2. from unguarded to guarded inlets;
3. from inlet lips located in the front to those located on the sides or at the bottom;
4. from subsonic to supersonic.

Development trends in the protection of compressors against surge can be formulated as a shift:

1. from single-spool to multi-spool design;
2. from a single protective element to a combination of multiple elements at a time;
3. from surge suppression to surge prevention equipment (with the priority to prevent surging in engines by means of electronic control systems);
4. from mechanical surge prevention and suppression elements to software control and optimization of engine operation for surge prevention and suppression;
5. from manual to automated (computer controlled) engine control procedures for surge prevention and suppression;
6. from slower to more rapid automatic procedures of surge prevention and suppression;
7. in increasing the resistance of compressor components against undesired mechanical, chemical and thermal conditions.

From a global perspective, inlet designs have been optimized for better aerodynamics, and surge detection in engine compressors, as well as their protection against surge has grown more rapid and automated.

6. Conclusion

The analysis of the existing AA and PAA statistics has shown that compressor surge events in air-breathing engines in jet fighter, fighter-trainer and trainer aircraft in service of the former Czechoslovakia and the present Czech Republic were far from rare (71 cases in 56 years). Moreover, some of them resulted in emergency situations or even had disastrous consequences for the aircraft crews.

According to traceable investigation files, most of the cases were caused by undesirable changes in the amount of air supplied to the compressor (41 cases – 68.3 %). For all 71 cases tracked down, the most common main cause factors were TF (38 cases – 53.5 %) and HF-fp (16 cases – 22.5 %).

Development trends in the design of aircraft engines and anti-surge equipment show that the influence of technical and humans factors on the possibility of surge event occurrence has gradually decreased. The influence of technical factors has decreased thanks to advances in aircraft design and construction technology. The influence of flight personnel human factor has decreased through the introduction of computer-controlled automatic fuel supply systems and systems to restrict the possibility to fly the aircraft outside its flight envelope (especially with regard to permissible airspeed and load factor limits). So far, however, there is no pilot-warning system for excessive lateral movements of the aircraft in transverse direction (slips, falls or spins) that can cause inlet distortions and lead to an engine surge. Also, the environment factor influence, as regards the air flow dynamics and foreign object ingestion hazard, has not significantly decreased.

In this context, it is desirable that flight personnel members in particular be well informed on the risks and principles of engine surge incidence, especially at supersonic flight speeds, maneuvering, altitudes approaching the aircraft's ceiling, animal or foreign object ingestion, including ingestion of ice (for example, in the event of the aircraft's anti-icing system failure), by operational deterioration or at flying in aggressive environments (mechanical wear – erosion from dust particles, ingestion of volcanic ash, or chemical wear – salt corrosion or other chemical contamination of the blades surface resulting in changes in their aerodynamic properties). It is necessary to consider the environmental influences and adapt to them the mode of utilization of aircraft, as well as types and frequency of inspections and maintenance.

Obviously, the speed of computer-controlled anti-surge systems may further increase, but there is a physical limit that cannot be conquered: the natural dynamics of physical phenomena associated with air flow and compression and with the combustion of air-fuel mixtures.

It is therefore likely that jet engine surge events will, albeit more rarely, occur in the future and they cannot be avoided altogether until a switch to a different principle of propulsion and aircraft engine design that could eliminate them is made.

It follows from all of the foregoing that the issue of jet aircraft engine surges is by no means a matter of the past. On the contrary, this is a very topical problem because it has not yet been possible to find compensatory mechanisms for all known causes of their origin. The causes that are still present, not only in the Czech Republic, include unpredictable changes in direction and velocity of airflow in the atmosphere (atmospheric dynamics – turbulence), bird strikes and ingestion of foreign objects into the engine compressor. Although new generations of engines, as well as new designs of inlets, are already aerodynamically optimized and tested for ingestion of solid objects, these types of resistance are still severely limited due to the wide range of possible and established variants. Moreover, a new threat emerged – drones. Particularly high risks arise from their uncontrollable traffic and use in both civilian and military spheres. Even low-weight drones (approx. over 0.5 kg) can cause devastation or destruction to the engine when ingested. This is a challenging issue for the future flight safety, which, according to the authors of this study, should be a matter of further scientific research.

Acknowledgement

This study has been supported by the project: SP2018/152 – Developments in flight safety of military jet aircraft in conjunction with fire occurrence and aircraft crew ejection during flights.

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